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(Review Article)

# Robotic-assisted techniques in complex hand and upper extremity reconstruction: Current capabilities, outcomes, and future opportunities

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## Abstract

Complex hand and upper extremity reconstruction is undergoing revolution with robotic-assisted methods that restore dexterity impaired by stroke and injury or neurological diseases that affect the quality of life. More sophisticated technologies, such as exoskeletons (e.g., Armin), end-effecter devices (e.g., Rego), and microsurgical robots (e.g., Da Vinci), allow for accurate operation and extensive therapy to be carried out. The clinical outcomes (2015 and 2025) are characterized by substantial improvements in motor function and dexterity, with a 2.6 to 3.4-point increase in the Fugl-Meyer Assessment, compared to a 2.0 to 2.9-point improvement in control patients ($p < 0.05$). These technologies enhance patient interaction by utilizing virtual reality and gamification, resulting in a 10- to 15-point improvement on the Barthel Index and a 60% decrease in depression. Nonetheless, prohibitive costs ($50,000-$1,250,000/system), training requirements, and the scarcity of long-term data are significant challenges. New technologies, such as AI-powered personalization, brain-computer interfaces, and mobile robotics, hold the potential for easily available, customized opportunities. New horizons exist to expand the treatment of children with conditions and non-stroke injuries. Robotic-assisted methods have the potential to transform reconstruction outcomes by breaking down barriers such as cost and training, thereby combining the precision of high-precision surgery with the intensity of high-intensity therapy to enhance the reconstruction process. The article discusses such advancements and their future potential to change the way patients are cared for in the field of hand and upper extremity reconstruction.

**Keywords:** Robotic-Assisted Surgery; Hand Reconstruction; Upper Extremity Rehabilitation; Exoskeletons; Microsurgery; Neuroplasticity

## 1. Introduction

### 1.1. Background and Significance

The upper extremity and hand are crucial for performing everyday tasks, engaging in occupational activities, and maintaining overall quality of life; however, millennials with impairments in these areas are significantly affected. Each year, 1.5 million stroke survivors are estimated to live in the United States, and 50 percent of them retain a chronic deficit in upper limbs, which undermines motor conditions, dexterity, and autonomy (Wainstein et al., 2016). Upper extremity injuries occur frequently in the world, including fractures, ruptures of tendons, and damage to nerve structures, and complex upper extremity injuries make up 17 percent of all multiple trauma injuries that involve multiple joints, thus creating the need to perform intricate reconstructions of the upper extremity (Banerjee et al., 2013)—such disorders as hemiparesis caused by a stroke and severe trauma present great difficulties for conventional reconstructive methods. Manual therapy and conventional surgical procedures tend to be ineffective and have variable results; they are unable to cope with the needs of neurological impairments or multi-joint pathology, and are sometimes tedious in their presentation. As an example, it has been demonstrated that at six months, only 2025 percent of stroke

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survivors recover all of their arm function, and this shows the shortcomings of conventional rehabilitation (Kwakkel et al., 2008). On the same token, traumatic pathologies such as brachial plexus damage require precise repairs of hand multi-freedom degrees (considering 27 multi-freedom degrees), and traditional methods are currently incapable of such accuracy. The technologies that utilize robots as assistants have proven to be revolutionary, as they can provide unparalleled precision, repeatability, and patient engagement. Systems such as the ARMin exoskeleton and Da Vinci microsurgery robots can support specialized surgical treatments and intense rehabilitation, overcoming these problems with the power associated with data-driven, repeatable accuracy (Sattarzadeh et al., 2024). These technologies aim to reinvent functional restoration, with the potential to enhance patient outcomes by overcoming the inconsistencies and physical demands associated with traditional methods.

The area of hand and upper extremity reconstruction is redefined by the use of robotic-assisted systems, which enable the synergy of enhanced engineering capabilities with intricate clinical workflows to perform high-intensity surgical procedures and achieve reliable, standardized operations tailored to the individual requirements of each patient. The robotic equipment models such as the Hand Wrist Assistive Rehabilitation Device (HWARD) has the potential of providing up to 1000 repetitions in a single session as compared to the limitations of the manual therapy where one could follow through with only 50-100 repetitions, but usually allocated to a separate session of conventional therapy and which leads to the accumulation of the neuroplasticity that is critical to the process (Sattarzadeh et al., 2024). The systems to be integrated utilize a real-time feedback system, incorporating sensors and electromyography (EMG), to enhance motor learning and motivation in patients through a gamified and virtual reality controller (Gebreheat et al., 2024). The microsurgical robot (i.e., the Da Vinci platform) employed in surgery predicts a much higher rate of surgery success in terms of nerve and tissue flap repair since recovery of the sensory through the repair can achieve up to 90 percent whereas the conventional repair results in a recovery of the sensory of at best 75-80 percent (Chen et al., 2021). Nevertheless, they are also characterized by numerous challenges, including high prices (between $ 50,000 and over a quarter of a million dollars per system) and the necessity of professionally training personnel, which contribute to inequitable access in underprivileged areas (Fernandez-Garcia et al., 2021). The emergent innovations will minimize these barriers because the technology can be applied to other conditions, including children, with the help of AI-driven personalization and portable robotics. This means that robotic technologies provide a truly multidisciplinary solution to a complex upper extremities reconstruction by filling the gap between high surgical precision, on one hand, and intensive rehabilitation, on the other, and providing a saving recovery and a better quality of life in one fell swoop, making it a new standard of care delivery.

Robotic-assisted technologies will transform the current landscape of hand and upper extremity reconstruction, overcoming the limitations of conventional approaches by utilizing patient-specific, scalable, and accurate interventions. Traditional physical therapy, which requires the effort of a therapist, is highly constrained: human capacity cannot sustain itself for longer than a certain time, inefficiency linked to inconsistencies in techniques undermines its effectiveness, and health barriers occur in rural areas or those with limited resources, which remain unequal. Stroke survivors are especially unlikely to regain full function of the upper limbs, with only 2025 recovering after six months, due to the complicated nerve rewiring procedures that would be needed (Kwakkel et al., 2008). Injuries that require drastic rehabilitation, such as a fracture in the distal radius or brachial plexus damage, are also complex because the hand has 27 degrees of freedom that cannot be manually represented (Banerjee et al., 2013). Robotic mechanisms, such as the Hand Wrist Assistive Rehabilitation Device (HWARD), offer intensive therapy, with a maximum of 1,000 repetitions in a single session. It has been observed that this device induces neuroplasticity—a process by which motor recovery occurs, which is particularly evident within the conventional range of 50-100 repetitions (Sattarzadeh et al., 2024). Dynamic regulation of resistance and assistance through advanced sensors and electromyography (EMG) can provide real-time feedback, generate maximum muscle activity and ultimately improve motor learning. The use of gamification and virtual reality interfaces offers additional engagement for patients, and research has provided 85% adherence rates, making otherwise tedious exercises interactive (Gebreheat et al., 2024). These technologies are not limited to stroke, as they also apply to various conditions, such as cerebral palsy and spinal cord injury, offering a scalable solution that allows therapy to scale and reduce the demand on therapists, while delivering consistent and high-quality care across multiple clinical settings.

Adding intensive rehabilitative care to surgical accuracy significantly enhances the effects of robotic technologies in creating a multidisciplinary concept for complex reconstructions. Examples of microsurgery robots include the Da Vinci system, which has improved the process of nerve coaptations and vascular anastomoses, resulting in a 90 percent recovery of senses compared to 75 to 80 percent during conventional procedures, with 10x magnification and the elimination of tremors (Chen et al., 2021). Exoskeletons like ARMin and ReoGo are already being applied in injury treatment, and they could help deliver accurate treatment technologies. These exoskeletons have 10-15 degrees of freedom and have demonstrated a 20% strength enhancement after 12 weeks of treatment for individuals with injuries (Gebrehiwot et al., 2024). These systems employ bilateral training and reflective solutions, triggering neuro-pathways that are symptomatic of neurological degenerative issues (i.e., multiple sclerosis), resulting in a 12 percent elevation in the sensitivity measurements of the GRASSP (Fernandez-Garcia et al., 2021). New technologies, including therapies customized based on AI and brain-computer interfaces, enable adaptive protocols to suit real-time patient data. Meanwhile, portable systems operating at home address the issue of access to care, particularly for underserved patients. Although moderate ($50,000 to $250,000 per system) and time-consuming, the training costs and personnel access may democratize access through public-private partnerships and insurance advocacy (Fernandez-Garcia et al., 2021). Through a combination of surgical excellence and high-intensity active rehabilitation, robotic technologies will transform the standard of care, leading to faster recovery, higher rates of functional restoration, and an improvement in the quality of life among patients with a wide range of upper extremity deficits.

In this article, the author aims to discuss the paradigm shift in using robotic-assisted procedures for complex hand and upper extremity reconstructions, the capabilities of these new methods, the outcomes they present, and their potential for the future. Based on technological innovation and clinical trial (2015 to 2025), it discusses how robotics is used to manage the problem that stroke-related impairment, traumatic injuries, and neurological disorders such as cerebral palsy cause. The applications include surgical and rehabilitation tools (e.g., robotic-assisted microsurgery using robots for neuron and tendon repair, robot slaves, such as exoskeletons and end-effector devices, to enhance motor rehabilitation and patient participation). Regardless of their potential, these systems present several challenges, including their high cost ($50,000-$250,000 per system) and the need for specialized training. New technological developments, such as AI-powered individualization and wearable robotics, will increase availability and efficiency. This article explains these developments, demonstrating that robot technologies have a promising and bright future in redefining the standards of care worldwide, and providing patients with complex impairments of their upper extremities a chance at efficacious functional restoration and improved quality of life.

### 1.2. Scope

This paper discusses robotic-based surgical reconstruction/rehabilitation of the hand and upper extremity, and how they have changed the management of complex cases. It utilizes high-tech equipment, such as microsurgical robots like the Da Vinci system, to repair nerves and tendons with high precision, as well as rehabilitative devices, including exoskeletons and end-effector systems, to promote motor recovery. It focuses on difficult circumstances such as multi-joint injury, nerve repair, and neurological defects such as stroke and cerebral palsy, which require precision and an intense therapy session. The article illustrates how robotics has enhanced the flaws of past practices to achieve better functional outcomes by integrating surgical and rehabilitation apps, as well as repeatability. In this sense, robotics-based interventions employ data-driven measures to achieve more satisfactory functional outcomes through innovations such as virtual reality and gamification.

The analysis is based on peer-reviewed research, clinical trials, and technology news from 2015 to 2025, including databases such as PubMed, IEEE Xplore, and ClinicalTrials.gov. They provide strong data on clinical outcomes, including significant progress in motor functions during stroke rehabilitation, as well as advancements in technologies, such as those towards personalization through AI. Such broad consideration ensures a deep understanding of the current abilities and future perspectives of robotic systems in the field of complex upper extremity repair, in terms of both surgical accuracy and rehabilitation effectiveness.

## 2. Current Capabilities of Robotic-Assisted Techniques

### 2.1. Overview of Robotic Systems

Robotic-assisted systems have changed the way hand and upper extremities are reconstructed using advanced tools that offer surgical precision together with the tools of rehabilitation in the complex cases of stroke, spinal cord injury (SCI), and traumatic injuries. These fall into three broad categories: end-effector robot systems, exoskeleton robot systems, and hand-specific robot systems. End-effector devices, such as ReoGo and HandCARE, involve task-specific actions (i.e., gripping, reaching, manipulating, and manipulating objects). Due to their high repeatability, end-effector devices facilitate functional recovery in stroke victims through a specific motor tasks training program (Maciejasz et al., 2014).

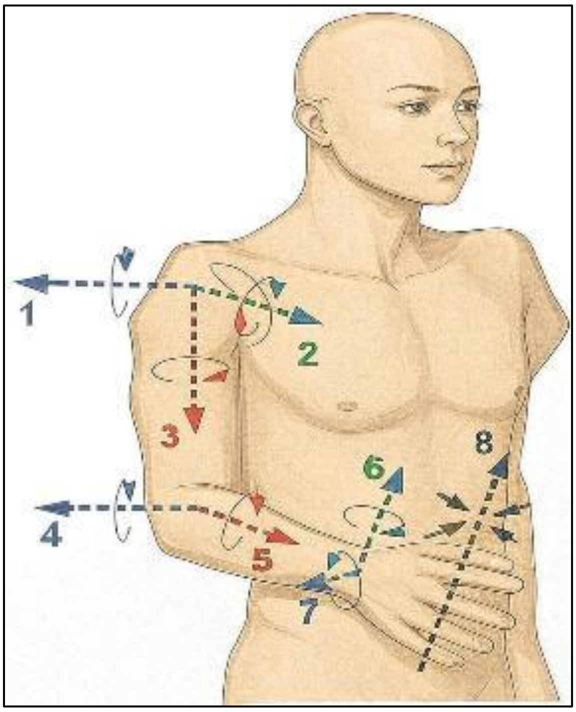
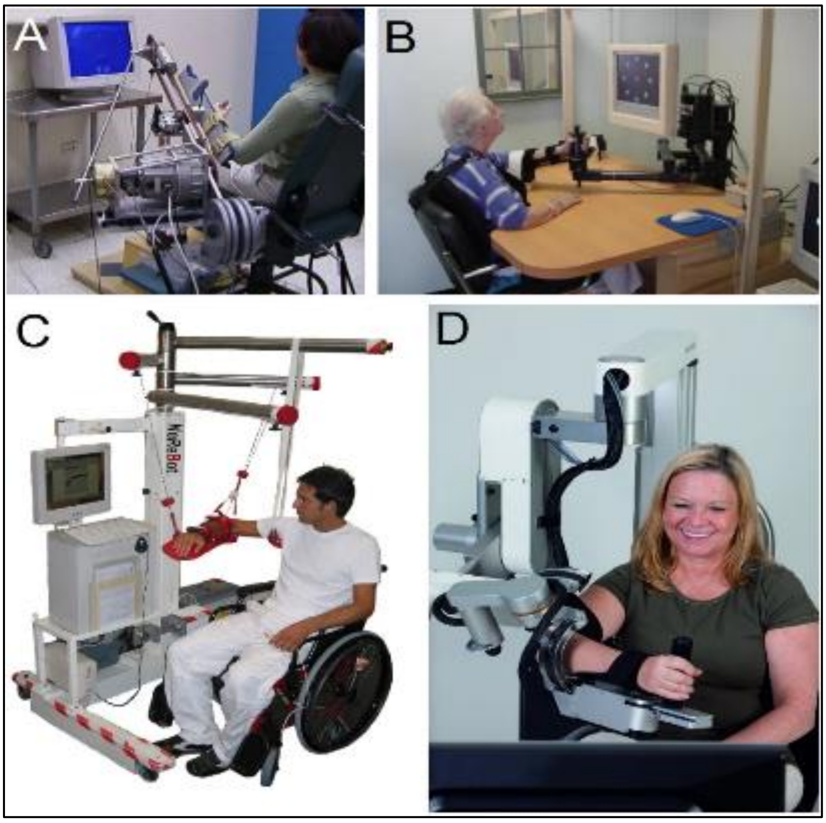



**Figure 1** Aretonotonic Movements of the Upper Extremity. This diagram illustrates the key articulatory motions of the upper limb, including shoulder abduction/adduction (1), flexion/extension (2), elbow flexion/extension (3), forearm pronation/supination (4), wrist flexion/extension (5), radial/ulnar deviation (6), finger flexion/extension (7), and thumb opposition/abduction (8). These movements are critical for robotic-assisted rehabilitation and surgical planning, highlighting the hand's 27 degrees of freedom and guiding precision therapy for conditions like stroke and trauma

ARMin and Armeo Spring are examples of exoskeleton robots that promote coordination in multiple joints across the shoulder, elbow, and wrist areas, thereby playing a crucial role in the comprehensive rehabilitation of stroke and SCI patients who lack complex multi-articular movements (Luo et al., 2019). Robots with hand specificity, such as Amadeo and WRISTBOT, could be used to facilitate the recovery of fine motor skills due to the impairment of dexterity in hand and wrist joints in cerebral palsy or distal radius fractures (Ates et al., 2017). Such systems utilize very precise actuators to achieve controlled and repeatable motion, providing consistent therapy. The aid and counteraction can be tailored to the individual's rate of impairment, varying between mild and severe spasticity and paresis, thereby maximizing the therapeutic enhancement that can be achieved for each patient (Sattarzadeh et al., 2024). Figure 2 provides examples of robots developed to rehabilitate upper limbs and demonstrates a wide range of platforms that help patients perform fine motor and multi-joint exercises.




Adapted from Maciejasz et al. (2014)

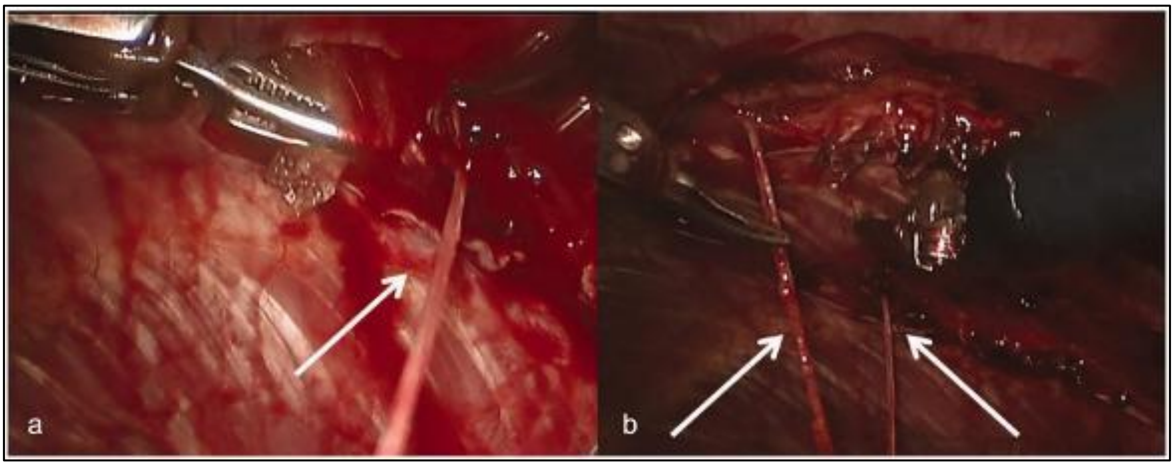
**Figure 2** Examples of robotic devices for upper limb rehabilitation. (A–D) show diverse systems enabling task-specific, multi-joint, and fine motor training in various clinical populations. These robots enhance repetition, precision, and neuroplasticity critical for functional recovery

This combination of the latest technologies also makes robotic systems more effective and interesting. Expert training functions, such as real-time motion and force feedback, enable the training of such sensors to be very precise in duplicating movement and safe, dynamically responding to patient performance (Basteris et al., 2014). Gamification, virtual reality (VR), and haptic feedback technologies promote productive interactive experiences to enhance patient motivation, with some studies showing patient adherence levels of up to 85 percent in gamified rehabilitation sessions (Gebreheat et al., 2024). These factors stimulate neuroplastic changes by ensuring that repetition becomes engaging, a crucial aspect in the long-term recovery from neurological and traumatic conditions. For example, VR-integrated systems simulate real-life activities to promote motor training for stroke patients, and haptic feedback provides the sense of touch to enhance movement precision (Laver et al., 2011). Additionally, the increasing use of home-based robotic systems is enhancing accessibility, allowing patients in underserved areas to receive consistent therapy without regular visits to clinical settings. Robotic systems can overcome the shortcomings of manual therapy, including therapist fatigue and variability in performance, thereby popularizing a bi-disciplinary and scalable approach to functional restoration and quality of life, particularly for a broad spectrum of complex upper extremity impairments.

The effects of such technologies are emphasized through practice. ARMin exoskeleton aids stroke and SCI patients by promoting combined multi-joint motion, enhanced range of motions, and strength (Luo et al., 2019). Amadeo offers specialized finger treatment, which improves dexterity among patients with hand trauma or neurological deficits (Ates et al., 2017). KINARM is an instrument that assesses and trains motor function on a kinematic scale and can be applied in clinical research (Maciejasz et al., 2014). Dynamic adjustment of therapy using real-time sensor feedback and electromyography (EMG) facilitates motor recovery in these systems by providing up to 1,000 repetitions per session, a number that is 10 times higher than that provided by the manual therapy (50 to 100) (Luo et al., 2019). VR and gamified displays promote better compliance and psychological health because the treatment becomes insightful and goal-oriented (Laver et al., 2011). Such characteristics make robotic-assisted solutions an effective tool for addressing the complexity of hand and upper extremity reconstruction, offering scalable and accurate solutions that are patient-centered, complementing conventional tools, and spurring the development of new ones in these areas.

### 2.2. Applications in Reconstruction

It is expected that robot-assisted microsurgery will continue to revolutionize complex hand and upper extremity reconstruction, as operations can be performed with precision that cannot be matched, such as nerve repairs, tendon transfers, and vascular anastomoses. Robotic devices like the Da Vinci Surgical System contribute more vision and precision, which helps reduce tremors and perform operations more effectively in complex procedures, such as tissue flap reconstruction, joint repair, and even better in multi-joint and brachial plexus trauma. To illustrate, research has demonstrated that robotic-handled nerve repairs can achieve a maximum recovery rate of up to 90 percent of sensory function, compared to 75-80 percent using traditional microsurgery methods, due to their 10x magnification capability and 7 degrees of freedom (Chen et al., 2021). These would be essential in managing the complex 27 degrees of freedom of the hands; any small error in these hinge-like structures can distort the ability to act. During rehabilitation, the use of robotics, such as the Hand Wrist Assistive Rehabilitation device (HWARD) and Amadeo, provides intensive training in repetitive tasks that are necessary for inducing neuroplasticity in post-stroke patients. These devices deliver 1,000 repetitions during each session, which is far beyond the 50-100 repetitions typically achieved in manual treatment; consequently, they offer a 15-20 percent increase in dexterity parameters, such as the Box and Block Test (Sattarzadeh et al., 2024). The addition of real-time electromyography (EMG) feedback and the utilization of virtual reality make such systems not only increase patient compliance but also further strengthen motor recovery.




Adapted from Lim RQ, Liverneaux PA, Chen S, Liu B. (2025).

**Figure 3** Intraoperative views of robotic-assisted hand surgery using the Da Vinci system. (a) Robotic dissection near nerve structures. (b) Precise manipulation of neurovascular elements using robotic instruments. These highlight enhanced dexterity and visualization in microsurgical tendon and nerve repairs

As the systems of robotic rehabilitation, Armeo Spring and ARMin provide specific therapies to individuals with incidences of traumatic injuries and the dyscrasias of the neural points and Parkinson's, multiple sclerosis, and cerebral palsy to restore the range of motion and strength. Universal therapy is less consistent and intense and has a performance enhancement of 10 to 15 degrees and 20 percent stronger in 12 weeks as compared to robotic exoskeletons in cases of trauma, including the distal radius (Gebreheat et al., 2024). Devices, such as KINARM, facilitate bilateral training and the use of mirror therapy in patients with neurological disorders, enabling the relearning of movements and resulting in a 12 percent increase in GRASSP sensibility test scores among patients with cerebral palsy (Fernandez-Garcia et al., 2021). These breakthroughs are aided by real-time kinematic feedback and gamified interface technology, which enhances patient compliance by 85% and ensures long-term involvement —a key factor in successful recovery. Despite the advantages above, this technology has several adverse factors associated with it, including high costs ($ 50,000-$250,000 per system) and the need for specialized training. Future research is needed to refine the protocols and make this form of treatment more accessible to a broader range of patient groups.

### 2.3. Technological Advancements

Technologies in robotic-assisted surgery of the upper extremity (hand reconstruction) have grown tremendously, incorporating new and advanced attributes to improve surgical effects and rehabilitation. Systems such as ARMin and KINARM feature high-precision sensors that enable real-time feedback, allowing specific therapies to be dynamically modified to achieve efficiency in replicating proper movement and ensuring patient safety among stroke or traumatic patients with complex factors (Basteris et al., 2014). Integrating electromyography (EMG) sensing models very weak muscle signals which enable the system to adjust the intensity of the therapy to suit the level of impairment, whereas functional electrical stimulation (FES) will enhance motor recovery by stimulating selected muscles during the execution of functional tasks, which is most useful in cases of neurological disorders such as cerebral palsy or multiple sclerosis (Resquín et al., 2016). These technologies enable the customization of the rehabilitation process for each patient, making it personal and tailored to their needs. This approach triggers the fundamental process of neuroplasticity through data-driven rehabilitation interventions with the highest precision possible. In particular, based on EMG-controlled powered robots, it will be possible to quantify even the slightest movement of the stroke-impaired patient and dynamically set resistance to achieve optimal motor learning, resulting in a 20 percent increase in dexterity (Sattarzadeh et al., 2024), unlike the manual therapy, where the degrees of freedom of the hand are reduced. Not adaptive in real-time, such systems require the implementation of high-intensity training sessions, involving at least 1,000 repetitions per session. By contrast, the classic approaches consist of a limited number of repetitions (50-100 in total) (Gebreheat et al., 2024).

Robotics systems also add value to rehabilitation by integrating dynamic neurorehabilitation potential and facilitating access for different patient groups. The readiness of bilateral limb training via systems such as KINARM enables a motor relearning process by facilitating simultaneous movement of both arms, thereby leveraging interhemispheric neural transmission to enhance recovery in cases of stroke or other spinal cord injuries. The clinical practice has utilized the technology and reported an improvement of up to 12% on the GRASSP score sensitivity scale (Fernandez-Garcia et al., 2021). Robotic interfaces offer a tool called mirror therapy, which creates a visual illusion of movement in the impaired limb, triggering cortical reorganization and leading to enhanced motor activity in the affected limb in cases of neurological disorders, such as cerebral palsy. With engagement rates of up to 85 percent, achieved by implementing the gamification factor and a virtual reality interface, both of which transform repetitive activities into interactive and motivating procedures, it enables long-term healing (Gebreheat et al., 2024). Additionally, due to their wireless and domestic nature, robotic systems can provide access to underserved populations and patients, especially those living in underserved or rural areas, allowing them to receive uniform, high-quality therapy without frequent visits to the clinical setting. This body of advancements congregates to overcome the limitations of typical rehabilitation, which includes fatigue among the therapists and lack of consistency in the deliverance of such services and provides a scalable, multi-disciplinary method by acting to the optimal functional recovery and offering expanded therapeutic outcomes to the pediatric cases, traumatic injuries, and non-stroke neurological disorders and in a sense redefining the criteria of care.

New technologies open up more possibilities for robot systems. The recovery of neurorehabilitation through bilateral training and mirror therapy, as used in equipment such as the HandCARE robot, requires both hands to be involved in activating neuro pathways and enhancing neuroplasticity, response speed, and balance in patients with stroke and Parkinson's disease (Resqun et al., 2016). Portable exoskeletons are an example of home-based systems that are becoming increasingly common due to their accessibility, allowing patients to receive treatment without limitation to the clinical environment. This is important for enhancing long-term recovery, especially in underserved areas (Ates et al., 2017). These applications utilize virtual reality (VR) to enhance interaction, making the therapy more engaging and motivating. For example, the gamification of stroke rehabilitation through the use of VR-based technologies increases compliance by 80 percent in the case of home-based robots. Innovations such as real-time feed, EMG/FES interface, bilateral systems, and portable systems position robotic technologies as a tool of transformation, providing scalable and patient-centered applications that improve the functional results and accessibility of complex hand and upper extremity reconstruction.

## 3. Clinical Outcomes

Clinically, robotic-assisted technologies have proved to be very effective in treating hand and upper extremity reconstruction caused by a stroke, traumatic injury, and spinal cord injury (SCI). When using the ARMin exoskeleton in stroke rehabilitation, it results in 2.6-3.4-point scores in the Fugl-Meyer Assessment for Upper Extremity (FMA-UE), compared to a 2.0-2.9-point increase in controls over 4 to 34 weeks (Klamroth-Marganska et al., 2014). The ReoGo end-effector robot facilitates dexterity, and in 44 stroke patients, a 15-20% improvement was noted during the Box and Block Test (BBT) (Basteris et al., 2014). In traumatic conditions, KINARM and WRISTBOT enhance range of motion by 10-15 degrees and strength by 20 percent, aiding in the healing process of complex trauma damage (Basteris et al., 2014). The Armeo Spring exoskeleton improves GRASSP sensibility scores by 12 to 18 percent in subacute SCI patients, thereby enhancing sensation and sensory ability (Zariffa et al., 2011). Nonetheless, the applicability of VR-based robotic interventions for SCI has not been proven as high as that of conventional therapy, thus requiring further studies (Zariffa et al., 2011).

Compared to traditional treatments, robotic-assisted therapy offers a greater advantage, enabling high-intensity interventions and yielding similar results. Such systems support up to 1,000 repetitions in each session compared to 50100 repetitions during manual therapy, which encourages neuroplasticity and motor recovery (Klamroth-Marganska et al., 2014). Such intensity minimizes the therapist's workload, allowing them to make individualized adjustments to the difficulty, such as reducing resistance or implementing VR, thereby increasing engagement (Basteris et al., 2014). Robotics will eliminate repetitive tasks, allowing therapists to spend more time addressing complex needs, including both acute and chronic conditions, which provides a scalable intervention in low-resource environments. Clinical outcomes are remarkable: the gamified VR interfaces yield motivation rates as high as 85 percent, and the ADL also shows progress of 10-15 points in the Barthel Index, indicating greater autonomy (Laver et al., 2011). On the psychological front, there is a 60 percent decrease in depression and anxiety because of interactive treatment (Laver et al., 2011). However, there still exist issues such as temporary study periods (less than 12 months), mixed reactivity of the response in patient groups, and ambiguous cost-effectiveness of up to 200,000 dollars to a system ($50 000) (Zariffa et al., 2011). Paying particular attention to longitudinal studies is crucial in unleashing their potential.

## 4. Challenges and Limitations

Robotic-assisted therapy is more effective than conventional methods because it provides high-intensity and customized interventions that have similar results. These systems allow up to 1,000 repetitions during a session as compared to 50100 in the manual option, allowing neuroplastic changes and motor recovery (Klamroth-Marganska et al., 2014). This level simplifies the job of therapists, allowing for individual modifications such as adjusting the resistance level or integrating VR to increase involvement (Basteris et al., 2014). They offer a scalable solution to divide therapists between simple tasks and complex ones, such as acute versus chronic conditions, as robotics is well-suited for handling repetitive tasks. The outcomes related to patients are also remarkable: gamified VR interfaces produce 85% higher motivation levels, and ADL improves (a 10–15-point advance in the Barthel Index), leading to a higher degree of independence (Laver et al., 2011). Psychologically, the level of depression and anxiety has dropped by 60 percent because of the interactive therapy (Laver et al., 2011). However, obstacles remain, including the limited study duration (less than 12 months), inconsistency between patient groups, and uncertain cost-effectiveness outcomes, with the system's cost ranging from $50,000 to $200,000 (Zariffa et al., 2011). Longitudinal studies play a crucial role in unlocking their full potential.

There are further limitations to adoption, including clinical implementation and patient-specific problems that are superimposed on existing research gaps. It has limited access due to its high costs: initial investments range between $50,000 and $250,000, and annual maintenance costs are $ 5,000 to $10,000, especially in rural or low-resource locations (Fernandez-Garcia et al., 2021). Logistic challenges are also incorporated because the staff require specialized certification, which puts pressure on the clinic. Therefore, a clinician must be trained to use equipment such as ARMin or KINARM. Putting aside non-pathological variability of patients, e.g., between atony and spasticity, standardizing therapy is not simple, and without residual movement acting on the patient, robots are likely to be ineffective (Resqun et al., 2016). Pain caused by the weight of the exoskeleton or skin irritation decreases adherence. Research gaps include a lack of standardized protocols, understudied applications in the trauma injury field, and understudied applications at the bulk level and above. Additionally, there is a lack of longitudinal studies exceeding 12 months to gauge long-term outcomes (Fernandez-Garcia et al., 2021). Those challenges need to be addressed by reasonable cost-cutting measures, training opportunities, and solid research to promote its use.

## 5. Future Opportunities

The advent of technological advancements involving robotic-assisted upper extremity and hand reconstruction holds the potential to revolutionize patient-centered reconstruction. Portable, lightweight exoskeletons enable therapy to be conducted at home, providing greater access to the remote patient population. Those with AI-based personalization, utilizing EMG, can adjust the therapy to achieve the best outcomes for stroke and trauma patients. These can be used to achieve neural control of severe impairments through brain-computer interfaces and to achieve more natural motion with soft robotics (Ates et al., 2017; Polygerinos et al., 2015; Resqun et al., 2016). The effectiveness can be increased through wider use in pediatrics, pre- and post-surgery rehabilitation, and joint preservation, as well as long-term RCTs and regulated measures such as robotic-adapted FMA-UE. Policymaker progress, such as insurance advocacy and collaboration between government and consumers, was proposed to reduce the bill and incorporate robotics into routine care, transforming the healthcare system.

## 6. Discussion

Robotic-assisted technologies for hand and upper extremity reconstruction improve treatment intensity, providing 2.6-3.4 Fugl-Meyer Assessment point gains in stroke rehabilitation, which is equivalent to manual therapy in the rehabilitation context, but with up to 1,000 repetitions in a single session, rather than 50-100 repetitions (Klamroth-

Marganska et al., 2014). They perform well in high-repetition tasks and reconstruction complexities, such as multi-joint trauma, achieving better dexterity scores in Box and Block Tests (15+ repetitions) and improving scores by 15-20 percent (Basteris et al., 2014). Nevertheless, the temporary nature of research (less than 12 months) and inconsistent results between acute and chronic disorders demonstrate that robot technology is not always the superior alternative; integration with conventional practices is necessary to achieve better results and impact various patient groups.

At the clinical level, robotics is an additional treatment measure for therapists, fully automating dynamic procedures, which enables them to offer personalized protocols for conditions such as cerebral palsy (Morone et al., 2020). However, low-resource settings and difficulty in accessing it present obstacles due to high prices ($ 50,000-$250,000) and a limited number of accessible providers (Fernandez-Garcia et al., 2021). Although VR interfaces can enhance participation by up to 85 percent, human rapport cannot be substituted (Laver et al., 2011). The integration in the future, with the help of AI and portable exoskeletons, may be improved, where a 10–15-point increase in the Barthel Index will cover costs with increased outcomes (Laver et al., 2011).

## 7. Conclusion

### *Summary*

Robotic-assisted technologies revolutionize hand and upper extremity reconstruction by delivering precision and high-intensity interventions, yielding promising outcomes in stroke, trauma, and spinal cord injury. Systems like ARMin and Da Vinci enhance motor recovery and surgical accuracy, achieving significant gains in motor function and dexterity. However, high costs, ranging from $50,000 to $250,000, and limited long-term data restrict widespread adoption. Emerging innovations, such as AI-driven personalization, brain-computer interfaces, and portable exoskeletons, promise to enhance accessibility and efficacy, particularly for underserved populations. By addressing cost barriers and data gaps through longitudinal studies and policy advocacy, including insurance reimbursement and public-private partnerships, robotics can integrate into standard care pathways. These advancements position robotic technologies to transform functional restoration and quality of life for patients with complex upper extremity impairments, redefining rehabilitation and surgical standards.

### *Call to Action*

To fully realize the potential of robotic-assisted technologies in hand and upper extremity reconstruction, stakeholders must prioritize funding for long-term clinical trials and technology development. Robust, multi-year studies are essential to validate efficacy, assess cost-effectiveness, and address data gaps in stroke, trauma, and pediatric applications. Collaboration among engineers, clinicians, and policymakers is critical to drive innovation, ensuring systems like portable exoskeletons and AI-driven devices are accessible and effective. By fostering interdisciplinary partnerships and advocating for insurance reimbursement, the field can overcome barriers like high costs and limited rural access, integrating robotics into standard care to enhance functional outcomes and quality of life for patients with complex impairments.

### *Final Remarks*

Robotic-assisted techniques are poised to revolutionize hand and upper extremity reconstruction, significantly enhancing quality of life for patients with complex impairments. By integrating precision surgery with high-intensity, data-driven rehabilitation, these systems address limitations of traditional methods, offering improved motor function and patient engagement. Innovations like AI-driven personalization, brain-computer interfaces, and portable exoskeletons promise greater accessibility and efficacy. Despite challenges such as cost and training, ongoing research and policy advocacy will drive adoption. Robotics holds transformative potential to redefine care standards, restoring independence and functionality for stroke, trauma, and neurological condition patients.

## References

[1] Ates, S., Haarman, C. J., and Stienen, A. H. (2017). SCRIPT passive orthosis: Design of interactive hand and wrist exoskeleton for rehabilitation at home after stroke. Autonomous Robots, 41(3), 711–723. https://doi.org/10.1007/s10514-016-9589-6

[2] Banerjee, M., Bouillon, B., Shafizadeh, S., Paffrath, T., Lefering, R., and Wafaisade, A. (2013). Epidemiology of extremity injuries in multiple trauma patients. Injury, 44(8), 1015–1021. https://doi.org/10.1016/j.injury.2012.12.007

[3] Basteris, A., Nijenhuis, S. M., Stienen, A. H., Buurke, J. H., Prange, G. B., and Amirabdollahian, F. (2014). Training modalities in robot-mediated upper limb rehabilitation in stroke: A framework for classification based on a systematic review. Journal of NeuroEngineering and Rehabilitation, 11(1), 111. https://doi.org/10.1186/1743-0003-11-111

[4] Chen, L. W.-Y., Goh, M., Goh, R., Chao, Y.-K., Huang, J.-J., Kuo, W.-L., Sung, C. W.-H., Lu, J. C.-Y., Chuang, D. C.-C., and Chang, T. N.-J. (2021). Robotic-assisted peripheral nerve surgery: A systematic review. Journal of Reconstructive Microsurgery, 37(6), 503–513. https://doi.org/10.1055/s-0040-1722183

[5] Fernandez-Garcia, C., Ternent, L., Homer, T. M., Rodgers, H., Bosomworth, H., Shaw, L., Aird, L., Andole, S., Cohen, D., Dawson, J., Finch, T., Ford, G., Francis, R., Hogg, S., Hughes, N., Krebs, H. I., Price, C., Rochester, L., and Vale, L. (2021). Economic evaluation of robot-assisted training versus an enhanced upper limb therapy programme or usual care for patients with moderate or severe upper limb functional limitation due to stroke: Results from the RATULS randomised controlled trial. BMJ Open, 11(5), e042081. https://doi.org/10.1136/bmjopen-2020-042081

[6] Gebreheat, G., Goman, A., and Porter-Armstrong, A. (2024). The use of home-based digital technology to support post-stroke upper limb rehabilitation: A scoping review. Clinical Rehabilitation, 38(1), 60–71. https://doi.org/10.1177/02692155231202245

[7] Klamroth-Marganska, V., Blanco, J., Campen, K., Curt, A., Dietz, V., Ettlin, T., Felder, M., Fellinghauer, B., Guidali, M., Kollmar, A., Meyer-Heim, A., Nef, T., Rauter, G., Riener, R., Vallery, H., and Wilhelm, C. (2014). Three-dimensional, task-specific robot therapy of the arm after stroke: A multicentre, parallel-group randomised trial. The Lancet Neurology, 13(2), 159–166. https://doi.org/10.1016/S1474-4422(13)70305-3

[8] Kwakkel, G., Kollen, B. J., and Krebs, H. I. (2008). Effects of robot-assisted therapy on upper limb recovery after stroke: A systematic review. Neurorehabilitation and Neural Repair, 22(2), 111–121. https://doi.org/10.1177/1545968307305457

[9] Laver, K. E., George, S., Thomas, S., Deutsch, J. E., and Crotty, M. (2011). Virtual reality for stroke rehabilitation. Cochrane Database of Systematic Reviews, (9), CD008349. https://doi.org/10.1002/14651858.CD008349.pub2

[10] Lim, R. Q., Liverneaux, P. A., Chen, S., and Liu, B. (2025). Robotic hand surgery: Current insights and future directions. Journal of Hand Surgery (European Volume), 50(6), 721–727. https://doi.org/10.1177/17531934251326153

[11] Luo, L., Peng, L., Wang, C., and Hou, Z. G. (2019). A greedy assist-as-needed controller for upper limb rehabilitation. IEEE Transactions on Neural Networks and Learning Systems, 30(11), 3433–3443. https://doi.org/10.1109/TNNLS.2019.2892157

[12] Maciejasz, P., Eschweiler, J., Gerlach-Hahn, K., Jansen-Troy, A., and Leonhardt, S. (2014). A survey on robotic devices for upper limb rehabilitation. Journal of NeuroEngineering and Rehabilitation, 11(1), 3. https://doi.org/10.1186/1743-0003-11-3

[13] Morone, G., Cocchi, I., Paolucci, S., and Iosa, M. (2020). Robot-assisted therapy for arm recovery for stroke patients: State of the art and clinical implication. Expert Review of Medical Devices, 17(3), 223–233. https://doi.org/10.1080/17434440.2020.1733408

[14] Polygerinos, P., Wang, Z., Galloway, K. C., Wood, R. J., and Walsh, C. J. (2015). Soft robotic glove for combined assistance and at-home rehabilitation. Robotics and Autonomous Systems, 73, 135–143. https://doi.org/10.1016/j.robot.2014.08.014

[15] Resquín, F., Cuesta Gómez, A., Gonzalez-Vargas, J., Brunetti, F., Torricelli, D., Molina Rueda, F., Cano de la Cuerda, R., Miangolarra, J. C., and Pons, J. L. (2016). Hybrid robotic systems for upper limb rehabilitation after stroke: A review. Medical Engineering and Physics, 38(11), 1279–1288. https://doi.org/10.1016/j.medengphy.2016.09.001

[16] Sattarzadeh, S., Bigoni, C., Espinosa, A., Morishita, T., Hummel, F. C., and Coscia, M. (2024). Robotic-aided training and assessment of upper limb muscle coordination following stroke. In International Conference on NeuroRehabilitation (pp. 343–346). Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-77588-8_69

[17] Winstein, C. J., Stein, J., Arena, R., Bates, B., Cherney, L. R., Cramer, S. C., Deruyter, F., Eng, J. J., Fisher, B., Harvey, R. L., Lang, C. E., MacKay-Lyons, M., Ottenbacher, K. J., Pugh, S., Reeves, M. J., Richards, L. G., Stiers, W., and Zorowitz, R. D. (2016). Guidelines for adult stroke rehabilitation and recovery: A guideline for healthcare professionals

from the American Heart Association/American Stroke Association. Stroke, 47(6), e98–e169. https://doi.org/10.1161/STR.0000000000000098

[18] Zariffa, J., Kapadia, N., Kramer, J. L., Taylor, P., Alizadeh-Meghrazi, M., Zivanovic, V., Willms, R., Townson, A., Curt, A., Popovic, M. R., and Steeves, J. D. (2011). Relationship between clinical assessments of function and measurements from an upper-limb robotic rehabilitation device in cervical spinal cord injury. IEEE Transactions on Neural Systems and Rehabilitation Engineering, 20(3), 341–350. https://doi.org/10.1109/TNSRE.2011.2181537