Comparative Study on Finger Exoskeleton Rehabilitation Robots: Design, Control, and Clinical Validation

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Abstract. Neurological disorders, especially stroke, have become a great health problem in the world; therefore, a rising number of people need effective hand recovery. Finger exoskeleton rehabilitation robots have become a hopeful means to regain small motor skills through doing the same training again and again. This paper provides a comprehensive review and comparison of the most recent developments in China and around the world after 2020, with regard to mechanism design, actuation, control, Human-Robot interaction, and clinical trials. Methodologically, it uses comparative literature analysis to show the change from engineering feasibility to clinically oriented research. From the results, it is seen that domestic research focuses more on mechanical innovation and control innovation. International researches focus on safety standards and large-scale clinical trials. Compare the trajectory of the two results of the research, and need to combine the engineering innovation with standardization of the clinical testing and regulatory requirements. Also, the results from it can lead the world into rehabilitation robotics and add theory and practical information to change technological advances into a clinical solution.

Keywords: Rehabilitation robot; Finger exoskeleton; Mechanism design; Control strategy; Clinical validation.

1. Introduction

Neurological diseases are becoming more common as the world's population ages, and the condition is a big concern for doctors who help sick people get better. According to the WHO's Global Stroke Fact Sheet, over 12 million new strokes happen yearly, and over a third of those who survive have upper-limb or hand disabilities that make daily life hard [1]. In China, the 2023 China Stroke Report estimates over 14.9 million people are living with stroke, with about 3.3 million new cases every year, and roughly 80% experience difficulty moving their fingers precisely, which significantly affects their quality of life and places considerable social and economic strain [2].

Traditional rehabilitation mainly depends on manual therapy from a physiotherapist. However, the current therapist-to-patient ratio is around 1:3500, which is much lower than the WHO-recommended standard of 1:1000, indicating that only one therapist is available for every three and a half thousand patients [3]. This shortage results in making sure of sufficient, continuous, and personal therapy hard, showing an immediate necessity for smart rehabilitation technologies, especially finger exoskeleton robots able to give accurate, repetitive, and measurable motor training [4].

Since 2020, fast progress in soft robotics, artificial intelligence, multimodal intention detection, and lightweight materials has sped up the move from laboratory prototypes to medical-grade finger exoskeletons [5-7]. With the increase of peer-reviewed publications and clinical trials, both technological advancement and promising therapy are shown [8].

Therefore, a systematic review of the development of finger exoskeleton rehabilitation robots after 2020 is conducted from aspects such as mechanism design, actuation, control method, human-robot interaction, safety, and clinical results [9-12]. Also, summarizes the current problems and gives directions for future research, to support the academics and industries in the field of rehabilitation robotics [13].

2. Research Status

2.1. Chinese Research Progress

China started research on finger exoskeleton rehabilitation robots later than many developed countries, but it has made great progress over the past five years. Between 2020 and 2025, the number of Chinese papers on hand or finger rehabilitation robots has grown by over 180%, indicating that there is a transition from studying engineering feasibility to clinical development [1-3]. Recently, studies focused on lightweight structural design, improved human-robot interaction, and earlier clinical trials. Still, there are considerable differences between innovation in the lab and clinical trials on a grand scale.

Mechanism and structural innovation-wise, Chinese researchers have concentrated on curbing mechanical redundancy and enhancing adaptability. Luo has developed an exoskeleton for rehabilitation that uses a circle-shaped sliding rail accompanied by a dynamic, self-tensioned system to lessen the degree of force-transmitting change compared to the traditional hard-bodied exoskeleton in the number of roughly 25% [1]. Zhang made a finger-wrist exoskeleton that could work on single joints or many joints at once [3]. It was 40% better than the old versions that only worked on one joint, so it helped with more kinds of motion. Qiao developed a hybrid cable-driven exoskeleton that has both rigid and compliant structures [7]. The hybrid exoskeleton has the ability to provide bidirectional independent actuation to five joints with a 35% reduction in structural weight and a 20% increase in user comfort from the grip force test. These studies, although they may differ in their approach but share the same common goal to mimic the natural finger movements instead of increasing the actuator or degree of freedom.

2.2. International Research Progress

International research on finger exoskeleton rehabilitation robots has taken various technological routes and differs from that of China. Compared to China’s engineering-driven and prototype-centric focus, international studies have started to focus more on translational design, regulatory compliance, and validation of clinical outcomes. These developments can be summarized into 4 quantifiables.

2.2.1 Rigid and underactuated structures

Rigid-link and underactuated mechanisms continue to be a basic research direction. Dragusanu et al. [13] designed an underactuated hand exoskeleton with a gear-based differential mechanism, reducing the number of actuators from 10 to 5 and preserving 95% of the natural finger motion. Moreno-SanJuan et al. [14] characterized a lightweight model (mass = 0.95 kg) with one active and one passive DoF per finger to achieve over 90% torque transmission. These results showed that there was a strong emphasis towards achieving the numeric efficiency of mechanical efficiency and reproducible behavior, as it is evident that all the systems with differential drives had a 22% decrease in their system's consumption of power and 15% better kinematic adaptability than full drive active ones. Underactuation is thus both a cost-saving and a practical approach to reproducing physiological motion [15].

2.2.2 Flexible and soft exoskeletons

The soft and hybrid exoskeleton is an international phenomenon. Lee et al. optimized the geometry of a pneumatic-driven soft glove, increasing workspace by 35% and actuator pressure required by 28% after pilot testing with 12 stroke survivors [16]. Tejada et al. improved the PneuNet type actuator to obtain a 130° bending curvature at 50 kPa, increasing the compliance by 40% compared to the previous models [17]. Saldarriaga et al. summarized that fabric-reinforced elastomers and cable-driven hybrid structures can reduce the device weight to less than 500 g per hand with adequate output torque (> 2 N·m) [18]. This shows that people have become more interested in being safe, wearing the item, and using less energy to make it work, which is a big change all over the world for making things that help people get better from being sick or hurt.

2.2.3 Safety standards and wearability

International research has embedded regulatory compliance in the design framework in a systematic way. More than 70% of studies published after 2020 refer to the ISO 13482 and IEC 80601-2-78 standards [19, 20]. Developers made improvements using those frameworks. They raised safety validation efficiency by 30% and lessened delays in getting certified in the preclinical phase by 25%. Ergonomic and risk assessment modules have merged into devices with less than 90-second donning times, less than 0.3 N/cm2 contact-pressure distribution - measurable factors of comfort and safety. This quantitative standardization accelerates the prototype-to-certified-medical-device transition to hospital and home rehab.

2.2.4 Clinical validation and outcomes

Clinical trials overseas tend to be bigger and more organized. Barría et al. reported that 32 stroke patients using RobHand exoskeleton showed a 23% improvement of grip strength, 18% of finger dexterity (Fugl-Meyer + Box-and-Block tests) [15]. Yeh et al. performed a randomized trial on 45 chronic stroke patients who were using a powered exoskeleton, where the upper-limb functions increased by 21% relative to the baseline [21]. Gaeta et al. reported that the magnetically-controlled soft glove increased daily-living task scores by 17% in 20 participants, and maintained over 85% of user satisfaction [22]. A meta-analysis of 64 studies by Banyai et al. reported moderate overall effectiveness (overall functional improvement 19% on average, $p < 0.05$) and small sample size (mean = 22), with varying evaluation measures [23]. The data-driven results show that although the clinical gains are apparent, more large randomized controlled trials are necessary to establish the evidence and guide the clinical guideline.

3. Key Technical Issues

3.1. Mechanism Design and Kinematic Adaptation

It’s all about how you can copy people moving using machines that are good at copying people moving, but also work well with a human body. Recent designs use semi-rigid hybrids—rigid pieces for torquing and flexible interfaces for alignment tolerance, which reduces the system’s weight by 20-30%, peak contact pressure by more than 25%, and can be used for either clinical or at-home rehabilitation. To address the misalignments and to increase the comfort, compliance, and flexible mechanisms, such as multisection continuous structures and tendon-driven, are employed. The design can hold around 80% of the nominal output torque even with a 5° angle off.

3.2. Actuation and Transmission Methods

Actuation controls the mechanical and clinical feasibility. Not one size fits all: motor-driven for precision adds weight; pneumatics & hydraulics are safe but have no space; cable reduces distal load, making maintenance hard. The current research is in favor of a combination of the motor torque and the cable mobility. Magnetic actuation is compact and silent, but still in the early stages of clinical validation.

3.3. Control Methods and Intention Detection

Rehabilitation robots must not only move, but they must also be able to understand a person’s intentions. Conventional fixed-trajectory or constant velocity control is stable but not personalized. Impedance-based control adjusts the amount of help based on the user's resistance, encouraging them to do more [5][6]. For intention detection, EMG captures pre-motion muscle activity, but it is sensitive to noise, while EEG captures motor plans, but is unstable and clunky. Vision-based tracking estimates motion without contact sensors, but it is computationally expensive [1]. Recently, the research studies favoring the multimodal fusion of EMG, EEG, force, and emotion cues to increase robustness and adaptability are [6][18].

3.4. Human–Robot Interaction and Comfort

User acceptance is determined by how comfortable a person finds the item, how easy to use the product, and how engaging it is. Long time to don/ setup reduced compliance. Rigid frames with a lot of fasteners are hard to use, but soft, fabric gloves are easier to wear [16][18]. Uneven pressure or misalignment causes discomfort; flexible fabrics and adjustable splints better fit the skin [11]. Gamified feedback increases motivation and emotions to a functional and sensory-based experience for rehabilitating the body.

3.5. Safety and Standardization

Finger exoskeletons need to interact with the sensitive joints, fingers, and soft tissues. Safety needs to be considered in design. The current systems are using Mechanical Stops, Velocity Limiter, and Software Watchdog to prevent the system from moving too far and from applying too much torque. However, the lack of safety benchmarking means different research prototypes have very different results. Though international norms like ISO 13482 (person care robots) and IEC 80601-2-78 (rehabilitation robots), there is still non-uniform adherence among academic research [19, 20].

Some international projects have integrated risk assessment and hazard testing from the design phase, matching medical-device regulatory pathways [15][19]. Contrary to this, many of the domestic research studies are not limited to laboratory validation, and there is no documentation proving that they follow the standard safety norms. This noncompliance is a major roadblock for clinical translation because safety must be validated in the regulatory environment, with documentation of fault responses, contact-pressure mapping, and actuator thermal analysis.

And standardization is just as necessary for the clinical evaluation. Reviews show great differences between studies with regard to their outcome measures, such as grip strength, dexterity tasks, which makes meta-analysis and comparison difficult [23]. Establishing a minimal common outcome set that includes impairment, activity, participation, and device telemetry will increase the reliability and speed of reaching consensus about clinical effectiveness.

Overall, Mechanism, Actuation, Control, Human-Robot Interaction (HRI), and Safety form the technical foundation for the finger exoskeleton. To move such systems away from the experimental platforms onto certified devices, to match the system's strengths with the adaptability, with the precision, with the comfort that is required for medical usage, while retaining a method of safety and assessment that is standardized.

3.6. Technical Bottlenecks and Current Challenges

Although there have been significant improvements in the design of mechanisms, actuators, and controls, there are still some technical and practical issues that limit the use of finger exoskeleton rehabilitation robots in the clinic. And these challenges can be summed up into 4 main areas: structural adaptability, clinical validation, cost-effectiveness, and algorithmic robustness.

3.6.1 Structural weight and adaptability

Rigid-linkage design, though it maintains the accuracy of torque transmission, tends to place an excessively heavy load when used for a long time. Rigid prototypes tend to be 1.5-2.5 kg, and they will make the user very tired after 30 minutes of use. Conversely, soft-structure exoskeletons are less than 1 kg, but they produce only about 60–70% of the needed output torque to effectively extend a finger. [14] [16]. Structural robustness and ergonomic comfort have remained a central engineering problem to be solved. Hybrid semi-rigid architecture is now underway to reduce average system weight by 25 - 35% and maintain a stable output torque, but there is still insufficient large-scale ergonomics verification.

3.6.2 Clinical validation and standardization

Previous research has involved fewer than 50 participants. And the difference between samples from acute stroke to chronic stroke makes it difficult to compare them with each other [15, 21, 23].

And evaluation metric standards are not uniform as well; grip strength, range of motion, and Fugl-Meyer scores are all listed without standardized criteria. Therefore, it weakens the statistical reliability, and the lack of randomized controlled trials (RCTs) weakens the clinical evidence. Standardizing the testing protocol, including the length of tasks, training frequency, and outcome measurement, is necessary for moving from the laboratory prototype to a clinical device that can be recognized by clinicians.

3.6.3 Algorithmic stability and user-specific adaptation

Electromyography (EMG) - and electroencephalography (EEG) - based intention detection methods are still quite prone to noise, movement of the electrodes, and variations in an individual's physiology [6][18]. Average classification accuracy is between 80% and 92%, but real-time reliability goes down with fatigue or motion artifacts. Furthermore, adaptive control algorithms using AI tend to demand a lot of computational power and have no proven long-term stability and safety in the clinical environment. Achieving real-time and low-latency signal processing and adaptive personalization that works with all kinds of people is still a big problem when we try to use it in the real world.

To summarize, issues related to mechanical optimization, clinical validation, cost, and algorithm robustness continue to limit the transition of finger exoskeletons from experimental prototypes to valid rehabilitation tools. To address these issues, we need a mix of mechanical innovation, big clinical trials, support from the policies, and AI-driven adaptive control systems. Only in this way can the finger exoskeleton rehabilitation robot truly be scaled, accessible, and have long-term clinical efficacy.

4. Future Perspectives

The progress of the finger exoskeleton rehabilitation robots is moving from showing that it is possible to showing that it works. Look to the future, and some directions must be important for progress.

First, future development of rehabilitation exoskeletons will tend to be lightweight and flexible, making them more comfortable and usable for a longer period of time without sacrificing the precision of the motion. Adopting soft robotics, textile-reinforced actuators, and tendon-driven systems are intended to reduce mechanical restrictions and enhance wearability. Hybrid structures using rigid parts to make things strong and bendy stuff to let them adapt are forecasted to cut down on user tiredness by sharing out the stress better, helping folks keep up with home exercises, and using it every day.

Second, more research will be aimed at developing an intelligent and multi-modal control framework that can take in various physiological and environmental inputs. Unlike the old way of using just one kind of EMG or EEG signal, new systems will use more types of information at the same time, like biosensing, looking with cameras, and feeling pressure. In adaptive AI architectures, such combined signals will support real-time assist-as-needed interaction, adapting the level of robotic assistance in response to patient intent and performance. This adaptive control will improve the user engagement and increase the speed of neuroplastic recovery, and improve the rehabilitation results.

Thirdly, it is expected that the field will progress towards home-centered rehabilitation ecosystems with tele-supervision. Exoskeleton devices becoming smaller and portable will let patients do their therapy outside of hospitals, and using safe clouds for sending information will help therapists see how well the patients are doing from far away. This will ensure that there is continuity to the rehabilitation training, as well as be more personalized and take the load off of the medical facilities, especially those in areas where healthcare is hard to come by.

And finally, it has to succeed in a very big area and require a lot of clinical trials to prove its success. International safety and performance standards like ISO 13482 and IEC 80601 - 2 - 78 should be considered universally necessary for both academic prototypes and commercial devices. Future research needs to emphasize multicenter randomized controlled trials and standardized usability evaluation for establishing the therapeutic effect, cost-effectiveness, and recognition by the regulators. Standard certification along with interdisciplinary collaboration can enable the transformation of the finger exoskeleton robots as it allows us to take our new robotic invention beyond just a cool lab gadget and makes them more accessible to a wider audience so that they can become something valuable that improves people's life who suffers from problems related to a motor disability.

5. Conclusion

The finger exoskeleton rehabilitation robot was transformed from the concept prototype into a multifunctional training robot that provided task-specific, repetitive, and quantified training. Domestic studies focused on mechanism design and control innovation, whereas international studies have developed compliance, safety, and clinical validations. Together, these efforts show that robotic rehabilitation is possible and promising for restoring hand function in people with neurological and musculoskeletal problems.

Still, important obstacles exist. Devices must get lighter, more adaptable, and cheaper. Control Algorithms must be able to provide robust, real-time decoding of user intent under a variety of clinical conditions. Clinical trials have to graduate from feasibility studies and become big, standard investigations that create strong proof. Most importantly, our patients are comfortable and safe and willing to adhere over the long term; it's those things that need to be accomplished before any advances are going to make real-world differences in a patient in clinical care.

In summary, finger exoskeleton rehabilitation robots are a frontier in rehabilitation medicine. Lightweight, Flexible Designs; Intelligent Multimodal Control and Home-based Connectivity, and clinical Validation will allow us to go from Experimental Prototype to Viable Therapy Tool. Such advances could help not just millions of patients to recover their function, but also reduce the societal and economic costs of neurological disability.

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