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Review Article

# Elbow-Hand Robotic Exoskeletons for Active and Passive Rehabilitation on Post-Stroke Patients: A Bioengineering Review

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**Abstract**

The clinical applications and benefits of the use of a Robotic Exoskeleton for Rehabilitation (RER) in the elbow and hand are described because a RER is a high-quality alternative capable of restoring compromised functions and neurorehabilitation at the same time in post-stroke patients. Passive rehabilitation (PR) is usually applied in the early stages of post-stroke recovery. The responsibility of assisting Physical Medicine and Rehabilitation (PM&R) doctors and the patient with passive exercises is a robotic system (RS); while active rehabilitation (AR) is applied regularly in late stages, it is like PR and its implications but requires the strength and support of the person to perform the exercises voluntarily. The objective of the present study is to collect, synthesize, and report relevant scientific studies related to the implementation of exoskeleton systems for elbow-hand rehabilitation. Various scientific literature on the topic was reviewed in the main biomedical databases using the population, intervention, comparison, results, and context (PICOC) criteria. This study presents the potential and describes a comprehensive and updated vision of the consequences and improvements obtained with the use of the RER and its advances. In conclusion, the usefulness and importance of a RER in various applied clinical practices have found numerous advantages, such as a better evaluation of spasticity, neuromotor recuperation, promoting neuroplasticity, and much more, which is of global relevance since this study gives us a greater understanding of the potential of these new perspectives to improve the rehabilitation of compromised functions in post-stroke cases with the use of RER.

*Keywords:* Robotic Exoskeleton; Rehabilitation; Stroke; Hand; Elbow; Upper Extremities.

## 1. Introduction

Stroke is a disease that affects a person mainly at a neurological and cardiovascular level that can cause different aftermaths due to the obstruction of blood vessels, interrupting circulation, causing lack of oxygen in a part of the brain,

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and the death of brain cells [1]. To better understand the importance of stroke, it is necessary to mention some of the clinical manifestations attributable to stroke, like numbness or weakness of the extremities, dysarthria, vision problems, and difficulty performing fine and gross movements. Worldwide, stroke stands out as one of the main causes of mortality. According to the World Health Organization (WHO), these have an incidence of 200 cases per 100,000 inhabitants/year, with an anticipated increase of 27% between 2000 and 2025 in Latin America and the Caribbean. There was an increase from 465,634 cases in 1990 to 708,355 cases in 2019 [2]. Therefore, stroke has obtained second place as one of the causes of death worldwide with approximately 11% mortality [3]. Moreover, it has been identified that 70 to 80% of stroke survivors reveal limited functional use or no ability at all to move the upper limb (UL), which significantly impacts their quality of life as it affects the ease of carrying out basic activities such as eating, writing, dressing, and bathing [4-6]. In its beginnings, traditional rehabilitation therapy for patients who survived a stroke mainly involved massages, acupuncture, physiotherapy, and electrical stimulation, being widely applied to improve and recover compromised body functions; however, in many cases it leads to an increase in personnel costs and dependence on human factors [7, 8].

Currently, new biomedical technologies can be used for surgical [9-14] and rehabilitation applications [7, 15], such as Robotic Exoskeletons for Rehabilitation (RER), which are being developed. Hence, clinical applications in post-stroke patients are continuously updated [16, 17]. In fact, the focus is on neurorehabilitation, analyzing the neurophysiological bases of the potential for rehabilitation centered on neuroplasticity [18]. Exoskeletons such as SaeboGlove [19], NEUROExos Shoulder-elbow Module - γ (NESM- γ) [20], ArmeoSpring application, which allows the patient to work not only on motor function but also on cognitive abilities at the same time [21], MyoPro, helping with neuro re-education [22], Automatic Recovery Arm Motility Integrated System (ARAMIS), improving rehabilitation in ways that a single exoskeleton cannot achieve by itself [23], ExoReha exoskeleton, detecting users' intentions only with encoders integrated with the units, allowing active kinesiotherapy without adding sensory systems [24], and so much more, allowing this way greater versatility, resource-saving, exercises and rehabilitation tasks update, better neuromotor coordination in the movements to be performed, thus complementing the rehabilitation work of therapists [25, 26] such as Physical Medicine and Rehabilitation (PM&R) physicians [27]. There are various ways to classify orthoses among them, according to the degrees of freedom (DOF), the location of the device on the body, the method of action according to the actuators, the application domain, as well as the control mechanism and power transmission [11, 28].

Highlighting that upper extremity orthoses target fine motor control and focus on achieving a functional range of motion, ensuring correct control of movement through passive rehabilitation (PR) and active rehabilitation (AR), with the elbow-hand RER being the focal point of this study. It is proposed that the use of RER through goal-directed movements presents a high-quality alternative to regain mobility and precision [29]. This manuscript addresses 2 types of rehabilitation treatment, passive and active. PR is typically applied during the initial stages of post-stroke recovery, where a robotic system (RS) assists the patient by providing greater joint expansion, movement, and flexibility in the upper limbs through passive mechanisms [12, 30]. Moreover, AR is used mainly in advanced stages with a passive mechanism that requires the strength and support of the sufferer to perform the movement voluntarily. This approach allows for greater irrigation of the affected area, improves neuroplasticity, reduces healing time, and refines grip position coordination [31]. Therefore, considering that stroke is an important Public Health problem, the objectives of this research are: (1) Compile, synthesize and report on relevant clinical studies related to the implementation of exoskeleton systems for elbow-hand rehabilitation, (2) identify the potential of PR and AR regarding RER in the global context, and (3) present a comprehensive and updated view on the current state of clinical applications and results derived from the use of biomedical devices in elbow and hand rehabilitation in post-stroke survivors [15, 32].

The aim of this paper is to reduce the distance of the clinical practice knowledge between bioengineering and medicine, that the current literature does not specified, the clinical applications and benefits of RER are generally known among the biomedical community and it also can be more visible in the whole medical field, this is a step to encourage the promotion of research in biomedical robotics that seeks solutions to improve the quality of health, trough different approaches implied in the exchange of skills of different professionals with technical and scientific backgrounds that collaborate in the development of RER. This study has included scientific studies from various geographical regions such as America, Europe, Asia and different healthcare settings from authorized Physical Medicine and Rehabilitation specialists to Rehabilitation Institutes and Health Centers that show a comprehensive understanding of RER in the elbow and hand clinical applications and benefits in post-stroke patients' rehabilitation.

## 2. Material and Methods

A scientific literature search was conducted on studies published over a 10-year period related to Elbow-Hand Robotic Exoskeleton Systems for Passive and Active Rehabilitation on Post-Stroke Patients, which have a correlation with clinical outcomes. This study was conducted to address the main question: What are the current clinical applications of elbow-hand Robotic Exoskeleton for Rehabilitation (RER) in post-stroke patients? The primary aim of this paper is to enhance understanding based on reports from relevant studies regarding the implementation of Elbow-Hand Exoskeleton systems. Additionally, it aims to identify the potential of both passive rehabilitation (PR) and active rehabilitation (AR) in the context of robotics within the field of RER, providing a comprehensive and updated overview of the current state of scientific inquiry and outcomes resulting from the use of biomedical devices such as RER in hand-elbow rehabilitation. The methodology applied in this study was a review of the literature. The research was carried out between January 2024 and March 2024. The objectives are aligned with the population, intervention, comparison, outcomes, and context (PICOC) criteria. Table 1 illustrates the PICOC strategy employed in this research [33].

**Table 1. PICOC strategy**

| PICOC criteria | Description |
|---|---|
| **Population** | Post-stroke patients requiring PR and AR |
| **Intervention** | Use of elbow-hand RE during PR and AR in post-stroke patients |
| **Comparison** | Passive and Active elbow-hand RE |
| **Outcomes** | Mobility, autonomy, and functional recovery of post-stroke patients |
| **Context** | Medical-based evidence that supports the use of elbow-hand RE in the PR and AR of post-stroke patients. |

## 2.1. Data Source and Search Strategy

The scientific literature search was carried out on: Scopus (www.scopus.com), EMBASE (www.embase.com), IEEE Xplore (ieeexplore.ieee.org), and PubMed (pubmed.ncbi.nlm.nih.gov) databases. The search strategy included the use of DeCS and MeSH descriptors in each database, Boolean operators (“AND” and “OR”) and the search terms targeted robotic exoskeletons used for active and passive rehabilitation therapy. The objectives are aligned with the population, intervention, comparison, outcomes, and context (PICOC) criteria. Table 1 illustrates the PICOC strategy employed in this research [33].

The main search strategy was as follows: #1 TS = ('robotic exoskeleton passive elbow rehabilitation' OR (robotic AND ('exoskeleton'/exp OR exoskeleton) AND passive AND ('elbow'/exp OR elbow) AND ('rehabilitation'/exp OR rehabilitation))); #2 TS = ('robotic exoskeleton passive hand rehabilitation' OR (robotic AND ('exoskeleton'/exp OR exoskeleton) AND passive AND ('hand'/exp OR hand) AND ('rehabilitation'/exp OR rehabilitation))); #3 TS = ('robotic exoskeleton active elbow rehabilitation' OR (robotic AND ('exoskeleton'/exp OR exoskeleton) AND ('active'/exp OR active) AND ('elbow'/exp OR elbow) AND ('rehabilitation'/exp OR rehabilitation))); #4 = ('robotic exoskeleton active hand rehabilitation' OR (robotic AND ('exoskeleton'/exp OR exoskeleton) AND ('active'/exp OR active) AND ('hand'/exp OR hand) AND ('rehabilitation'/exp OR rehabilitation))).

## 2.2. Selection Criteria

The types of scientific publications searched included “original full-text articles and evidence-based medicine studies", the scientific literature selected included publications from 2015 to 2024 and the languages considered were English, one of the main scientific languages, and Spanish. The scientific publications excluded from the research were the scientific literature older than 10 years, review articles for the results section. The resulting scientific articles were located, then those that were not related to the central research topic were discarded. Next, all the articles were read to later be able to identify those scientific articles that focus on the research objectives.

A total of 176 articles were initially identified, of which 140 were excluded based on the exclusion criteria. Subsequently, 20 studies on passive rehabilitation and 16 studies on active rehabilitation were included, with a further breakdown of 13 and 7 studies focused on the elbow, and 6 and 10 studies focused on the hand, respectively. Ultimately, 36 articles met the inclusion criteria and were included in the review. The selection strategy is shown below (Figure 1).

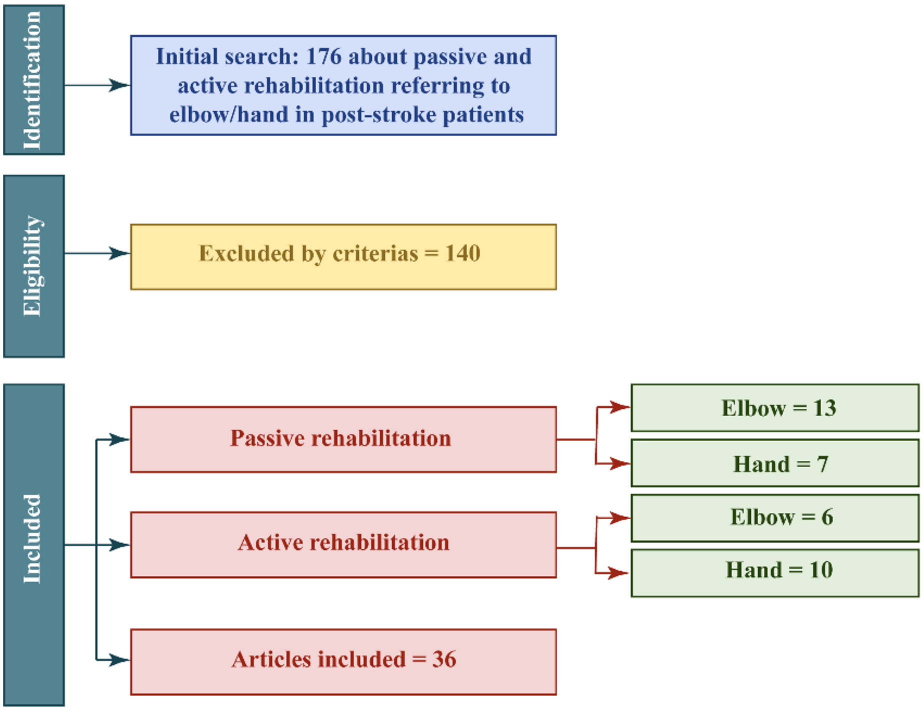


**Figure 1. Selection strategy diagram**

### 2.3. Limitations

This study was limited to only 2 languages, considering English as the main language in scientific research on this topic, aside English and Spanish, Scientific literature from other languages belonging to several of the main countries where the highest biomedical technology is being developed and applied clinically and whose scientific research is registered in those languages was not taken into consideration.

### 2.4. Ethical Aspects

Ethical committee approval was not required as this was a literature review.

## 3. Results

### 3.1. Passive Rehabilitation

In passive rehabilitation, a robotic exoskeleton system is utilized to facilitate exercises for post-stroke patients without requiring exertion from the individual, thereby enhancing range of motion and facilitating recovery of neuronal connections lost due to various traumas. This approach aids in performing movements more easily, gradually restoring independence in motor control when such movements could not be performed or were performed insufficiently. Passive rehabilitation is typically initiated in the early stages of post-stroke rehabilitation. Despite being termed passive, the system employed is active, as it executes pre-programmed movements without requiring user support.

Passive rehabilitation with a RER is applied in post-stroke survivors due to the notable consequences of spasticity. Spasticity is characterized by an abnormal increase in muscle tone, tendon reflexes, as well as clonus, contractures, pain, and limited joint mobilization [34]. Traditionally it is evaluated using the Modified Ashworth Scale (MAS) and the Modified Tardieu Scale (MTS) [35] carried out by PM&R physicians, with results largely dependent on their experience and expertise.

#### a. Elbow

Passive rehabilitation with a robotic exoskeleton at the elbow allows the use of exoskeletons that allow many characteristics to be objectively captured as precise monitoring through the cinematographic information obtained [25, 36-40] and often to guarantee its reliability is accompanied by the use of electromyography (EMG) [41-44] as shown in Table 2. However, its use is not recommended when it reaches a value of 4 on the modified MAS or the presence of fixed contraction in the affected limb [45].

The use of RER for the elbow allows real-time cinematographic data during each session carried out at a constant speed, measuring and calculating the resistance force obtained and muscle rigidity, transmitting the results to a computer [36, 37] allowing to safely carry the muscle strengthening by accommodating the strength systems to each patient. A study with the use of the KAPS robot [37] compared the results between healthy people and post-stroke survivors through passive stretching exercises of the elbow with flexion and extension movements obtaining significant differences such as the decrease in speed and the final angle, also allows to creep in the latter group, check the sensible and quantitative evaluation provided by the exoskeleton. Similarly, in another comparative study with REAplan [40], a person's performance was evaluated before and after a motor nerve block. This study quantified the decrease in resistance force in passive extension after the block and observed an increase in spasticity at high speeds.

The joint kinematic model RER for the elbow is often used to extract data metrics accompanied by EMG tests, which measure the electrical activity of the muscle and capture the intensity of the involuntary reflex, evidencing a positive and significant correlation between the two [42, 43]. The training carried out by the NEUROExos Elbow Module (NEEM) [44] was used together with EMG to evaluate biomechanical parameters, muscular performance, and muscular activity. This validates the use of the exoskeleton as an innovative methodology for the evaluation of spasticity and rehabilitation.

Regarding elbow motor recovery by RER, passive training consists of movements led by the exoskeleton, recommended in cases of severe spasticity and post-stroke onset, leading to motor improvements and proprioception [46]. For a remote evaluation, the use of two ARMin robots [25] was proposed, one used by the physiotherapist and the other by the patient, managing to evaluate the level of deterioration of the arms such as the altered quality of movement, resistance to passive exercise and range of movement reduced. However, it is recommended to complement the use of active-passive exoskeletons for more effective recuperation [47, 48]. These are some of the multiple benefits derived from the use of RER in elbow in post-stroke patients in passive rehabilitation therapy (Figure 2).

**Table 2. Clinical results of passive elbow rehabilitation by robotic exoskeleton.**

| Author (Year) | Country | Actuation Mechanism | Application | Results |
|---|---|---|---|---|
| McGibbon et al. (2013) [42] | Canada | The stretch reflex assessment uses a simple wearable sensor system to capture data during passive testing, along with a joint cine model to extract metrics from the cine and EMG data to capture the intensity of the involuntary reflex. | 9 stroke patients. | Kinematic metrics and EMG data are positively and significantly correlated with each other. |
| Grimm et al. (2016) [48] | Germany | Using the exoskeleton, lifting and gripping exercises were performed. Excessive assistance of the robot may lead weakening. | 5 patients with severe chronic stroke. | An improvement was observed in cinematographic parameters. range of motion, the precision of motion, and speed of movement A passive robot powered by the user's healthy elbow was designed, and the motor flaccidity was calculated using EMG. |
| Centen et al. (2017) [36] | Canada | Passive stretching of the elbow in flexion and extension, evaluating the difference in maximum speed. final angle and creep(release). | 96 healthy people and 46 stroke patients. | The results are compared between the affected limb and the healthy one, showing a decrease in the final angle in spasticity. KAPS Robot Provides Sensitive and Quantitative Assessment. |
| Crea et al. (2017) [40] | Italy | NEEM was used through passive mobilization exercises and adverse effects were evaluated. mechanical, electrical, or software failures. | 17 post-stroke patients, over 25 days after the stroke. | |
| Dehem et al. (2017) [39] | France | Each patient was evaluated before and after the motor nerve block, and the robot passively mobilized at various speeds. | 12 stroke patients Inclusion criteria were: adult (>18 years). | No adverse events or increased spasticity were reported. |
| Tze Hui et al. (2017) [4] | Singapore | The continuous passive encoder was designed based on user, intent detected by surface electromyography sensors attached to the biceps and triceps, using fabric and elastomeric pneumatic actuators. | It was tested on 6 healthy subjects. | The REA plan quantified the resistance strength of the upper limb. |
| Posteraro et al. (2018) [38] | Italy | Using the NEEM and rehabilitation sessions, spasticity was measured during the rehabilitation period. | 5 post-stroke patients between 19-79 years (mean age, 61). | The elbow brace was able to achieve approximately 50% of the full range of motion of extension and flexion of the elbow joint among all subjects. |
| Washabaugh et al. (2018) [47] | USA | A passive robot was designed powered by the user's healthy elbow; the motor flaccidity is calculated by EMG. | 6 survivors of unilateral stroke. | Subjects had high levels of muscle activation in the arm powered by self-power compared to those performed by externally powered reduced motor camp. |
| Baur et al. (2019) [25] | Germany | Two robots were used. ARMin, one used by the physical therapist and another by the patient, evaluates the level of alteration of arm movements. | 15 stroke patients and physiotherapists participated. 36 right-handed participants with stroke. | It was possible to quantify the common deficiencies in patients with stroke: altered quality of movement, resistance to passive movement, and reduced range of motion. |
| Mochizuki et al. (2019) [37] | Canada | Kinematic information on shoulders and elbows was collected during the tasks performed and transmitted to a computer in real-time. | 70 patients with stroke. | Patients with spasticity have greater deficits in motor function and proprioception. |
| Sin et al. (2019) [43] | Korea | Developed an isokinetic device that combines with EMG. | 17 patients with stroke and mild elbow flexor spasticity. | Isokinetic movement improves inter-rater confidence by giving more standardized angle measurements and sensation capture. |
| Chiyohara et al. (2020) [46] | Japan | The exoskeleton proportionally introduces a sensory state of the desired movement. | 36 right-handed participants with stroke. | Passive training improved the reproduction of ordered movement and proprioceptive acuity. |
| Pilla et al. (2020) [44] | Italy | Through training by NEEM together with EMG, biomechanical parameters, muscle activity, and motorcycle performance are evaluated. | 60 post-stroke patients were evaluated. | The use of an exoskeleton was validated as an innovative methodology for evaluation of spasticity and functional rehabilitation with EMG recordings. |

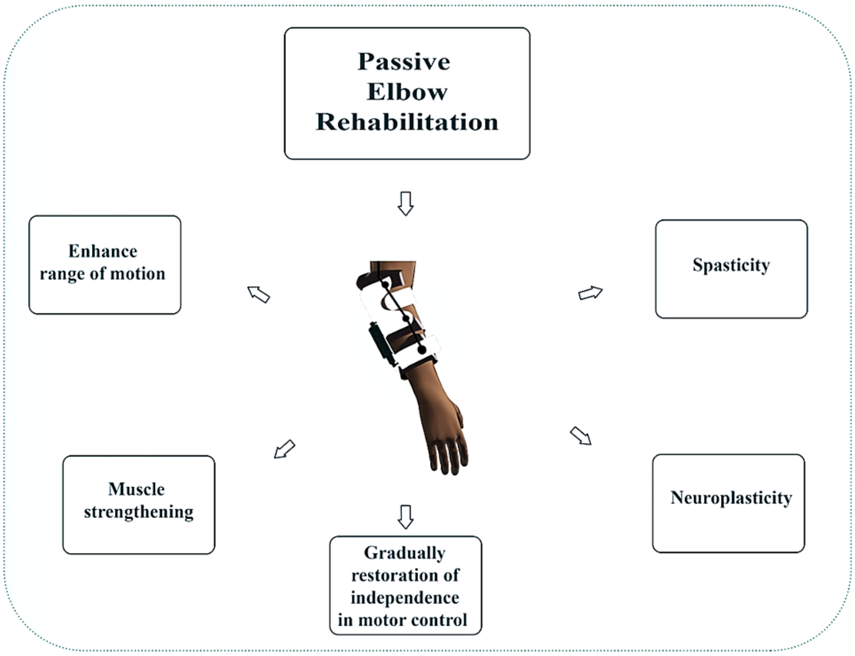


**Figure 2. Passive Elbow Rehabilitation**

## b. Hand

Passive rehabilitation with a robotic exoskeleton in the hand can be used in the aftermath mainly of stroke, Duchenne muscular dystrophy [49], and cerebral palsy [50], since it provides mechanical support for the patient to acquire resistance, support, and perform activities of daily living (ADL). The mechanism that manages this type of exoskeleton consists of a passive system with the help of external forces that cause joint displacement, respecting the degrees of freedom [51] that a normal hand must manage, thus allowing a wide range of exercises to improve hand rehabilitation with the latest therapies combined with (PM&R) doctors experience. For example, the design of a glove may have a series of elastic actuators, with characteristics of basic mechanical modules: the actuator, responsible for forces, speeds, and displacements, that is, the glove motor, and, on the other hand, the set of transmissions that communicate the indicated commands to the actuator, all of this being part of the mechanics that made possible to carry out movements in an area with pain due to joint stiffness, also a precise anatomical fit to each area of the affected hand is also considered, allowing for a desired arc length and range of motion [51]. In contrast, a lightweight and mobile three-dimensional (3D) printed hand exoskeleton is presented, operating via tensioners and elastic cords that grant the user the ability to maintain active control of finger flexion and extension, thereby enabling effective grasping or releasing of objects [52].

Recovery of neural connections with the use of RER is a clinically important feature during post-stroke hand rehabilitation, this can be analyzed by collecting measures of cortical excitability through a resting motor threshold and potential signals over the hemispheres recorded at a predefined parameter, where EMG controls device communications through brain excitability by activating passive flexion-extension movement of the fingers and wrist joint by measuring electrical signals in skeletal muscles. Additionally, MyoPro emphasizes its PR approach in Bobath therapy [53, 54] through myoelectric signals from the paretic muscles, aiming to repeat the performed movements. This approach also helps moderate the co-contractions occurring in the agonist and antagonist muscles [55].

Some of the benefits of proper passive hand rehabilitation with RER include motor improvement, neuroplasticity, and spasticity control, which is speed-dependent on the programmed exoskeleton. Research indicates that this type of therapy allows the range of movement of the hand to be increased to a certain extent [56]. An example of this is the 3D-printed hand exoskeleton, which by reducing the amount of effort needed to grasp objects allows greater movements without fatigue. This, in turn, increases the number of repetitions and aids in the practice of regaining strength and repetitive movements to perform ADL [52]. After a stroke, the interneuronal connections that help in the coordination and motor movement of the affected limbs are lost, which is why at the end of the therapies aimed at these people, a decrease in interhemispheric asymmetry and greater cortical excitability is shown in the ipsilesional zone hemisphere [57]. Furthermore, the exoskeleton and the tension in its cables counteract spasticity so that the individual reaches a certain range of extension with the fingers [52], as shown in Table 3. These are some of the multiple benefits derived from the use of RER in hand in post-stroke patients in passive rehabilitation therapy (Figure 3).

**Table 3. Clinical results of passive hand rehabilitation by robotic exoskeleton**

| Author (Year) | Country | Actuation Mechanism | Application | Results |
|---|---|---|---|---|
| Hu et al. (2014) [58] | China | Robotic neuromuscular electrical stimulation system powered by EMG, cyclic signals in the muscles that improve strength, trigger neuroplasticity, and functional reorganization of damaged muscle areas (prevents muscle atrophy). | 73 patients with unilateral ischemic brain injury or intracerebral hemorrhage of at least 6 months. | Effective at improving motor function and coordination at the wrist and shoulder/elbow compared to robots without neuromuscular electrical stimulation. |
| Borboni et al. (2016) [51] | Italy | It is based on two main modules: the actuator, which generates forces and displacements, and the elastic transmissions that go to the fingers. This approach allows for efficient activation and precise motion transmission. | 35 participants aged 45 to 80 years, with upper extremity functional disabilities after acute stroke. One group of 16 patients with total paralysis and the other groups included 14 patients with partial paralysis. | The partial paralysis group demonstrated a more significant decrease in wrist swelling and pain. However, the pain reduction did not reach the threshold considered clinically significant. |
| Wu et al. (2017) [59] | China | Electromyography-driven neuromuscular electrical stimulation robot system to perform sequential movements of elbow extension, wrist and hand opening, and wrist and elbow flexion, to assist arm reaching, grasping, and withdrawal function in daily activities. | 24 post-stroke patients with upper limb motor deficits who received 20 training sessions. | Helps to loosen muscle contractions, improve limb coordination, and perform daily activities. |
| Ambrosini et al. (2019) [60] | Italy | Hybrid RS combining electromyography-activated functional electrical stimulation with a passive exoskeleton for upper extremity training. | 7 adults in the subacute stage of stroke who underwent the RETRAINER-ARM system. | Improvement of motor functions, better range and accuracy of motion. |
| Dudley et al. (2019) [52] | USA | The passive exoskeleton of the hand has tensioners and elastic cords that allow extension and flexion. Manufactured with 3D printing and PLACTIVE$^{MT}$, it facilitates mobility in hands affected by a stroke. | A man aged 67, over six months post-stroke, experienced the effects on his right hand due to the stroke. | The scores of the Fugl-Meyer evaluation, Box and Block tests were improved with the use of the device. Additionally, the subject had greater EMG activation in his extensor. |
| Brihmat et al. (2020) [50] | France | The ArmeoSpring device is a passive exoskeleton for upper limb rehabilitation. Patients perform assessment exercises in a three-dimensional space, with adjustable weight support, allowing autonomous movements with visual and auditory feedback. | 30 hemiparetic patients after stroke. | The study concludes that ArmeoSpring is effective in reliably and quantitatively assessing motor deficits in post-stroke patients. Accuracy in structuring testing sessions is improved with specific parameters such as PeakVel and Score. |
| Huang et al. (2020) [61] | China | Electromyography-driven neuromuscular electrical stimulation robotic hand and another EMG-driven robotic hand system for chronic stroke patients. | 30 post-stroke patients had 20 experimental robotic hand training sessions. | The device with neuromuscular electrical stimulation had better results in voluntary motor recovery, muscle coordination and patients obtained greater release of contractures. |
| Singh et al. (2021) [57] | India | Predefined threshold in EMG for the activity of the EDC muscle through wrist extension and finger flexion. | 23 patients with chronic stroke. | Improvement of cortical excitability in the ipsilesional hemisphere that may be due to new neuronal reorganizations. Decrease in interhemispheric asymmetry. |
| Hsu et al. (2022) [56] | Taiwan | Through an automatic passive range of motion exercises, it provides three-finger, five-finger, and mirror-guided movement models for flexion and extension of the affected hand. | 12 chronic stroke patients with severe upper extremity hemiparesis. | Combined robotic exoskeleton therapy with traditional manual training increased hand function and strength. |
| Pundik et al. (2022) [55] | USA | Myoelectric signals are collected through a predefined threshold through electromyogram sensors of paretic muscles (flexors, finger extensors, biceps and triceps), activating the motors and initiating practice and coordinated movement. | 13 people with chronic moderate/severe arm weakness due to stroke (n = 7) or traumatic brain injury (n = 6). | Increased function in the extremity and decreased motor impairment in response to the device. |

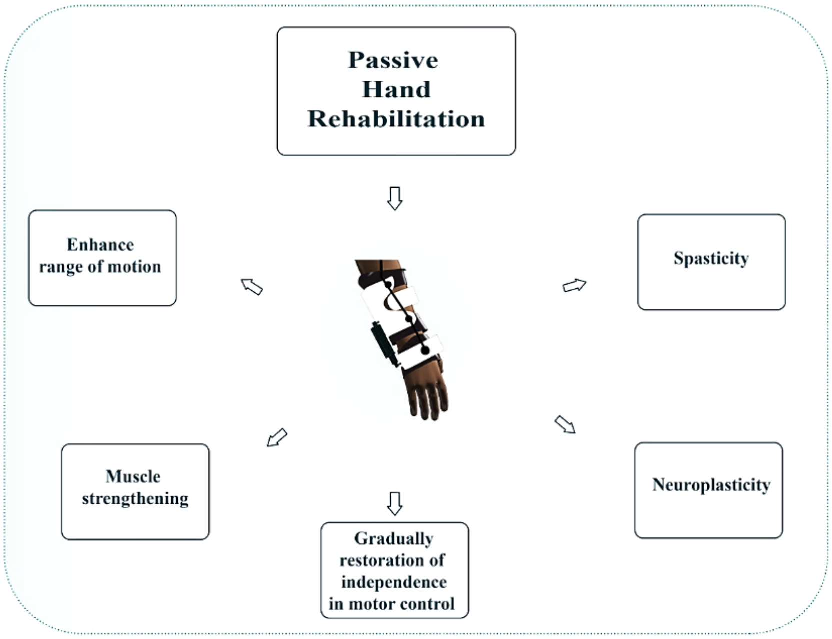


**Figure 3. Passive Hand Rehabilitation**

### 3.1. Active Rehabilitation

In active rehabilitation, the use of a robotic exoskeleton system is used as a guide for post-stroke patient's performance of exercises and activities, making movements in a range from very low to higher intensity as necessary, allowing, for example, so that the patient can recover to a certain extent and even completely the functions compromised in a stroke and at the same time the neuronal connections recovery. It is classified as active when voluntary physical effort is made mainly in carrying out movements. In this case, it is usually used when there is no longer extreme pain caused by the consequences of the stroke, weakness, atrophy, paralysis, spasticity, and mainly neuromuscular coordination compromise. Unlike PR, this retrains the brain to communicate with the muscles, leading to better neurorehabilitation and allowing them to relearn certain movements [62], further reducing muscle pain. Also, AR is usually applied in the first periods of rehabilitation of post-stroke patients. Although it is called AR, the system used is passive as it primarily requires the user's support to perform the exercises.

Furthermore, AR primarily focuses on achieving greater voluntary motor activity, muscle strengthening, flexibility, stability, precision, and improving blood flow. It enables a greater extent of liberated muscle spasticity [61], provides comfort [63], and contributes to reducing the presence of pathological muscle coactivation [64] and pain.

#### a. Elbow

Active rehabilitation with a robotic exoskeleton that trains the elbow joint allows the recovery and improvement of the functions corresponding to the musculoskeletal and nervous system involved, such as the elbow joint itself, as well as the related muscles, which mainly include the triceps brachii, biceps brachii muscles through the various movements performed [59, 65, 66], Additionally, it contributes to its trajectory synchronization and coordination [17]. The use of exoskeletons is recommended when there is a difficulty performing movements due to muscle weakness or spasticity [17, 65] affecting the range of extension and flexion of the elbow joint, adding that in many cases there is a poor response of the arm commanded by the brain [17]. Due to this, unlike PR, it generates better conditions for the development of neuroplasticity [23] and requires voluntary physical effort on the part of the individual when performing movements with the elbow joint.

Among the benefits of AR with RER for the elbow, it has been observed that improvements in spasticity and motor function [65] are more pronounced when the exercises are performed consistently with adequate rest periods. are more pronounced when the exercises are performed consistently with adequate rest periods It is recommended to have guidance and supervision from a specialist during rehabilitation sessions [17].

The functioning RER mechanisms for active elbow rehabilitation vary according to different degrees of technology, for example, the case of basic exoskeletons for AR consists of a robotic skeletal frame that adapts to the elbow and allows stretching or flexion of the arm in the same direction as the affected arm, allowing the healthy arm to guide the movements of the affected arm, in addition, increasing the variety of different rehabilitation exercises, interest and motivation in them, accuracy, levels of cooperation, reducing the effort, rehabilitation time and improve stability [59, 65-68] as shown in the results of Table 4. These are some of the multiple benefits derived from the use of RER in elbow in post-stroke patients in active rehabilitation therapy (Figure 4).

**Table 4. Clinical results of active elbow rehabilitation by robotic exoskeletons**

| Author (Year) | Country | Actuation Mechanism | Application | Results |
|---|---|---|---|---|
| Herrnstadt et al. (2015) [17] | Canada | The exoskeleton operated using a master arm and a slave arm. | All the proprioceptive and haptic feedback exercises were performed by 7 chronic stroke patients. | The error in the proprioception measurement was reduced. |
| Pignolo et al. (2016) [23] | Italy | The robotic exoskeleton works by a master-slave exoskeleton system. | 52 stroke patients participated, and the exercises performed were single and multiple movements including elbow flexion-extension. | Improved the efficiency and the variety of rehabilitation exercises in comparison to a single exoskeleton structure. |
| Das Neves et al. (2019) [65] | Brazil | Using EMG, in conjunction with the peak torque of the elbow flexor muscles in maximum voluntary contraction and considering the kinematic range. | 12 healthy volunteers and 15 post-stroke volunteers performed different movements quantifying the range of motion of the elbow. | Certain poststroke volunteers exhibited a significant increase in the range of elbow motion. |
| Kopke et al. (2020) [66] | USA | This exoskeleton works using EMG technology. | 12 stroke patients and 12 control patients completed the study, and the exercises included both movements and holding the position, with proprioceptive and visual feedback. | It allowed to recognize the ability of an LDA-based classifier to calculate user intent in patients' tasks. |
| Liu et al. (2021) [67] | China | It has a coordination quantifier to permit generate the initial path and the position controller that allows to track the final path that is corrected by human contact force. | Between the rehabilitation exercises, the 4 stroke patients drank water and touched their heads to see coordination issues. | This work managed to maintain the active motivation of the patient while increasing movement coordination, keeping the safety and predicting the elbow joint data much better. |
| Ren et al. (2023) [68] | China | Through different controls including bilateral control and sEMG. | 6 healthy patients performed exercises of bilateral coordination. | This exoskeleton showed a better prediction effect and a little tracking error in joint motion, also the Unity3D-based game system increased the interest in the rehabilitation. |
| Wu. et al. (2023) [59] | China | Surface electromyography (sEMG). | 4 healthy persons and 4 stroke patients performed repetitive trajectory exercises six times according to each condition. | Promote the active participation of patients and the safety of training, also, benefits the position control accuracy, upgrading the active cooperation level, smoothness, reducing the effort and improving stability. |

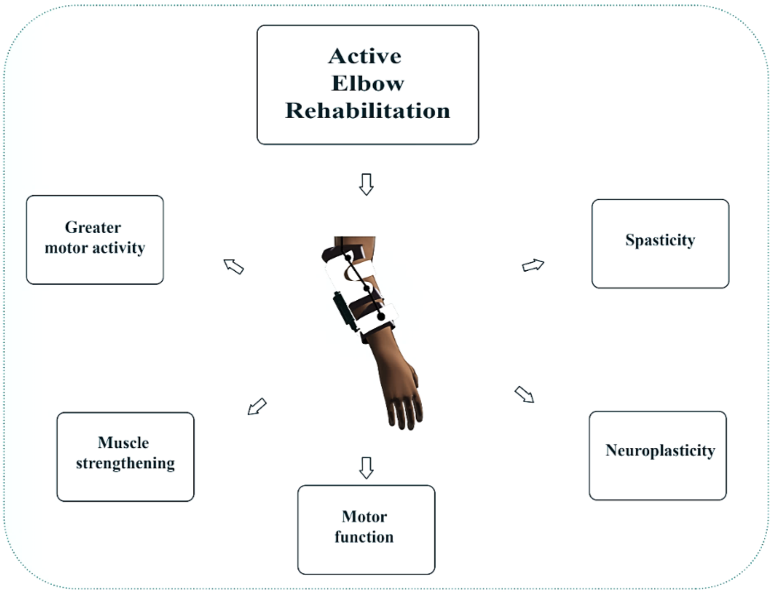


**Figure 4. Active Elbow Rehabilitation**

## b. Hand

Active rehabilitation with a hand-robotic exoskeleton consists of a persistent human-machine interaction involving assisted assistance of the robotic device subject to the user's intention to move the hand [69, 70]. Patients chosen for this type of therapy have a greater range of motion and a lower level of spasticity, measured by tests such as the MAS and the MTS, it can be said that this criterion determines their participation [57]. Other determining factors include neuroplasticity, muscle recovery, medication regimen, absence of neurological or nervous injuries, and musculotendinous or bone fracture [69]. The use of RER for hand is supervised by personnel who usually know the protocols using the myoelectric system [57].

As for the materials that can be used for manufacturing RER applied on hand, polylactic acid is mainly used in three-dimensional printing, while others choose to use Velcro material for the supporting parts. In addition, the ergonomics of the patient are ensured since the gloves have a design based on the physiological anatomy of the hand, allowing the structure to accommodate the flexion/extension points of each joint, mainly in the thumb and index finger, enabling the execution of fine movements. In the same way, the concept of DOF is usually associated with the metacarpophalangeal (MCP), distal interphalangeal (DIP), and proximal interphalangeal (PIP) joints. It is also commonly observed that there are more than 5 DOF, as there are 2 DOF per finger or even more if there is simultaneous and coordinated movement among them [57, 71].

There is evidence of different types of RER for hand activation, some studies of robotic hand devices such as ReHand, explain that their system works through Brain-Computer Interfaces (BCI) and that it includes a stage of acquisition, processing, control of external devices and feedback of brain signals [69, 71]. This provides a better understanding of how exercises recommended by the PM&R physicians can be implemented and prioritized. Other works indicated that the glove allows the extension of the fingers through the tensioners and the correct position during the exercises, either with intention or with the help of electrical stimulation in the muscles, and conversely retracts the fingers once the movement is completed [70] meaning that voluntary movement can be guided by RER functions in a safe way. Finally, it is common to see various hand-held exoskeletons such as the Hero device that has a gyroscope or sensors that detect the intention of movement through a threshold that allows the activation of the system and the performance of exercises [72-75].

In RER for hand use, several conditioning factors must be considered, including neuroplasticity, muscle recovery, the medication regimen, the absence of neurological or nervous injuries, and musculotendinous or bone fracture, being these few reasons that explain why the use of RER for hand is supervised by specialists who know the neuromuscular system and the protocols. Therapy sessions focus on five standard ranges of motion, guiding device operation through a medical and biomedical framework for practical applications of RER [74, 76]. The related information is shown in Table 5. These are some of the multiple benefits derived from the use of RER in hand in post-stroke patients in active rehabilitation therapy (Figure 5).

**Table 5. Clinical results of active hand rehabilitation by robotic exoskeleton.**

| Author (Year) | Country | Actuation Mechanism | Application | Results |
|---|---|---|---|---|
| Franck et al. (2018) [70] | Netherlands | A dynamic hand orthosis was used. The hand is maintained in an extension position with the support of the device and in flexion by the patient's hand movement. The support can be adjusted to the hand opening support. In addition, an electrical stimulation device, the Mcrostie, was placed by placing a cathode and an anode to stimulate the arm muscles. | Involving 8 sub-acute stroke patients. | 75% of accident patients with Subacute stroke improved their ability to use the affected arm in daily activities between the start of training and follow-up. However, as all eight participants were included during the subacute phase after stroke, the improvements in arm-hand skill performance may also be attributable to other factors, i.e., (a) spontaneous recovery, and (b) therapy received as such, usual, (c) the application of the dynamic orthosis in combination with electrical stimulation, or (d) a combination of these factors allows the affected arm-hand to be used for passive and active stabilization tasks, such as preparing bread while making a sandwich. |
| Yurkewich et al. (2019) [72] | Canada | Through the extension and flexion force (push-pull force from a single screw-driven linear servo actuator that is mounted on the dorsal surface of the glove on the inside. line with the next two sets of cable guides) received by brides in the index, middle and thumb fingers. A gyroscope detects movement. | 2 chronic stroke survivors with severe hand disability. To determine the threshold that activates movement, 4 patients (18 to 35 years old; 3 women). participated. Finally, there were 5 participants. | The patients showed reduced touch sensation in the fingers, palm, and forearm, using a standardized assessment, also, the participants did not show pain, according to a standardized scale. The HERO glove showed greater extension in the index finger and progressive progress was seen in the thumb and index fingers. The robot allows gripping or pinching movements to be carried out and patients showed greater performance on tasks as part of the exercises. |
| Yurkewich et al. (2020) [73] | Canada | Through the extension and flexion force (push-pull force from a single screw-driven linear servo actuator that is mounted on the dorsal surface of the glove on the inside. line with the next two sets of cable guides) received by brides in the index, middle and thumb fingers. A gyroscope detects movement. | 11 people who had minimal or no finger extension (Chedoke McMaster hand stage 1 to 4) after stroke to assess how well they could perform ADL and assessments of finger function with and without using the HERO Grip glove. | The participants showed statistical improvement using standardized scales, all during the period of use of the HERO glove. Tasks assigned as part of the exercises, such as: grip or pinch, finger extension, range of motion, etc., were better performed with the use of the orthosis. |
| Cantillo-Negrete et al. (2021) [69] | Mexico | EEG signals were recorded using a cap with 11 active electrodes. BCI systems comprise four stages: acquisition, processing, control of external devices, and feedback of brain signals. Mental rehearsal of movement, movement attempt, or motor intention (MI) elicits activations in the sensorimotor cortex. | 7 subacute and 3 chronic stroke patients ($M = 59.9 \pm 12.8$) with severe upper limb impairment were recruited in a crossover feasibility study to receive 1 month of BCI therapy and 1 month of conventional therapy in random order. | Patients were less affected after either of the interventions, suggesting that both interventions effectively increased upper extremity motor function in stroke patients. The ReHand-BCI could also benefit motor recovery due to the closed-loop communication it provides between the patient and the affected upper limb. This hypothesis is reinforced by other BCI studies reporting accident rehabilitation outcomes lower cerebrovascular outcomes in control groups that received feedback only passive movement or sham feedback. |

| | | | | |
|---|---|---|---|---|
| He et al. (2021) [74] | China | The interaction forces between the patient and the binding cuffs were analyzed to pinpoint the patient's intention to move, applying six-dimensional pressure sensors and force/torque sensors to the forearm and upper arm binding cuffs. In that sense, the forces of interaction were converted to the speed of command in the articular space with a method of admission control. | This project involved 8 participants with hemiplegia due to a first-ever, unilateral stroke. | These results are only preliminary due to the limited number of subjects. Patients showed significant improvements in movement, smoothness in joint space, postural synergy error, and intention response rate. |
| Singh et al. (2021) [77] | India | The device is actively initiated by the EDC (Communist Finger Extensor) muscle electromyogram (EMG) reading, with the robot's movement activated only if EMG thresholds are exceeded and provides real-time adaptive performance, interactive visual biofeedback. | This project involved more than 300 patients ($n > 300$) who were chosen from the outpatient clinic of the Department of Neurology, AIIMS, New Delhi, for three years, from July 2016 to January 2019. | All patients in RG (Robotic-therapy Group) ($n = 12$) and CG (Control Group) ($n = 11$) (all right-handed patients with stroke, age = $41.9 \pm 11.1$ years, Male: Female = 19:4) completed successfully the therapy-sessions in 30–34 days. |
| Pundik et al. (2022) [55] | USA | The device completes the movement started by the user and directs the action of the coordinated movement (such as dissipating the joint contraction of the agonist and antagonist muscles). Both of these aspects are essential elements of ML (motor learning). The motors inside the device start only when the EMG voluntarily generated by the individual reaches a threshold level; This activates the device to help the patient complete a movement. | This study was associated with thirteen individuals with moderate/severe chronic arm weakness due to stroke ($n = 7$) or head trauma ($n = 6$). | Post-hoc analysis was used to assess differences between time points. Given the limitations of sample size, it was only adjusted for lesion type and baseline score, understanding that the interpretation of results related to lesion type is intertwined with age differences. |
| Xia et al. (2022) [71] | China | The host computer processes data collected by the slave computer and sends commands via the interface program. The overall control system is composed of four major parts, including the hand exoskeleton, host computer, slave computer and a wearable controller. Hand rehabilitation exoskeleton control flow diagram for the three rehabilitation modes. | This project was conducted on healthy volunteers. | The effectiveness of the handheld exoskeleton system in stroke patients in this project is visualized for testing in patients. |
| Chen et al. (2023) [75] | China | The admission control method was applied to overcome robotic inertia and transform intentions into desired postures with mechanical outputs to calculate and complete the instantaneous discrepancy between the target position and the UE (upper extremity) position in real-time via the Jacobian matrix. | This project involved 80 patients randomly assigned to the intervention and included in the analysis. | Relative to ANCOVA, higher baseline scores were significantly associated with correspondingly greater improvements in EAMT therapy; No significant differences were found after adjustment for the remaining features. The results were stable with sensitivity analyses on models that imputed missing data, unadjusted models, and models by the protocol set. |

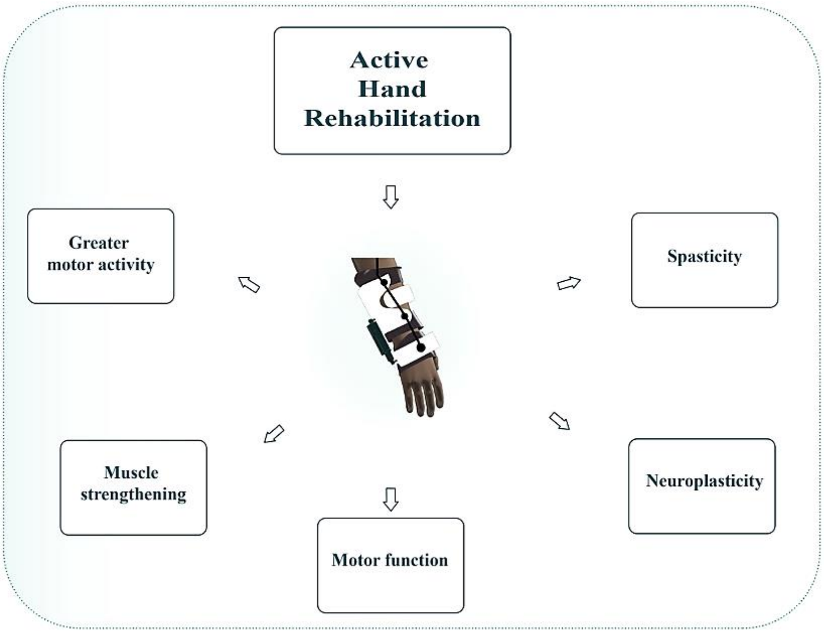


**Figure 5. Active Hand Rehabilitation**

## 4. Discussion

After reviewing and analyzing the various publications included, it becomes evident that early rehabilitation during hospitalization has made significant strides in the treatment of post-stroke patients. The recovery of motor function hinges on factors such as training time, exercise frequency, exoskeleton intensity, spasticity assessment, improvements in neuroplasticity, and post-application follow-up of RER for elbow-hand [65, 78]. The exoskeletons used for this purpose suggest a good position and correct functioning, that is, achieving a natural range of movement in the joints of interest, also improving the speed of action, without significantly affecting the non-target joints, avoiding stiffness in unwanted areas and improving motor function [5]. Furthermore, their implementation through dynamic therapies and rehabilitations with a certain degree of complexity as more realistic practice, high frequency, progression, and feedback seeks to reestablish neuronal integration, allowing neuroplasticity in these patients [18, 57].

The WHO, in its package of rehabilitation interventions for adult stroke patients, including survivors of cerebral ischemic stroke and cerebral ischemic stroke, recommends functional stroke rehabilitation interventions for motor functions and mobility focusing on the use of the hand and arm use, indicating that for assessment of hand and arm use is 20 minutes, for constraint-induced movement therapy is up to 60 minutes and for functional training, which may include virtual reality training, use on hand and arm is 20 minutes per rehabilitation session, there are also medical sessions centered on exercise tolerance functions, ADL, work and employment, participation in community and social life, among others [79]. Similar positive outcomes have been observed with alternative training systems in post-stroke patients. For instance, a program comprising 27 sessions of 30 minutes each, utilizing passive exoskeleton technology, has demonstrated efficacy [60]. Similarly, in EMG-driven robotic systems 30-minute therapies are performed for lateral and vertical activities with 10 minutes of rest to avoid muscle fatigue [61], and the one used in the neuromuscular electrical stimulation robotic system consists of 40 minutes of repeated exercises and assisted movements with 10-minute rest between each 20-minute practice due to muscle fatigue [80].

Passive rehabilitation with RER in contrast to traditional rehabilitation methods indicates greater effectiveness in the early stages of post-stroke recovery. One of the consequences of surviving a stroke is hemiplegia, in which cases, passive rehabilitation is used in early recovery therapy, When the patient cannot contract the muscles adequately, in traditional rehabilitation the required exercise repetition numbers, force used, and precision are limited based on human assistance compared to RER assistance that passively follows a training trajectory in predefined time with high tracking precision enabled by the specialist-regulated RER, contributing to improving muscle contraction function and at the same time can eliminate joint spasm [62]. Some studies indicated that scores of the Fugl-Meyer scale with RER compared to conventional therapy show greater improvement after receiving rehabilitation [23].

### 4.1. The Evaluation of Spasticity

Currently, in the rehabilitation with RER for elbow-hand, after a stroke episode in patients, the degree of spasticity is evaluated by MAS [43] and MTS performed by the PM&R. However, despite their usefulness, they are not completely reliable since they depend on the experience and knowledge of the specialist [25], which is why the importance of accurate measurement through the use of an exoskeleton is highlighted for a correct rehabilitation strategy. Likewise, several studies mention clinical evaluation to measure the impact of robotic therapy by comparing clinical results before and after the intervention [43], these include the Fugl-Meyer Upper Extremity Evaluation (FMA UTE) that rates motor impairment from 0 to 66, the Action Research Arm Test (ARAT) to measure the function of the upper extremities and especially the Functional Independence Measure (FIM) [81], the latter consists of a scale that evaluates not only the manual part but also the dependence or independence of the patient across levels of functionality, Moreover, during repetitive exercises, it has been observed that patients may apply grip pressure that is either insufficient or excessive compared to the given reference, a phenomenon attributed to spasticity-induced abnormal muscle activation [82].

One of the resulting challenges lies in the limitations of traditional methods, which fail to capture all the characteristics of muscle hypertonia, which is why a quantitative and objective evaluation is proposed through multiple techniques to validate the reliability of the exoskeleton when differentiating the results obtained in healthy and affected populations or limbs using various parameters such as maximum speed, final angle used in passive elbow stretch. One of the advantages is the continuous monitoring during each rehabilitation session even during each movement highlighting small changes in addition to the early detection of the recovery plateau avoiding excessive sessions, as well as characterizing kinematic and proprioceptive deficits providing sensitive and quantitative information [38, 45, 83]. There is a lack of sufficient research on the correlation between medical scales and measurements performed by robotics applied in rehabilitation [45]. However, a significant relationship has been observed between the activity of the muscles captured by EMG and the kinematic recordings of the sensors on the flexion/extension of the elbow joint [65], so its use is proposed to obtain metrics related to the MAS clinical scale [40, 42-44].

### 4.2. Motor Recovery Importance

The use of elbow-hand RER has helped in the improvement of patients, several studies have concluded that there is significantly better motor recovery in those assisted by robotic devices [60]. Robotic assistance is tailored to execute pre-programmed passive and continuous movements, which effectively reduce muscle tone, enhance joint mobility, and facilitate active movements between the machine and the operator. These interventions contribute to the restoration of motor control through positive cortical reconfiguration following traumatic brain injury such as stroke [4]. Additionally, other studies indicated that working with a bimanual wearable robotic device (BWRD) favors motor recovery [17].

On top of that, other studies have indicated that integrating the RER with functional electrical stimulation (FES) may have the potential to improve the recovery of motor functions and depends on its application area to facilitate effective training [60] and other works suggested incorporating neuromuscular electrical stimulation (NMES) in muscle activities can lead to enhance muscle coordination [58]. In patients with chronic stroke, if it is used in the distal muscles, it causes better recovery in the total upper limb, for example, in the wrist, it also can achieve improvement in the function of the elbow. In the long term, it is better to use the robotic device in conjunction with neuromuscular electrical stimulation driven by EMG, which in turn has better results in muscle coordination in the elbow joint [61, 80]. Moreover, it has been determined that to measure neuromuscular electrical stimulation of the superficial plane of the muscles, surface electrodes are sufficient [60], however, fine wire electrodes are required for deep-plane muscles. EMG is also combined with FES for passive exoskeletons designed for upper limb suspension resulting in satisfactory improvements in overall patients who can perform movements more smoothly and quickly without limitations in the coordination [60, 84].

A specific benefit of the use of RER, is that unlike traditional rehabilitation, where more physical human factors are considered in the application of rehabilitation therapy, the use of RER for active training of patients allows the neuromotor system rehabilitation [63], while adjusting the compliance of human-robot interaction in many areas of different jobs based on customized practical training requirements. which can be programmed to help the patient induce active participation during rehabilitation training with repetitive trajectory tracking that can be configured with a RER, which makes it possible for the patient with severe paralysis to comply with the RER-assisted training task and at the same time contributes to the safety of training [62].

### 4.3. Neuroplasticity Benefits

A specific benefit of RER in neuroplasticity is highlighted when traditional rehabilitation methods can show unsatisfactory results due to insufficient patient motivation compared with the repetitive task-oriented training mixed with game-based VR training may induce neuroplasticity of the motor system, some studies suggest this as key benefits in terms of upper extremity neurorehabilitation [60, 84].

Robotic devices such as exoskeletons designed for hand and elbow rehabilitation can induce positive cortical hemodynamic changes maximizing the sensorimotor aspect in patients with subacute stroke [85]. In this population, exoskeletons were used in the upper extremities, and brain electrical activity was recorded through electroencephalography (EEG), using software that analyzes 84 regions of interest according to the 42 Brodmann areas that exist for both hemispheres. This methodology enabled the measurement of brain integration between nodes and the degree of brain segregation, revealing the notable increase in neuronal connectivity for this type of case [86]. Moreover, some robotic models are controlled via BCI, this technology has been tested in post-stroke patients and helps in their recovery, promoting neuroplasticity. A study with this type of therapy indicates less cortical Event-Related Desynchronization (ERD) activity in sagittal regions in the alpha band, which signals a better connection of the sensorimotor cortex with the hand, as well as greater beta activity in the frontal region, probably because BCI therapy stimulates the growth of the motor cortex in response to the tasks performed [69].

This explanation is supported by other research demonstrating neuronal plasticity in response to action observation or visual stimulation, which motivates individuals to perform movements, thereby reinforcing motor memory [87]. Likewise, neuroplasticity not only focuses on the fractionation, direction, and improvement of the quantity and quality of repetitive movements but also focuses on the stimulation of synergistic control through reflexes, that generate reactions that are inherent to the stimuli of the afferent pathway, that is, without voluntary effort, as demonstrated in movement therapies [77]. Besides, it was found that exoskeleton therapy in post-stroke patients increases cortical excitability in the ipsilesional hemisphere and produces significant interhemispheric changes. This is verified by the decrease in the motor threshold at rest and the increase in the amplitude of the motor evoked potential, where it is speculated that thanks to plastic reorganization and use-dependent plasticity, the motor function would be recovered more easily [57]. However, in the context of BCI, some proposed neurorehabilitation systems can be understood as a prospective mode of telerehabilitation [88], therefore, when it is observed that stroke can cause the loss of axon functionalities, it is necessary to mention that there are new alternatives that can complement all of this, such as artificial neurotransmitters (ANT), powerful chips implantable in the brain area as proposed by Neuralink, which can improve rehabilitation [89], allowing the patient to connect to a smart device such as a computer, without direct physical connection only with thoughts [90] giving us a better view of the human brain at the same time [91] an a yet to be seen a better improvement of its functionality [92], Nonetheless, the implementation of such technologies raises medical, ethical, and moral considerations, and only time will reveal whether they represent the optimal approach in these domains.

On the other hand, the authors analyzed the kinetic parameters of the data obtained from a RER for elbow-hand: movement time and maximum speed, the first term indicates the temporal efficiency of the movement and the second refers to its ease. Consequently, and as expected, within and between test sessions carried out with the device, movement time was shorter with respect to maximum speed, indicating a greater sensitivity to change. This phenomenon can also be described as a "learning effect," which, in the context of hand and elbow rehabilitation, denotes the ability to recover neural connections by adapting to new circumstances [50].

### 4.4. Frontiers and Upcoming Potential Innovations

Actual studies recognized the need for long-term studies and larger population samples because some indicate that the testing period is short compared to the ideal time to conduct such studies [17], giving us a better understanding of the effectiveness of RER for elbow-hand. In addition, some identified the small sample size of the patients evaluated as their limitation of the study [66], others point out that the specific effects of RER for elbow-hand should be studied [23], because all this together will contribute to improving the clinical application of RER for elbow-hand. The need to adapt RER for elbow-hand to the individual needs of people and the importance of collaboration between health professionals, engineers and scientists of RER for elbow-hand applications and programming is manifested in different studies that indicated and suggested that the comfort of the RER for elbow-hand and its level of lightness is susceptible to improvement [59], integrating the RER for elbow-hand with patient-specific parameter settings could be beneficial [47], as some studies have already customized self-driven exercises, and expanding the protocol to obtain quantifiable measures of subjects' conditions is recognized as an excellent option [17], all of this could be possible with better possibilities if in the requisition of RER for elbow-hand, there was the participation of different professionals such as engineers, PM&R physicians, therapists [25] and physiotherapists [37] as medical technologist in physical therapy, medical technologist in occupational therapy, medical technologist in speech therapy, social worker, psychology, nutritionist and many more, when working and cooperating together better results can be achieved.

The potential of new technologies is recognized in the trend of recent times, so the current and future path of elbow-hand rehabilitation involves integrating the latest technological advances in RER for elbow-hand, a primary reason is that robotics has an inherent role in recovery because it has an inherent ability to perform tasks accurately, reliably, and is better suited to measuring and quantifying patient performance [17, 93], this is the robotic assistance path [50], bringing these promising systems into a stage of routine operation is the future [23] allowing to obtain and utilize kinematic data, such as movement time and peak velocity with more details [17] allowing to obtain and utilize kinematic data, such as movement time and peak velocity with more details [58], the latest advances in technology, such as the integrations of Artificial Intelligence (AI), can help the sick person and all the professional staff involved, reducing physicians and therapists' physical effort during complex exercises. These increase the frequency and length of the sessions and allow constant feedback during therapy itself [24], complementing all professional's work and maximizing the efficiency of the clinical applications in RER for elbow-hand.

## 5. Conclusion

The main objective of passive and active rehabilitation in post-stroke patients with elbow-hand exoskeletons is highlighted, which is neurorehabilitation while restoring motor functions to normal levels, optimizing interaction capacity, and saving time and resources, whose path is the implementation of new technologies and the potential that all this offers in the improvement of clinical applications with obtaining great, more effective, and efficient results. The potential of PR and AR regarding robotics in the global context has been identified and presented a comprehensive and updated view of the current state of clinical applications and results derived from using RER in elbow and hand in post-stroke patients (Figure 6).

Therefore, it is important to remember that patients with diabetes, uncontrolled hypertension, deterioration of mental status, severe aphasia, and wrist contractures are excluded as suitable candidates for the use of the exoskeleton. Likewise, if the RER is used for elbow-hand exceeding the times indicated by doctors and PM&R specialists, the risks suffered by the stroke survivor are discomfort and consequently the usage limitation of the exoskeleton; it is also observed that significant changes in muscle activity, mobility, decreased task performance, alterations. in balance and posture, as well as neurovascular supply, imbalances in gait parameters, and the precision of the movements. In summary, the current and future path of the RER for elbow-hand involves the constant integration of the latest technological advances, the improvement of future research times, the population, and the adaptation of RER for elbow-hand to the individual needs of post-stroke patients and professional collaboration to achieve better results in the clinical applications.

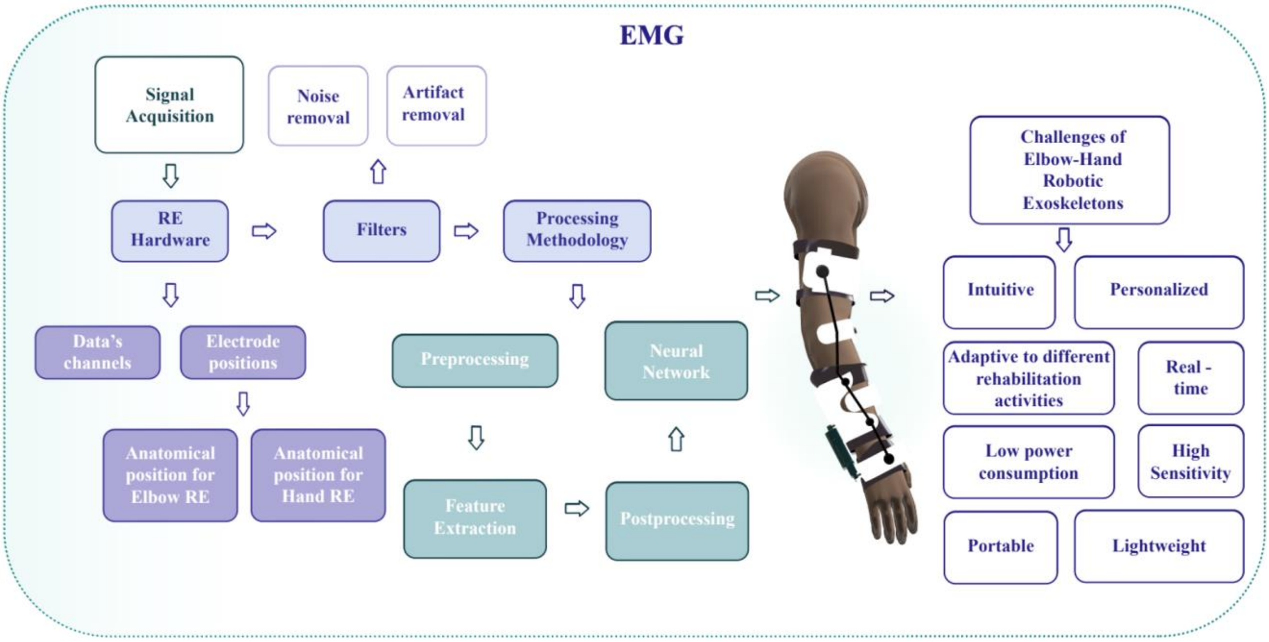


**Figure 6. Electromyogram System Analysis for Rehabilitation Exoskeletons**

## 6. Abbreviations

| | | | |
|---|---|---|---|
| **3D** | Three-dimensional | **FIM** | Functional Independence Measure |
| **ADL** | Activities of daily living | **MAS** | Modified Ashworth Scale |
| **AI** | Artificial Intelligence | **MCP** | Metacarpophalangeal |
| **AR** | Active rehabilitation | **MTS** | Modified Tardieu Scale |
| **ARAMIS** | Automatic Recovery Arm Motility Integrated System | **NESM- γ** | NEUROExos Shoulder-elbow Module - γ |
| **ARAT** | Action Research Arm Test | **NEEM** | NEUROExos Elbow Module |
| **ANT** | Artificial neurotransmitters | **PIP** | Proximal interphalangeal |
| **BCI** | Brain-Computer Interfaces | **PICOC** | Population, intervention, comparison, outcomes, and context |
| **DIP** | Distal interphalangeal | **PM&R** | Physical Medicine and Rehabilitation |
| **DOF** | Degrees of freedom | **PR** | Passive Rehabilitation |
| **EDC** | Extensor Digitorum Communis | **RS** | Robotic System |
| **EEG** | Electroencephalography | **RER** | Robotic Exoskeleton for Rehabilitation |
| **EMG** | Electromyography | **sEMG** | Surface Electromyography |
| **ERD** | Event-Related Desynchronization | **UL** | Upper Limb |
| **FES** | Functional electrical stimulation | **WHO** | World Health Organization |
| **FMA UTE** | Fugl-Meyer Upper Extremity Evaluation | | |

## 7. Declarations

### 7.1. Author Contributions

Conceptualization, M.V. and J.C.; data curation, M.V., J.C., Y.V., D.DLB., S.C., P.T-Y., R.R.M-G., L.M.M-A., A.A., C.C., M.B.C., R.C., and A.N.; formal analysis, M.V., J.C., Y.V., D.DLB., S.C., P.T-Y., R.R.M-G., L.M.M-A., A.A., C.C., M.B.C., R.C., and A.N.; investigation, M.V., J.C., Y.V., D.DLB., S.C., P.T-Y., R.R.M-G., L.M.M-A., A.A., C.C., M.B.C., R.C., and A.N.; methodology, M.V., J.C., Y.V., D.DLB., S.C., P.T-Y., R.R.M-G., L.M.M-A., A.A., C.C., M.B.C., R.C., and A.N.; project administration, M.V. and J.C.; resources, M.V. and J.C.; supervision, M.V. and J.C.; validation, M.V., J.C., J.C., R.P., and M.R.C.; visualization, M.V., J.C., Y.V., D.DLB., S.C., P.T-Y., R.R.M-G., L.M.M-A., A.A., C.C., M.B.C., R.C., and A.N.; writing—original draft, M.V., J.C., Y.V., D.DLB., S.C., P.T-Y., R.R.M-G., L.M.M-A., A.A., C.C., M.B.C., R.C., and A.N.; writing—review & editing, M.V., J.C., M.V.R., R.P., J.C., and J.A.DLC-V. All authors have read and agreed to the published version of the manuscript.

### 7.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author. The manuscript copyright is exclusively the property of the Instituto de Investigación en Ciencias Biomédicas (INICIB), Dr. Mariela Vargas, and Dr. José Cornejo.

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### 7.5. Institutional Review Board Statement

Not applicable.

### 7.6. Informed Consent Statement

Not applicable.

### 7.7. Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## 8. References

[1] Kuriakose, D., & Xiao, Z. (2020). Pathophysiology and treatment of stroke: present status and future perspectives. International Journal of Molecular Sciences, 21(20), 7609. doi:10.3390/ijms21207609.

[2] Phillips Morales, Ó. (2019). Update on Guillain-Barré Syndrome. Sinergia Medical Journal, 4(11), e290. doi:10.31434/rms.v4i11.290.

[3] Mendis, S. (2013). Stroke disability and rehabilitation of stroke: World Health Organization perspective. International Journal of Stroke, 8(1), 3–4. doi:10.1111/j.1747-4949.2012.00969.x.

[4] Bacalangco, J. E. I., Bawagan, K. G. F., Bernardo, C. C., Medina, R. L. S., Reyes, J. M. L., & Tolentino, R. E. (2021). Design and Control of Robotic Elbow Using Shape Memory Alloy as Actuators. 6th International Conference on Communication and Electronics Systems (ICCES), 13-20. doi:10.1109/ICCES51350.2021.9489192.

[5] Bardi, E., Gandolla, M., Braghin, F., Resta, F., Pedrocchi, A. L. G., & Ambrosini, E. (2022). Upper limb soft robotic wearable devices: a systematic review. Journal of NeuroEngineering and Rehabilitation, 19(1), 87. doi:10.1186/s12984-022-01065-9.

[6] Aguirre, J., Perez, M. B., Palomares, R., & Cornejo, J. (2022). Ergonomic Bio-Design and Motion Simulation of a Mechatronic Orthosis System for Knee Rehabilitation. Proceedings of the 2022 IEEE 29th International Conference on Electronics, Electrical Engineering and Computing, INTERCON 2022. doi:10.1109/INTERCON55795.2022.9870040.

[7] Rodriguez, V., Sanchez, L., Palomares, R., & Cornejo, J. (2022). Ergonomic Bio-Design and Motion Simulation of a Mechatronic Orthosis System for Elbow Rehabilitation. Proceedings of the 2022 IEEE 29th International Conference on Electronics, Electrical Engineering and Computing, INTERCON 2022. doi:10.1109/INTERCON55795.2022.9870083.

[8] Vargas, M., Cornejo, J., & Correa-López, L. E. (2016). Biomedical Engineering: The Technological Revolution for the Future of the Peruvian Health System. Revista de La Facultad de Medicina Humana, 16(3), 95-96. doi:10.25176/rfmh.v16.n3.659.

[9] Cornejo, J., Cornejo-Aguilar, J. A., Gonzalez, C., & Sebastian, R. (2021). Mechanical and Kinematic Design of Surgical Mini Robotic Manipulator used into SP-LAP Multi-DOF Platform for Training and Simulation. Proceedings of the 2021 IEEE 28th International Conference on Electronics, Electrical Engineering and Computing. doi:10.1109/INTERCON52678.2021.9532965.

[10] Cornejo, J., Cornejo-Aguilar, J. A., & Palomares, R. (2019). Biomedik Surgeon: Surgical Robotic System for Training and Simulation by Medical Students in Peru. Proceedings of the 2019 International Conference on Control of Dynamical and Aerospace Systems, XPOTRON 2019. doi:10.1109/XPOTRON.2019.8705717.

[11] Cornejo, J., Cornejo-Aguilar, J. A., Sebastian, R., Perales, P., Gonzalez, C., Vargas, M., & Elli, E. F. (2021). Mechanical Design of a Novel Surgical Laparoscopic Simulator for Telemedicine Assistance and Physician Training during Aerospace Applications. 3rd IEEE Eurasia Conference on Biomedical Engineering, Healthcare and Sustainability, ECBIOS 2021, 53–56. doi:10.1109/ECBIOS51820.2021.9510753.

[12] Cornejo, J., Cornejo-Aguilar, J. A., Vargas, M., Helguero, C. G., Milanezi De Andrade, R., Torres-Montoya, S., Asensio-Salazar, J., Rivero Calle, A., Martínez Santos, J., Damon, A., Quiñones-Hinojosa, A., Quintero-Consuegra, M. D., Umaña, J. P., Gallo-Bernal, S., Briceño, M., Tripodi, P., Sebastian, R., Perales-Villarroel, P., De La Cruz-Ku, G., … Russomano, T. (2022). Anatomical Engineering and 3D Printing for Surgery and Medical Devices: International Review and Future Exponential Innovations. BioMed Research International, 6797745. doi:10.1155/2022/6797745.

[13] Cornejo, J., Perales-Villarroel, J. P., Sebastian, R., & Cornejo-Aguilar, J. A. (2020). Conceptual design of space biosurgeon for robotic surgery and aerospace medicine. IEEE Andescon, Quito, Ecuador. doi:10.1109/ANDESCON50619.2020.9272122.

[14] Cornejo, J., Cornejo, J., Vargas, M., Carvajal, M., Perales, P., Rodríguez, G., Macias, C., Canizares, S., Silva, P., Cubas, R. F., Jimenez, M. C., Lincango, E. P., Serrano, L., Palomares, R., Aspilcueta, S., Castillo-Larios, R., Evans, L. A., De La Cruz-Vargas, J. A., Risk, M., … Elli, E. F. (2024). SY-MIS Project: Biomedical Design of Endo-Robotic and Laparoscopic Training System for Surgery on the Earth and Space. Emerging Science Journal, 8(2), 372–393. doi:10.28991/ESJ-2024-08-02-01.

[15] Quezada, J. P., Cabrera, K. S., Cornejo, J., Palomares, R., Cornejo-Aguilar, J. A., & Vargas, M. (2023). Mechatronic Conceptual Design and Kinematic Analysis of Serial-Type Robotic Exoskeleton for Assisted Rehabilitation Therapy on Upper Limbs. 2023 3rd International Conference on Advances in Electrical, Computing, Communication and Sustainable Technologies, ICAECT 2023. doi:10.1109/ICAECT57570.2023.10118243.

[16] Xiong, F., Liao, X., Xiao, J., Bai, X., Huang, J., Zhang, B., Li, F., & Li, P. (2022). Emerging Limb Rehabilitation Therapy after Post-stroke Motor Recovery. Frontiers in Aging Neuroscience, 14, 863379. doi:10.3389/fnagi.2022.863379.

[17] Herrnstadt, G., Alavi, N., Randhawa, B. K., Boyd, L. A., & Menon, C. (2015). Bimanual elbow robotic orthoses: Preliminary investigations on an impairment force-feedback rehabilitation method. Frontiers in Human Neuroscience, 9(March), 169. doi:10.3389/fnhum.2015.00169.

[18] Frolov, A. A., Kozlovskaya, I. B., Biryukova, E. V., & Bobrov, P. D. (2018). Use of Robotic Devices in Post-Stroke Rehabilitation. Neuroscience and Behavioral Physiology, 48(9), 1053–1066. doi:10.1007/s11055-018-0668-3.

[19] Nizamis, K., Stienen, A. H. A., Kamper, D. G., Keller, T., Plettenburg, D. H., Rouse, E. J., Farina, D., Koopman, B. F. J. M., & Sartori, M. (2019). Transferrable Expertise from Bionic Arms to Robotic Exoskeletons: Perspectives for Stroke and Duchenne Muscular Dystrophy. IEEE Transactions on Medical Robotics and Bionics, 1(2), 88–96. doi:10.1109/tmrb.2019.2912453.

[20] Pan, J., Astarita, D., Baldoni, A., Dell'agnello, F., Crea, S., Vitiello, N., & Trigili, E. (2023). A Self-Aligning Upper-Limb Exoskeleton Preserving Natural Shoulder Movements: Kinematic Compatibility Analysis. IEEE Transactions on Neural Systems and Rehabilitation Engineering, 31, 4954–4964. doi:10.1109/TNSRE.2023.3341219.

[21] Daunoraviciene, K., Adomaviciene, A., Grigonyte, A., Griškevicius, J., & Juocevicius, A. (2018). Effects of robot-assisted training on upper limb functional recovery during the rehabilitation of poststroke patients. Technology and Health Care, 26(S2), S533–S542. doi:10.3233/THC-182500.

[22] Chang, S. R., Hofland, N., Chen, Z., Tatsuoka, C., Richards, L. G., Bruestle, M., Kovelman, H., & Naft, J. (2023). Myoelectric Arm Orthosis Assists Functional Activities: A 3-Month Home Use Outcome Report. Archives of Rehabilitation Research and Clinical Translation, 5(3), 100279. doi:10.1016/j.arrct.2023.100279.

[23] Pignolo, L., Lucca, L. F., Basta, G., Sena, S., Pugliese, M. E., Sannita, W. G., & Dolce, G. (2016). A new treatment in the rehabilitation of the paretic upper limb after stroke: The ARAMIS prototype and treatment protocol. Annali Dell'Istituto Superiore Di Sanita, 52(2), 301–308. doi:10.4415/ANN_16_02_25.

[24] Falkowski, P., & Jeznach, K. (2024). Simulation of a control method for active kinesiotherapy with an upper extremity rehabilitation exoskeleton without force sensor. Journal of NeuroEngineering and Rehabilitation, 21(1), 22. doi:10.1186/s12984-024-01316-x.

[25] Baur, K., Rohrbach, N., Hermsdörfer, J., Riener, R., & Klamroth-Marganska, V. (2019). The "beam-Me-In Strategy" - Remote haptic therapist-patient interaction with two exoskeletons for stroke therapy. Journal of NeuroEngineering and Rehabilitation, 16(1), 1–15. doi:10.1186/s12984-019-0547-3.

[26] Copaci, D., Martin, F., Moreno, L., & Blanco, D. (2019). SMA Based Elbow Exoskeleton for Rehabilitation Therapy and Patient Evaluation. IEEE Access, 7, 31473–31484. doi:10.1109/ACCESS.2019.2902939.

[27] Cornejo, J., Cornejo Aguilar, J. A., & Perales Villarroel, J. P. (2019). International Innovations in Medical Robotics to Improve Patient Management in Peru. Journal of the Faculty of Human Medicine, 19(4), 105–113. doi:10.25176/rfmh.v19i4.2349.

[28] Gopura, R. A. R. C., Bandara, D. S. V., Kiguchi, K., & Mann, G. K. I. (2016). Developments in hardware systems of active upper-limb exoskeleton robots: A review. Robotics and Autonomous Systems, 75, 203–220. doi:10.1016/j.robot.2015.10.001.

[29] Chen, Z. H., Yang, Y. L., Lin, K. W., Sun, P. C., & Chen, C. S. (2022). Functional Assessment of 3D-Printed Multifunction Assistive Hand Device for Chronic Stroke Patients. IEEE Transactions on Neural Systems and Rehabilitation Engineering, 30, 1261–1266. doi:10.1109/TNSRE.2022.3173034.

[30] Cornejo, J., Vargas, M., & Cornejo, J. (2020). Innovative Applications of Robotics and Biomedicine in Public Health during the Covid-19 Pandemic. Journal of the Faculty of Human Medicine, 20(4), 756–757.

[31] Zavala Molina, D. A., Silva Cabrejos, R. J., Murillo Manrique, M. F., Rodríguez Bustinza, R. R., Cornejo Aguilar, J. L., & Palomares Orihuela, R. J. (2023). Geometric Modeling and Kinematic Simulation of Hand Prostheses for Adult Patients with Transradial Amputation. Engineering Profiles, 20(20), 179–200. doi:10.31381/perfilesingenieria.v20i20.6020.

[32] Vergaray, R. A., Del Aguila, R. F., Avellaneda, G. A., Palomares, R., Cornejo, J., & Cornejo-Aguilar, J. A. (2021). Mechatronic System Design and Development of iROD: EMG Controlled Bionic Prosthesis for Middle-Third Forearm Amputee. ETCM 2021 - 5th Ecuador Technical Chapters Meeting, Cuenca, Ecuador. doi:10.1109/ETCM53643.2021.9590715.

[33] Carrera-Rivera, A., Ochoa, W., Larrinaga, F., & Lasa, G. (2022). How-to conduct a systematic literature review: A quick guide for computer science research. MethodsX, 9, 101895. doi:10.1016/j.mex.2022.101895.

[34] Sainz-Pelayo, M. P., Albu, S., Murillo, N., & Benito-Penalva, J. (2020). Spasticity in neurological pathologies. An update on the pathophysiological mechanisms, advances in diagnosis and treatment. Revista de Neurologia, 70(12), 453–460. doi:10.33588/RN.7012.2019474.

[35] Jover-Martínez, E., Ríos-Díaz, J., & Poveda-Pagán, E. J. (2015). Relationship between spasticity scales and independence and functional status scales in patients with cerebral palsy. Physiotherapy, 37(4), 175–184. doi:10.1016/j.ft.2014.10.001.

[36] Centen, A., Lowrey, C. R., Scott, S. H., Yeh, T. T., & Mochizuki, G. (2017). KAPS (kinematic assessment of passive stretch): A tool to assess elbow flexor and extensor spasticity after stroke using a robotic exoskeleton. Journal of NeuroEngineering and Rehabilitation, 14(1), 1–13. doi:10.1186/s12984-017-0272-8.

[37] Mochizuki, G., Centen, A., Resnick, M., Lowrey, C., Dukelow, S. P., & Scott, S. H. (2019). Movement kinematics and proprioception in post-stroke spasticity: Assessment using the Kinarm robotic exoskeleton. Journal of NeuroEngineering and Rehabilitation, 16(1), 1–13. doi:10.1186/s12984-019-0618-5.

[38] Posteraro, F., Crea, S., Mazzoleni, S., Bert Eanu, M., Ciobanu, I., Vitiello, N., Cempini, M., Gervasio, S., & Mrachacz-Kersting, N. (2018). Technologically-advanced assessment of upper-limb spasticity: A pilot study. European Journal of Physical and Rehabilitation Medicine, 54(4), 536–544. doi:10.23736/S1973-9087.17.04815-8.

[39] Dehem, S., Gilliaux, M., Lejeune, T., Detrembleur, C., Galinski, D., Sapin, J., Vanderwegen, M., & Stoquart, G. (2017). Assessment of upper limb spasticity in stroke patients using the robotic device reaplan. Journal of Rehabilitation Medicine, 49(7), 565–571. doi:10.2340/16501977-2248.

[40] Crea, S., Cempini, M., Mazzoleni, S., Carrozza, M. C., Posteraro, F., & Vitiello, N. (2017). Phase-II clinical validation of a powered exoskeleton for the treatment of elbow spasticity. Frontiers in Neuroscience, 11(May), 261. doi:10.3389/fnins.2017.00261.

[41] Koh, T. H., Cheng, N., Yap, H. K., & Yeow, C. H. (2017). Design of a soft robotic elbow sleeve with passive and intent-controlled actuation. Frontiers in Neuroscience, 11(OCT), 597. doi:10.3389/fnins.2017.00597.

[42] McGibbon, C. A., Sexton, A., Jones, M., & O'Connell, C. (2013). Elbow spasticity during passive stretch-reflex: Clinical evaluation using a wearable sensor system. Journal of NeuroEngineering and Rehabilitation, 10(1), 61. doi:10.1186/1743-0003-10-61.

[43] Sin, M., Kim, W. S., Cho, K., & Paik, N. J. (2019). Isokinetic robotic device to improve test-retest and inter-rater reliability for stretch reflex measurements in stroke patients with spasticity. Journal of Visualized Experiments, 2019(148). doi:10.3791/59814.

[44] Pilla, A., Trigili, E., McKinney, Z., Fanciullacci, C., Malasoma, C., Posteraro, F., Crea, S., & Vitiello, N. (2020). Robotic Rehabilitation and Multimodal Instrumented Assessment of Post-stroke Elbow Motor Functions—A Randomized Controlled Trial Protocol. Frontiers in Neurology, 11, 587293. doi:10.3389/fneur.2020.587293.

[45] Adar, S., Demircan, A., Akçin, A. İ., Dündar, Ü., Toktaş, H., Yeşil, H., Eroğlu, S., Eyvaz, N., Beştaş, E., & Toksoy, C. K. (2023). Evaluation of finger strength and spasticity in hemiplegic patients using hand-finger robotic device a validity and reliability study. Medicine (United States), 102(49), E36479. doi:10.1097/MD.0000000000036479.

[46] Chiyohara, S., Furukawa, J. ichiro, Noda, T., Morimoto, J., & Imamizu, H. (2020). Passive training with upper extremity exoskeleton robot affects proprioceptive acuity and performance of motor learning. Scientific Reports, 10(1), 11820. doi:10.1038/s41598-020-68711-x.

[47] Washabaugh, E. P., Treadway, E., Brent Gillespiec, R., David Remy, C., & Krishnan, C. (2018). Self-powered robots to reduce motor slacking during upper-extremity rehabilitation: A proof of concept study. Restorative Neurology and Neuroscience, 36(6), 693–708. doi:10.3233/RNN-180830.

[48] Grimm, F., Naros, G., & Gharabaghi, A. (2016). Closed-loop task difficulty adaptation during virtual reality reach-to-grasp training assisted with an exoskeleton for stroke rehabilitation. Frontiers in Neuroscience, 10(NOV), 518. doi:10.3389/fnins.2016.00518.

[49] Bos, R. A., Nizamis, K., Koopman, B. F. J. M., Herder, J. L., Sartori, M., & Plettenburg, D. H. (2020). A Case Study with Symbihand: An sEMG-Controlled Electrohydraulic Hand Orthosis for Individuals with Duchenne Muscular Dystrophy. IEEE Transactions on Neural Systems and Rehabilitation Engineering, 28(1), 258–266. doi:10.1109/TNSRE.2019.2952470.

[50] Brihmat, N., Loubinoux, I., Castel-Lacanal, E., Marque, P., & Gasq, D. (2020). Kinematic parameters obtained with the ArmeoSpring for upper-limb assessment after stroke: A reliability and learning effect study for guiding parameter use. Journal of NeuroEngineering and Rehabilitation, 17(1), 130. doi:10.1186/s12984-020-00759-2.

[51] Borboni, A., Villafañe, J. H., Mullè, C., Valdes, K., Faglia, R., Taveggia, G., & Negrini, S. (2017). Robot-Assisted Rehabilitation of Hand Paralysis After Stroke Reduces Wrist Edema and Pain: A Prospective Clinical Trial. Journal of Manipulative and Physiological Therapeutics, 40(1), 21–30. doi:10.1016/j.jmpt.2016.10.003.

[52] Dudley, D. R., Knarr, B. A., Siu, K. C., Peck, J., Ricks, B., & Zuniga, J. M. (2021). Testing of a 3D printed hand exoskeleton for an individual with stroke: a case study. Disability and Rehabilitation: Assistive Technology, 16(2), 209–213. doi:10.1080/17483107.2019.1646823.

[53] Luke, C., Dodd, K. J., & Brock, K. (2004). Outcomes of the Bobath concept on upper limb recovery following stroke. Clinical Rehabilitation, 18(8), 888–898. doi:10.1191/0269215504cr793oa.

[54] Díaz-Arribas, M. J., Martín-Casas, P., Cano-de-la-Cuerda, R., & Plaza-Manzano, G. (2020). Effectiveness of the Bobath concept in the treatment of stroke: a systematic review. Disability and Rehabilitation, 42(12), 1636–1649. doi:10.1080/09638288.2019.1590865.

[55] Pundik, S., McCabe, J., Skelly, M., Salameh, A., Naft, J., Chen, Z., Tatsuoka, C., & Fatone, S. (2022). Myoelectric Arm Orthosis in Motor Learning-Based Therapy for Chronic Deficits after Stroke and Traumatic Brain Injury. Frontiers in Neurology, 13, 791144. doi:10.3389/fneur.2022.791144.

[56] Hsu, C. Y., Wu, C. M., Huang, C. C., Shie, H. H., & Tsai, Y. S. (2022). Feasibility and Potential Effects of Robot-Assisted Passive Range of Motion Training in Combination with Conventional Rehabilitation on Hand Function in Patients with Chronic Stroke. Journal of Rehabilitation Medicine, 54, 323. doi:10.2340/jrm.v54.1407.

[57] Singh, N., Saini, M., Kumar, N., Srivastava, M. V. P., & Mehndiratta, A. (2021). Evidence of neuroplasticity with robotic hand exoskeleton for post-stroke rehabilitation: a randomized controlled trial. Journal of NeuroEngineering and Rehabilitation, 18(1), 76. doi:10.1186/s12984-021-00867-7.

[58] Hu, X. L., Tong, R. K. Y., Ho, N. S. K., Xue, J. J., Rong, W., & Li, L. S. W. (2015). Wrist Rehabilitation Assisted by an Electromyography-Driven Neuromuscular Electrical Stimulation Robot after Stroke. Neurorehabilitation and Neural Repair, 29(8), 767–776. doi:10.1177/1545968314565510.

[59] Wu, Q., Wang, Z., & Chen, Y. (2023). SEMG-Based Adaptive Cooperative Multi-Mode Control of a Soft Elbow Exoskeleton Using Neural Network Compensation. IEEE Transactions on Neural Systems and Rehabilitation Engineering, 31, 3384–3396. doi:10.1109/TNSRE.2023.3306201.

[60] Ambrosini, E., Russold, M., Gfoehler, M., Puchinger, M., Weber, M., Becker, S., Krakow, K., Immick, N., Augsten, A., Rossini, M., Proserpio, D., Zajc, J., Gasperini, G., Molteni, F., Pedrocchi, A., Ferrante, S., Ferrigno, G., Gasperina, S. D., Bulgheroni, M., … Wiesener, C. (2019). A Hybrid robotic system for arm training of stroke survivors: Concept and first evaluation. IEEE Transactions on Biomedical Engineering, 66(12), 3290–3300. doi:10.1109/TBME.2019.2900525.

[61] Huang, Y., Nam, C., Li, W., Rong, W., Xie, Y., Liu, Y., Qian, Q., & Hu, X. (2020). A comparison of the rehabilitation effectiveness of neuromuscular electrical stimulation robotic hand training and pure robotic hand training after stroke: A randomized controlled trial. Biomedical Signal Processing and Control, 56, 101723. doi:10.1016/j.bspc.2019.101723.

[62] Hsu, H. Y., Koh, C. L., Yang, K. C., Lin, Y. C., Hsu, C. H., Su, F. C., & Kuo, L. C. (2024). Effects of an assist-as-needed equipped Tenodesis-Induced-Grip Exoskeleton Robot (TIGER) on upper limb function in patients with chronic stroke. Journal of NeuroEngineering and Rehabilitation, 21(1), 5. doi:10.1186/s12984-023-01298-2.

[63] Alhamad, R., Seth, N., & Abdullah, H. A. (2023). Initial Testing of Robotic Exoskeleton Hand Device for Stroke Rehabilitation. Sensors, 23(14), 6339. doi:10.3390/s23146339.

[64] Noronha, B., Ng, C. Y., Little, K., Xiloyannis, M., Kuah, C. W. K., Wee, S. K., Kulkarni, S. R., Masia, L., Chua, K. S. G., & Accoto, D. (2022). Soft, Lightweight Wearable Robots to Support the Upper Limb in Activities of Daily Living: A Feasibility Study on Chronic Stroke Patients. IEEE Transactions on Neural Systems and Rehabilitation Engineering, 30, 1401–1411. doi:10.1109/TNSRE.2022.3175224.

[65] das Neves, M. F., Aleixo, D. C., Mendes, I. S., Lima, F. P. S., Nicolau, R. A., Arisawa, E. A. L., Lopes-Martins, R. A. B., & Lima, M. O. (2020). Long-term analyses of spastic muscle behavior in chronic poststroke patients after near-infrared low-level laser therapy (808 nm): a double-blinded placebo-controlled clinical trial. Lasers in Medical Science, 35(7), 1459–1467. doi:10.1007/s10103-019-02920-3.

[66] Kopke, J. V., Ellis, M. D., & Hargrove, L. J. (2020). Determining User Intent of Partly Dynamic Shoulder Tasks in Individuals with Chronic Stroke Using Pattern Recognition. IEEE Transactions on Neural Systems and Rehabilitation Engineering, 28(1), 350–358. doi:10.1109/TNSRE.2019.2955029.

[67] Liu, Q., Liu, Y., Li, Y., Zhu, C., Meng, W., Ai, Q., & Xie, S. Q. (2021). Path Planning and Impedance Control of a Soft Modular Exoskeleton for Coordinated Upper Limb Rehabilitation. Frontiers in Neurorobotics, 15, 745531. doi:10.3389/fnbot.2021.745531.

[68] Ren, H., Liu, T., & Wang, J. (2023). Design and Analysis of an Upper Limb Rehabilitation Robot Based on Multimodal Control. Sensors (Switzerland), 23(21), 8801. doi:10.3390/s23218801.

[69] Cantillo-Negrete, J., Carino-Escobar, R. I., Carrillo-Mora, P., Rodriguez-Barragan, M. A., Hernandez-Arenas, C., Quinzaños-Fresnedo, J., Hernandez-Sanchez, I. R., Galicia-Alvarado, M. A., Miguel-Puga, A., & Arias-Carrion, O. (2021). Brain-Computer Interface Coupled to a Robotic Hand Orthosis for Stroke Patients' Neurorehabilitation: A Crossover Feasibility Study. Frontiers in Human Neuroscience, 15, 656975. doi:10.3389/fnhum.2021.656975.

[70] Franck, J. A., Smeets, R. J. E. M., & Seelen, H. A. M. (2019). Evaluation of a functional hand orthosis combined with electrical stimulation adjunct to arm-hand rehabilitation in subacute stroke patients with a severely to moderately affected hand function. Disability and Rehabilitation, 41(10), 1160–1168. doi:10.1080/09638288.2017.1423400.

[71] Xia, K., Chen, X., Chang, X., Liu, C., Guo, L., Xu, X., Lv, F., Wang, Y., Sun, H., & Zhou, J. (2022). Hand Exoskeleton Design and Human–Machine Interaction Strategies for Rehabilitation. Bioengineering, 9(11), 682. doi:10.3390/bioengineering9110682.

[72] Yurkewich, A., Hebert, D., Wang, R. H., & Mihailidis, A. (2019). Hand extension robot orthosis (hero) glove: Development and testing with stroke survivors with severe hand impairment. IEEE Transactions on Neural Systems and Rehabilitation Engineering, 27(5), 916–926. doi:10.1109/TNSRE.2019.2910011.

[73] Yurkewich, A., Kozak, I. J., Hebert, D., Wang, R. H., & Mihailidis, A. (2020). Hand Extension Robot Orthosis (HERO) Grip Glove: Enabling independence amongst persons with severe hand impairments after stroke. Journal of NeuroEngineering and Rehabilitation, 17(1), 33. doi:10.1186/s12984-020-00659-5.

[74] He, C., Xiong, C. H., Chen, Z. J., Fan, W., Huang, X. L., & Fu, C. (2021). Preliminary Assessment of a Postural Synergy-Based Exoskeleton for Post-Stroke Upper Limb Rehabilitation. IEEE Transactions on Neural Systems and Rehabilitation Engineering, 29, 1795–1805. doi:10.1109/TNSRE.2021.3107376.

[75] Chen, Z. J., He, C., Xu, J., Zheng, C. J., Wu, J., Xia, N., Hua, Q., Xia, W. G., Xiong, C. H., & Huang, X. L. (2023). Exoskeleton-Assisted Anthropomorphic Movement Training for the Upper Limb after Stroke: The EAMT Randomized Trial. Stroke, 54(6), 1464–1473. doi:10.1161/STROKEAHA.122.041480.

[76] Hohl, K., Giffhorn, M., Jackson, S., & Jayaraman, A. (2022). A framework for clinical utilization of robotic exoskeletons in rehabilitation. Journal of NeuroEngineering and Rehabilitation, 19(1), 115. doi:10.1186/s12984-022-01083-7.

[77] Singh, N., Saini, M., Kumar, N., Srivastava, M. V. P., Kumaran, S. S., & Mehndiratta, A. (2021). A Case Report: Effect of Robotic Exoskeleton Based Therapy on Neurological and Functional Recovery of a Patient with Chronic Stroke. Frontiers in Neurology, 12, 680733. doi:10.3389/fneur.2021.680733.

[78] Hossain, D., Scott, S. H., Cluff, T., & Dukelow, S. P. (2023). The use of machine learning and deep learning techniques to assess proprioceptive impairments of the upper limb after stroke. Journal of NeuroEngineering and Rehabilitation, 20(1), 15. doi:10.1186/s12984-023-01140-9.

[79] Rauch, A., Negrini, S., & Cieza, A. (2019). Toward Strengthening Rehabilitation in Health Systems: Methods Used to Develop a WHO Package of Rehabilitation Interventions. Archives of Physical Medicine and Rehabilitation, 100(11), 2205–2211. doi:10.1016/j.apmr.2019.06.002.

[80] Qian, Q., Hu, X., Lai, Q., Ng, S. C., Zheng, Y., & Poon, W. (2017). Early stroke rehabilitation of the upper limb assisted with an electromyography-driven neuromuscular electrical stimulation-robotic arm. Frontiers in Neurology, 8(SEP), 447. doi:10.3389/fneur.2017.00447.

[81] Keeling, A. B., Piitz, M., Semrau, J. A., Hill, M. D., Scott, S. H., & Dukelow, S. P. (2021). Robot enhanced stroke therapy optimizes rehabilitation (RESTORE): a pilot study. Journal of NeuroEngineering and Rehabilitation, 18(1), 10. doi:10.1186/s12984-021-00804-8.

[82] Leonardis, D., Barsotti, M., Loconsole, C., Solazzi, M., Troncossi, M., Mazzotti, C., Castelli, V. P., Procopio, C., Lamola, G., Chisari, C., Bergamasco, M., & Frisoli, A. (2015). An EMG-controlled robotic hand exoskeleton for bilateral rehabilitation. IEEE Transactions on Haptics, 8(2), 140–151. doi:10.1109/TOH.2015.2417570.

[83] De-la-Torre, R., Oña, E. D., Balaguer, C., & Jardón, A. (2020). Robot-aided systems for improving the assessment of upper limb spasticity: A systematic review. Sensors, 20(18), 5251. doi:10.3390/s20185251.

[84] Lee, Y. Y., Lin, K. C., Cheng, H. J., Wu, C. Y., Hsieh, Y. W., & Chen, C. K. (2015). Effects of combining robot-assisted therapy with neuromuscular electrical stimulation on motor impairment, motor and daily function, and quality of life in patients with chronic stroke: A double-blinded randomized controlled trial. Journal of NeuroEngineering and Rehabilitation, 12(1), 96. doi:10.1186/s12984-015-0088-3.

[85] Shin, S., Lee, H. J., Chang, W. H., Ko, S. H., Shin, Y. Il, & Kim, Y. H. (2022). A Smart Glove Digital System Promotes Restoration of Upper Limb Motor Function and Enhances Cortical Hemodynamic Changes in Subacute Stroke Patients with Mild to Moderate Weakness: A Randomized Controlled Trial. Journal of Clinical Medicine, 11(24). doi:10.3390/jcm11247343.

[86] Pournajaf, S., Morone, G., Straudi, S., Goffredo, M., Leo, M. R., Calabrò, R. S., Felzani, G., Paolucci, S., Filoni, S., Santamato, A., Franceschini, M., Zanetti, C., Calligola, D., Spina, S., Facciorusso, S., Fregna, G., Baroni, A., Cimino, V., Cinnera, A. M., … Pompilio, M. P. (2023). Neurophysiological and Clinical Effects of Upper Limb Robot-Assisted Rehabilitation on Motor Recovery in Patients with Subacute Stroke: A Multicenter Randomized Controlled Trial Study Protocol. Brain Sciences, 13(4), 700. doi:10.3390/brainsci13040700.

[87] Guo, N., Wang, X., Duanmu, D., Huang, X., Li, X., Fan, Y., Li, H., Liu, Y., Yeung, E. H. K., To, M. K. T., Gu, J., Wan, F., & Hu, Y. (2022). SSVEP-Based Brain Computer Interface Controlled Soft Robotic Glove for Post-Stroke Hand Function Rehabilitation. IEEE Transactions on Neural Systems and Rehabilitation Engineering, 30, 1737–1744. doi:10.1109/TNSRE.2022.3185262.

[88] Chowdhury, A., Meena, Y. K., Raza, H., Bhushan, B., Uttam, A. K., Pandey, N., Hashmi, A. A., Bajpai, A., Dutta, A., & Prasad, G. (2018). Active Physical Practice Followed by Mental Practice Using BCI-Driven Hand Exoskeleton: A Pilot Trial for Clinical Effectiveness and Usability. IEEE Journal of Biomedical and Health Informatics, 22(6), 1786–1795. doi:10.1109/JBHI.2018.2863212.

[89] Nieto-Chaupis, H. (2023). The Internet of Brain Things: Theoretical Basis for the Usage of Neuralink Chip. IEEE International Conference on Consumer Electronics - Berlin, ICCE-Berlin, 3–5. doi:10.1109/ICCE-Berlin58801.2023.10375671.

[90] Sharma, A., Khan, K., & Katarya, R. (2022). Human Augmentation Technology- A Cybersecurity Review for Widespread Adoption. 2022 13th International Conference on Computing Communication and Networking Technologies, ICCCNT 2022, 3–5. doi:10.1109/ICCCNT54827.2022.9984500.

[91] Abrams, Z. (2023). Breakthroughs in Brain Implants. IEEE Pulse, 14(6), 7–10. doi:10.1109/MPULS.2024.3353668.

[92] Gupta, G., Pequito, S., & Bogdan, P. (2018). Re-Thinking EEG-Based Non-Invasive Brain Interfaces: Modeling and Analysis. Proceedings - 9th ACM/IEEE International Conference on Cyber - Physical Systems, 275–286. doi:10.1109/ICCPS.2018.00034.

[93] Rivera, M. V., Cornejo, J., Huallpayunca, K., Diaz, A. B., Ortiz-Benique, Z. N., Reina, A. D., Lino, G. J., & Ticllacuri, V. (2020). Human space medicine: Physiological performance and countermeasures to improve astronaut health. Revista de la Facultad de Medicina Humana, 20(2), 303-314. doi:10.25176/RFMH.v20i2.2920.