

Rehabilitation Robots for Index Finger: From Rigid to Soft

Chong Ma

Department of Mechanical
Engineering, City University of
Hong Kong, Hong Kong, China
Corresponding author:
chongma2-c@my.cityu.edu.hk

Abstract:

This paper explores the optimization and structural design of finger exoskeleton robots for postoperative rehabilitation, with a focus on stroke patients. It reviews the theoretical foundations, domestic and international research progress, and latest clinical studies of two major categories of finger rehabilitation robots—rigid-driven and flexible-driven—based on a systematic literature search of 30 relevant studies published between 2020 and 2025. Six typical robots are analyzed in detail, including their working principles, advantages, and disadvantages. A comparative evaluation from aspects like functional recovery, training mode diversity, control accuracy, applicability, mechanical safety, biocompatibility, comfort, human-robot interaction, cost-effectiveness, and portability reveals that existing robots have made progress in functional recovery and mechanical safety, but face limitations in control accuracy, human-robot interaction, cost, and portability. Future research directions are proposed, such as enhancing control accuracy via multi-sensor fusion and adaptive algorithms, improving interaction through flexible materials and VR/AR, reducing costs with 3D printing, and optimizing portability using lightweight materials and wireless technologies, to advance the development and application of finger rehabilitation robots.

Keywords: Stroke; Finger Rehabilitation; Exoskeleton Robot.

1. Introduction

According to the World Stroke Organization's latest data, the global economic cost of stroke has reached staggering proportions, exceeding \$890 billion annually - equivalent to 0.66% of the world's total GDP. Epidemiological trends from 1990 to 2021 reveal a concerning escalation in stroke burden across all

metrics, with particularly disproportionate impacts on healthcare systems in low- and middle-income countries. Current estimates indicate that nearly 34% of total worldwide healthcare expenditures are allocated to stroke management and treatment [1]. These nations bear the brunt of stroke's consequences, accounting for 87% of global stroke-related deaths and 89% of disability-adjusted life years lost to the con-

dition [2]. Stroke patients demonstrate approximately 36% reduction in peak finger force generation in the impaired hand compared to the unimpaired side[3], with characteristic muscle weakness and motor deficits predominantly observed in limbs contralateral to the brain lesion. Restoring hand function represents one of the most challenging yet critically important objectives in post-stroke rehabilitation[4]. The human hand's motor system possesses extraordinarily sophisticated neural control mechanisms and highly complex biomechanical architecture, involving multilevel coordination among the cerebral motor cortex, spinal neural networks[5], and peripheral musculoskeletal systems [6]. Complete recovery of grasping and fine motor functions typically requires an extended and arduous rehabilitation process, primarily due to limitations in central nervous system plasticity and the efficiency of motor unit reorganization. Consequently, developing innovative approaches to overcome current technological constraints in effectively promoting hand functional reconstruction remains a pivotal scientific challenge in the field of neurological rehabilitation. In recent years, exoskeleton technology for hand rehabilitation has demonstrated significant advancements, with substantial evidence supporting its efficacy in facilitating finger motor recovery in stroke patients [7]. This paper reviews the theoretical foundations,

domestic and international research progress, and the latest clinical studies of the two major categories of finger rehabilitation robots, aiming to provide a theoretical basis for optimizing their development.

2. Rigid-driven and Flexible-driven Finger Rehabilitation Robots

The study conducted a systematic literature search across four electronic databases (PubMed, Web of Science, CNKI, and Semantic Scholar) for articles published between January 2020 and August 2025, limited to English and Chinese publications. The research used the following key terms:(stroke OR Cerebral Stroke OR Cerebrovascular Accident) AND (finger rehabilitation) AND (Exoskeleton robot OR Rehabilitation robot).

Inclusion criteria focused on rehabilitation robots with rigid or flexible mechanisms that provided motion simulation or clinical data, while excluding reviews, non-peer-reviewed studies, control system-only research, and incomplete datasets. From the initial search, 30 relevant papers were selected, with the most representative studies summarized in the review. The literature screening and processing procedure of this study is illustrated in Figure 1.

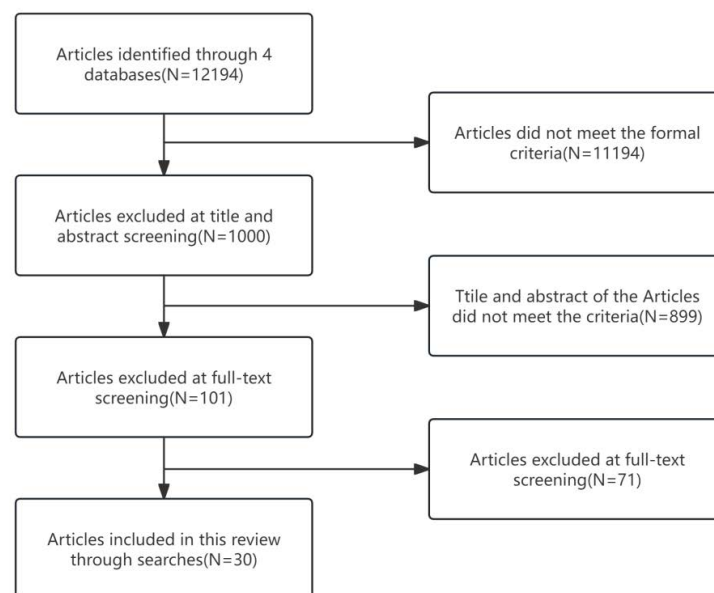


Fig. 1 Literature Screening Process (Picture credit: Original)

Finger rehabilitation robots can be classified into rigid-driven and flexible-driven types based on their actuation methods. Figure 2 presents several major categories of finger rehabilitation robots. The following sections will elaborate on the working principles, advantages, and dis-

advantages of each robot type according to the classification shown in Figure 2.

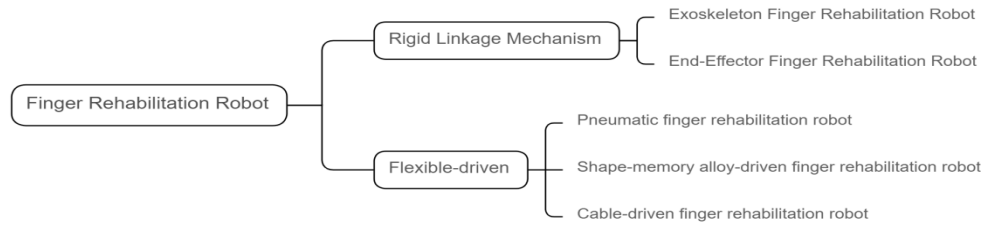


Fig. 2 Classification of Finger Rehabilitation Robots (Picture credit: Original)

2.1 Rehabilitation Robots Employing Rigid Linkage Mechanisms

Exoskeleton robots primarily consist of three core components: mechanical structures, actuation systems, and control systems. These devices establish rigid connections with patients' upper limb skeletons through their mechanical frameworks to either simulate or augment natural human movements. The actuation system provides powered assistance, while the control system precisely regulates training modalities and intensity levels based on the patient's movement intentions and rehabilitation requirements.

In 2021, Thomas Dickmann et al. proposed an underactuated finger exoskeleton rehabilitation robot [8], which is a new type of adaptive mechatronic exoskeleton system. Specifically designed for finger rehabilitation, it aims to enhance rehabilitation effectiveness through force control technology, as illustrated in Figure 3.

The system adopts an underactuated kinematic structure, utilizing linear electric cylinders to drive lightweight aluminum alloy linkages. By integrating angular position

sensors and force sensors, it can accurately quantify the dynamic characteristics of patients' fingers, including the range of motion (ROM) and force/torque trajectories. The rigid kinematic structure of the exoskeleton ensures natural finger movements while preventing excessive joint extension and the application of critical force levels, thus guaranteeing patient safety.

Through direct control of linear actuators and force sensors, the system achieves bidirectional force support, making it suitable for various rehabilitation modes such as active, active-assisted, and resistance training. Its compact and lightweight design renders it suitable for both clinical and home use, with easy wearability and adjustability.

Experimental verification has shown that the system can cover the functional ROM of patients with different hand types and accurately record joint angles and torque trajectories, providing objective data for clinical diagnosis and rehabilitation progress assessment. In addition, through the limitations of the force control algorithm, the system can adjust training intensity according to the patient's functional status, ensuring comfort and safety during the treatment process.

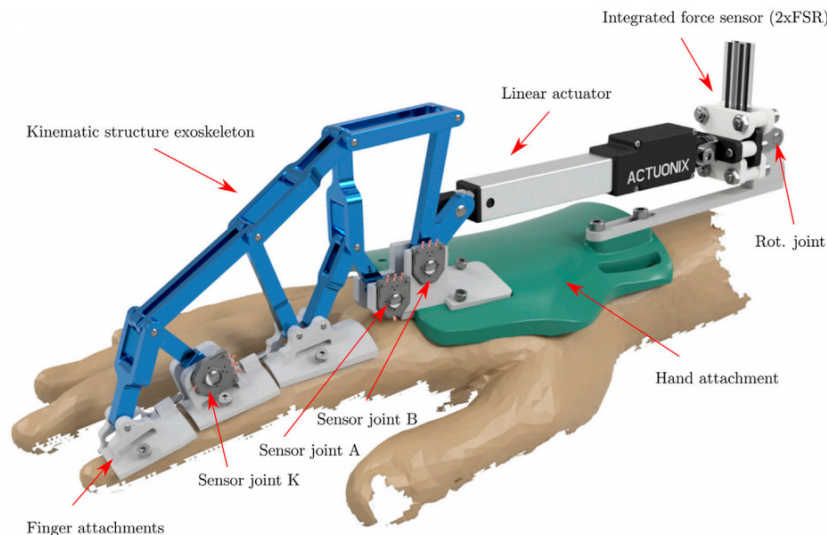


Fig. 3 underactuated finger exoskeleton rehabilitation robot [8]

In 2021, Tian et al. proposed an end-effector finger re- habilitation robot (EFRR) [9] specifically designed for

stroke patients, as illustrated in Figure 4. By incorporating innovative mechanical design and control strategies, the EFRR achieved both flexion/extension (F/E) and active adduction/abduction (A/A) movements of the fingers, significantly improving rehabilitation outcomes and patient experience.

In terms of mechanical design, the EFRR utilized a cam mechanism to replicate the natural motion trajectory of the fingers. A fitted polynomial equation optimized the movement path, ensuring smooth operation without requiring motor reversal. The A/A motion module was driven by a single motor via a synchronous pulley system with a speed ratio of 3:1, enabling faster movement of the index and little fingers while maintaining slower motion for the middle and ring fingers, aligning with biomechanical principles. Additionally, the modular design (e.g., synchronous belts, tensioning structures, and limit switches) enhanced the device's reliability and safety.

For the control strategy, the EFRR employed a fuzzy PD-based adaptive impedance control system. Pressure sensors monitored real-time human-machine contact forces, dynamically adjusting positional corrections to prevent secondary injuries caused by excessive muscle tension. Experimental results demonstrated that the adaptive impedance control reduced force fluctuations (3.6–5.95 N) compared to conventional impedance control (2.6–7.03 N), with only a 0.1-second increase in response time.

Preliminary experiments showed that the motor driving force test results closely matched theoretical calculations (error < 10%). Position tracking exhibited a maximum lag of 0.1 seconds with an error margin below 4 mm. Volunteer testing confirmed the device's stability and safety under conditions of 30 mm/s speed and 25 N applied force. Future improvements may involve lightweight materials (e.g., resin) and clinical trials with actual patients.

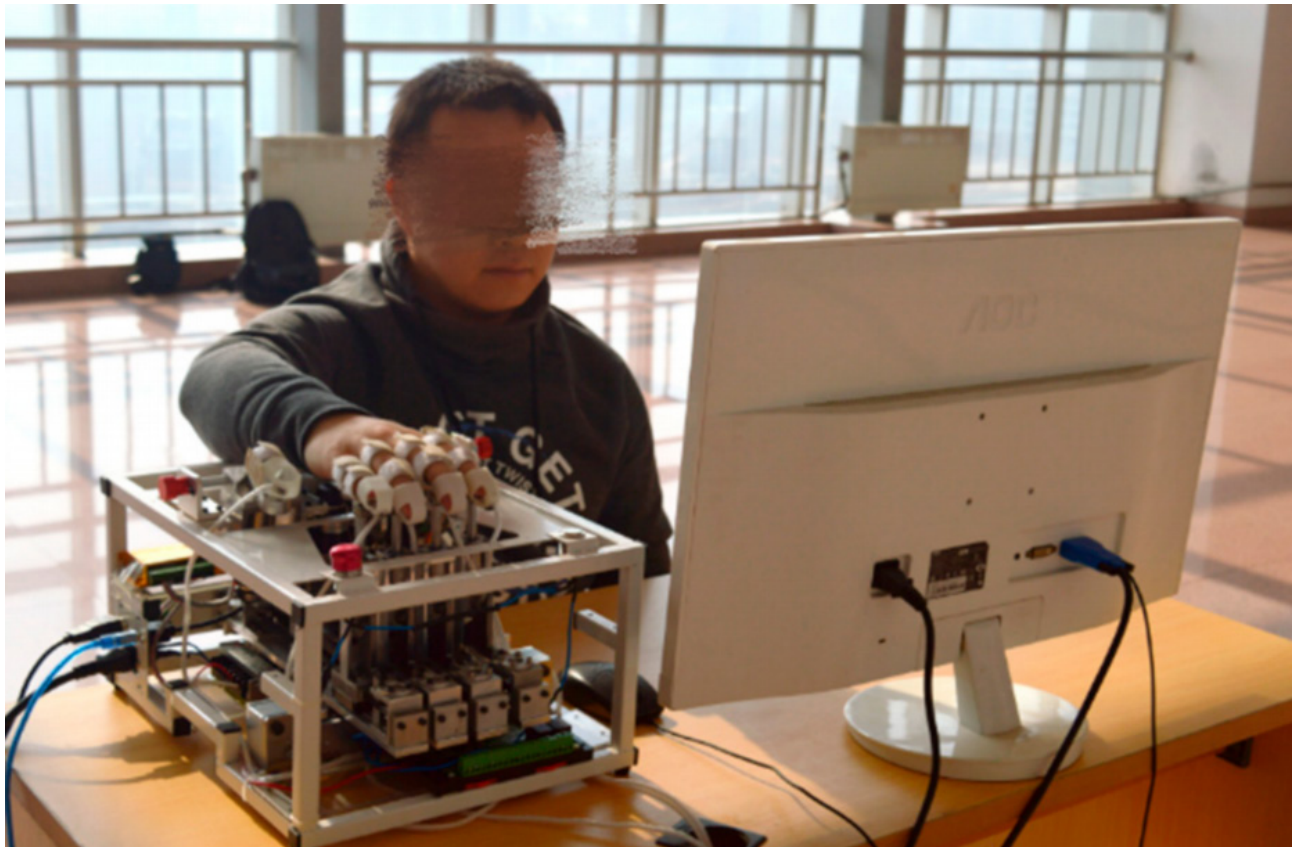


Fig. 4 end-effector finger rehabilitation robot [9]

In 2024, Lai et al. designed a lightweight and compact hand exoskeleton robot, as illustrated in Figure 5 [10]. In terms of exoskeleton design, it adopts a 1-degree-of-freedom structure, consisting of a driving structure and a guiding structure. The driving structure contains two DC motors (with a reduction ratio of 19:1), which drive

the metacarpophalangeal (MCP) joint through a parallel linkage mechanism and are equipped with angle sensors and force sensors. The guiding structure converts the multi-finger and multi-degree-of-freedom joints into an underactuated structure to realize synchronous movement, with an overall weight of 0.356 kg. The control system

adopts a simplified two-channel finger tension feedback algorithm to construct a remote rehabilitation system: the therapist side controls through the parent robot, the patient side sub-robot moves synchronously, and the force information is transmitted back to enable the therapist to remotely perceive muscle tension, supporting two scenarios of spasticity assessment and rehabilitation training. Experimental evaluation shows that in the tests involving 10 stroke patients and 3 therapists, the average time for

wearing the device is 135.2 seconds, and the average time for removing it is 26.2 seconds, indicating good wearability. The force output and angle control have high repeatability, with an average angle error of 1.16° and a contact force error of 0.25 N, and the back-drivability is excellent. The accuracy of remote assessment of muscle spasticity reaches 75%, which verifies the effectiveness of the device.

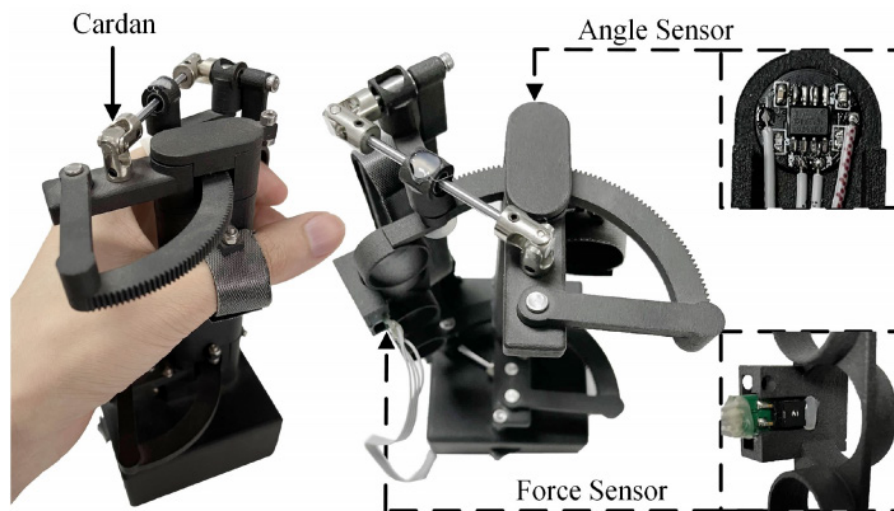


Fig. 5 lightweight and compact hand exoskeleton robot[10]

2.2 Flexible-driven Finger Rehabilitation Robot

In 2023, Manilyn Cabrera and colleagues developed a novel unbound soft robotic finger rehabilitation system [11], which innovatively uses heat-driven phase change materials (PCMs), eliminating the need for external components such as tubing, valves, or pumps, as illustrated in Figure 6. The soft robot is designed based on the PneuNet architecture, where the phase change material is sealed within an elastomer structure. By applying heat, the PCM transitions from liquid to gas, increasing the internal pressure of the elastomer, thereby enabling bending motion. Upon removal of the heat source, the phase change material returns to its liquid state, and the robot returns to its original position. The study tested several phase change materials, including acetone, 99% isopropanol, ethanol,

and Novec 7000. By comparing their boiling points, latent heat, health hazards, and activation temperatures, it was determined that Novec 7000, an engineering fluid, is the most suitable PCM for the soft robot due to its low activation temperature ($40-42^\circ\text{C}$), fast response time, and ability to bend into a complete circle within 90 seconds.

A benchmark pneumatic system was built to estimate the chamber pressure by comparing bending angles. The study also noted that evaporation of Novec 7000 and acetone could affect long-term reliability, an issue to be addressed in future work.

This soft robot aims to provide a convenient and comfortable solution for finger rehabilitation, especially for individuals with limited resources who require intensive rehabilitation training.

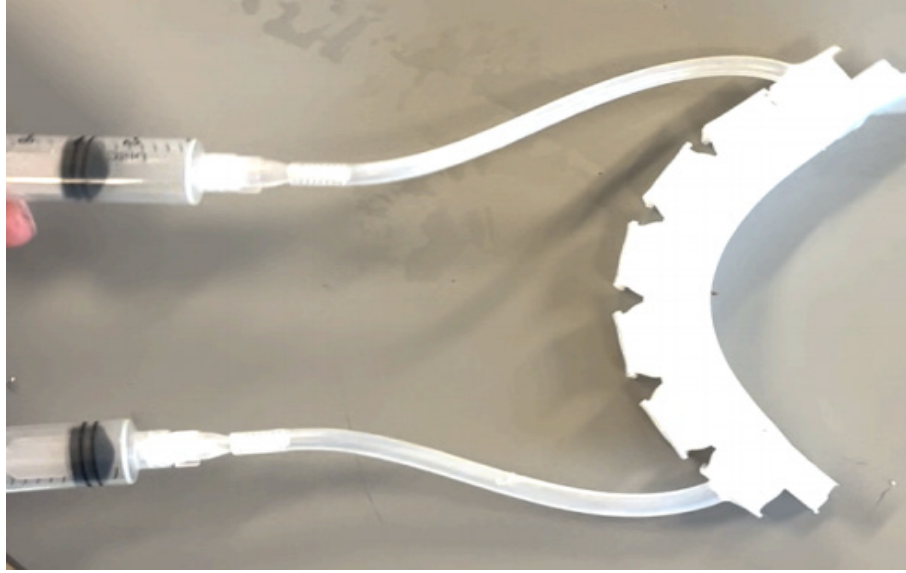


Fig. 6 novel unbound soft robotic finger rehabilitation system [11]

In 2023, Zuo et al. proposed a flexible finger rehabilitation robot [12] driven by shape memory alloy (SMA) wires, aiming to assist patients with hand motor impairments caused by stroke and other nervous system diseases in rehabilitation training, as illustrated in Figure 7. The total weight of the robot is 393 g, which can meet the basic needs of finger rehabilitation.

In terms of structural design, the robot adopts a bionic design based on the movement mechanism of finger joints and muscles: thermoplastic polyurethane (TPU) is used to make flexible gloves, traction wires are employed to simulate finger tendons, and a set of SMA wires are arranged on both the dorsal and palmar sides as actuators to simulate the flexion and extension functions of extrinsic muscles; to address the problem of low strain of SMA wires (maximum only 5%), a pulley block reciprocating folding range extender is designed to drive finger flexion and ex-

tension by amplifying phase transition displacement.

Experimental tests show that under a driving voltage of 20 V, the maximum joint angle of the robot is approximately 85% of that of a healthy person. The maximum fingertip forces of the thumb, index finger, and middle finger are 10 N, 12.5 N, and 12.5 N respectively, which can successfully grasp most daily objects, and they show good stability when grasping 2 kg objects. However, there are problems such as the range of motion of the MCP joint being limited by the ring fixation structure, and the TPU material having limited adaptability to different finger sizes.

In the future, it is necessary to optimize the structure to improve the degree of freedom and adaptability, establish a real-time feedback control system based on multi-signal fusion, and enhance the accuracy and effectiveness of rehabilitation training.

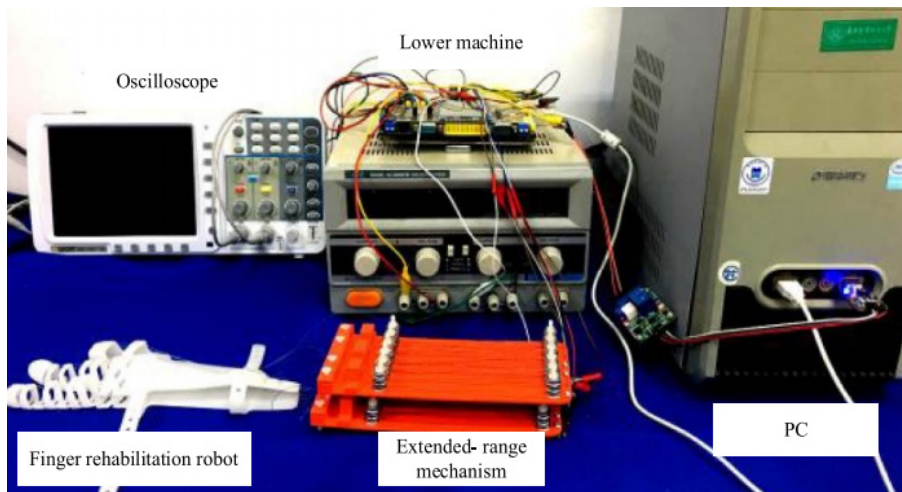


Fig. 7 flexible finger rehabilitation robot [12]

In 2025, Gan et al. developed a tendon-driven finger rehabilitation robot named REACH Exo-Glove [13], as illustrated in Figure 8. The device features a crisscross structure fabricated from thermoplastic polyurethane (TPU) material that mimics a scissor-lift mechanism, achieving spring-like flexibility and efficient elongation capability. The cable-driven system utilizes Bowden cables coupled with a quadruple rack-and-pinion transmission mechanism to convert servo motor rotation into linear motion, enabling independent actuation of the thumb, index, middle, and ring fingers. Experimental results demonstrate that the exo-glove generates sufficient fingertip forces

(thumb: 4.95 N, index: 4.66 N, middle: 6.61 N, ring: 3.89 N), with a maximum grasping force of 21 N, an open/close cycle time of 1.2 seconds, and the capability to manipulate objects weighing up to 450 g. While the device shows good adaptability for objects of various shapes, its grasping performance requires further improvement for certain geometries (e.g., spray bottle necks). The REACH Exo-Glove presents a promising solution for hand rehabilitation through its innovative design and performance, establishing a foundation for future research and applications in this field.

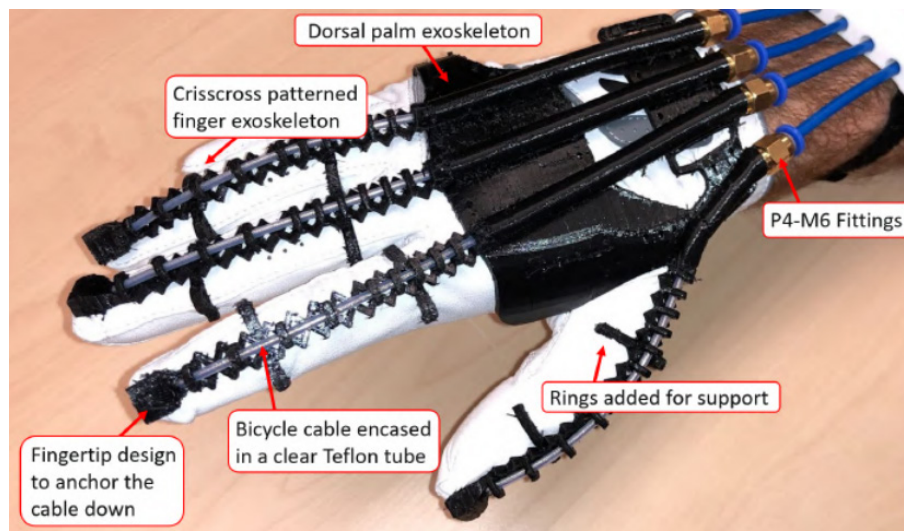


Fig. 8 REACH Exo-Glove [13]

3. Comparative Analysis and Future Perspectives

After reviewing the relevant literature, this paper will evaluate the six finger rehabilitation robots above-mentioned from the following aspects: functional recovery,

training mode diversity, control accuracy, applicability, mechanical safety, biocompatibility, comfort, human-robot interaction, cost-effectiveness and portability. The final results are shown in Table I, from which it can be seen that the current finger rehabilitation robots still have shortcomings in terms of control accuracy, human-computer interaction, cost of use, and portability.

Table 1. Evaluation Table of Various Finger Rehabilitation Robots

G stands for Excellent; A stands for Good; M stands for moderate; P stands for Poor

Typical Robot	functional recovery	training mode diversity	control accuracy	applicability	mechanical safety
Dickmann	G	P	M	A	G
Tian, Y	G	P	G	A	G
J. Lai	A	M	G	A	M
Cabrera	A	P	M	G	G
Zuo, K	G	P	M	M	G
Gan, L	A	P	M	G	M

Typical Robot	biocompatibility	comfort	human-robot interaction	cost-effectiveness	portability
Dickmann	G	G	P	G	G
Tian, Y	G	G	P	M	P
J. Lai	G	G	P	G	G
Cabrera	P	G	P	A	G
Zuo, K	G	G	P	M	P
Gan, L	G	G	P	M	P

To address the current limitations of finger rehabilitation robots in terms of control accuracy, human-machine interaction, cost-effectiveness, and portability, future research directions may focus on the following aspects.

Enhancing Control Accuracy. Integrate multi-sensor data (e.g., electromyography signals, force sensors, visual imaging) to establish a more precise dynamic model; incorporate adaptive control algorithms (e.g., reinforcement learning, fuzzy adaptive control) for real-time error correction and optimize transmission mechanisms (e.g., backlash-free gears, magnetorheological dampers) to minimize mechanical hysteresis and improve trajectory tracking and force control precision.

Improving Human-Machine Interaction. Enhance biocompatibility through flexible materials (e.g., silicone, shape-memory polymers) for better wearing comfort; develop multimodal interaction interfaces (e.g., EEG, eye-tracking) to accurately interpret user intent and integrate virtual reality (VR) or augmented reality (AR) to create immersive training environments, increasing patient engagement and motivation.

Reducing Manufacturing Costs. Utilize 3D printing for non-load-bearing components (e.g., resin or ABS engineering plastics); standardize and modularize core components for mass production and adopt low-cost sensors to decrease overall system expenses.

Optimizing Portability. Employ lightweight yet high-strength materials (e.g., engineering plastics, aerospace-grade aluminum alloys); integrate compact actuators (e.g., micro servo motors, artificial muscles) to minimize device size and develop wireless power and data transmission technologies to eliminate cable constraints, making the system more suitable for home or mobile use.

4. Conclusion

This paper reviews two types of finger rehabilitation robots (rigid linkage-driven and flexible-driven) based on 50 studies conducted between 2020 and 2025. An analysis of 6 typical robots shows that existing technologies have made progress in functional recovery, mechanical safety,

and basic applicability. For example, rigid robots excel in functional recovery and control accuracy, while flexible robots have advantages in comfort and adaptability. However, there are issues such as uneven control accuracy, poor human-robot interaction, inconsistent cost-effectiveness, and insufficient portability of some models.

In the future, it is necessary to improve control accuracy through multi-sensor fusion, enhance interaction via flexible materials, reduce costs using 3D printing, and optimize portability with lightweight materials to promote the development of robots. More advanced rehabilitation robots will become an important part of global rehabilitation and elderly care. Low-cost rehabilitation devices will effectively bring rehabilitation training to families and communities, enabling efficient rehabilitation services. This will greatly improve the accessibility and convenience of rehabilitation services, allowing technology to better benefit society.

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