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Design of Drive Mechanism for Finger Rehabilitation Robot

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Abstract:

The incidence of hand dysfunction caused by factors such as stroke and occupational injuries is increasing, severely impacting patients' daily living abilities. High-repetition training based on Continuous Passive Motion (CPM) theory can promote neuroplasticity; however, traditional manual rehabilitation suffers from issues such as high dependence, high cost, low efficiency, and poor compliance. Robot-assisted training, leveraging its high repetition, precise quantitative assessment, and programmable modes, has become a key direction for enhancing rehabilitation efficacy and reducing the healthcare burden. This paper focuses on three mainstream drive mechanisms: pneumatic drive, rigid linkage drive, and cable-driven drive. The pneumatic drive utilizes pneumatic pressure to deform flexible chambers, offering good compliance and high safety, but suffers from shortcomings such as insufficient control accuracy and slow response. The rigid linkage drive transmits power based on planar linkages, featuring high control accuracy, good ergonomics, and ease of achieving fine movements; however, multiple degrees of freedom lead to complex and bulky structures, affecting wear comfort and compliance. The cable-driven drive transmits power from remote motors via flexible cables, offering advantages such as lightweight design, good compliance, and strong adaptability; some designs utilize differential mechanisms to achieve self-adaptive grasping, but face challenges in friction control, elastic compensation, and efficient bidirectional driving. Analysis and comparison suggest that current designs need to strike a balance between safety, performance, and cost: pneumatic and cable-driven drives offer better compliance and adaptability, while the rigid drive demonstrates more pronounced advantages in precision.

Keywords: Drive Mechanism; Finger Rehabilitation Robot; Design.

1. Introduction

With the global aging trend, diseases such as stroke severely threaten the health of middle-aged and elderly people, and their incidence rates continue to rise. These diseases often lead to symptoms like motor dysfunction in limbs; additionally, the number of hand injuries caused by accidents, occupational hazards, and other factors is also increasing, with the loss of finger motor function being particularly prominent, severely impacting patients' daily living abilities [1].

Based on modern evidence-based medicine theory and the practical validation of Continuous Passive Motion (CPM) therapy, highly repetitive continuous motion can effectively stimulate the brain's motor control neural circuits, promote blood circulation in affected limbs, and thereby improve the rehabilitation process for patients with hand functional impairments. Clinical studies confirm that CPM therapy significantly reduces the risk of disability in affected limbs and promotes motor function reconstruction [2]. Current rehabilitation for hand functional injuries still predominantly relies on traditional manual therapy. This model has significant limitations: first, it heavily depends on therapist experience, making treatment efficacy difficult to quantify and standardize; second, one-on-one operation incurs high labor costs and inefficiency; third, patients generally lack active rehabilitation awareness, leading to insufficient compliance with home training, hindering sustainable progress in rehabilitation [3]. Long-term training under a rehabilitation physician's supervision can cause patient burnout, significantly reducing rehabilitation compliance and subjective initiative, thereby affecting training continuity. More critically, clinical studies confirm that approximately 30%–60% of patients fail to achieve the functional recovery threshold required for daily living after traditional rehabilitation interventions [4, 5].

In recent years, breakthrough advancements in robotics and physiological signal sensing technologies have injected new momentum into the field of hand function rehabilitation. Hand rehabilitation robotic systems based on multimodal control algorithms and biofeedback mechanisms have become key research focuses in universities and institutions. Such devices can be programmed to enable single-finger and multi-finger coordinated training, adaptive motion mode switching, and other functions. Their high-repetition training not only promotes functional reorganization in the brain's motor cortex but also quantifies parameters like grip strength and joint range of motion in real time, providing data support for dynamic adjustment of rehabilitation plans. Systematic robot-assisted training can significantly enhance patients' self-care abilities, reduce family caregiving costs and societal healthcare burdens, and deepen research on finger rehabilitation robots, offering both theoretical value in neural remodeling and public health economic significance.

This paper summarizes recent research content and achievements on finger rehabilitation robots, including pneumatic-driven, rigid-link, and cable-driven types, analyzes common similarities among these studies, and aims to propose possible conjectures and suggestions regarding the development trends of finger rehabilitation robots.

2. Pneumatically Actuated

Pneumatically actuated soft actuators rely on specific deformations of their internal chambers under air pressure to generate motion. By designing different chamber structures, adjusting wall thickness dimensions, or selecting components with distinct material properties, specific motion patterns required for the actuator can be achieved to meet complex motion requirements; variable stiffness designs can further enhance their motion performance. The structural designs are primarily divided into straight-chamber and pleated configurations. For straight-chamber actuators, bending through pressurization typically occurs in two ways: First, when the upper and lower walls use the same material (i.e., identical elastic modulus), directional bending requires the upper wall thickness to be designed smaller than the lower wall. Second, when the upper and lower walls are made of different materials (different elastic moduli) with identical wall thickness, the actuator bends toward the side with the higher elastic modulus. This high-elastic-modulus layer is often called the strain-limiting layer and is commonly fabricated using materials like PDMS or paper. The bending principle of pleated soft actuators is similar to that of straight-chamber types, also based on differential deformation between upper and lower sides. However, due to the normal interaction forces generated between adjacent pleated sidewalls during pressurization, pleated structures generally achieve larger bending angles than straight-chamber structures under the same air pressure [6].

Research from Harbin Institute of Technology addressed the poor adaptability and safety risks of rigid hand exoskeletons by designing a pneumatically driven soft hand rehabilitation robot [7]. They first analyzed the biological characteristics of fingers. Using the Vicon motion capture system, joint position changes during cylindrical object grasping were analyzed, and the relationship of joint angle variations was modeled to define target parameters for pneumatic actuator design. Based on experimental data, motion coupling relationships between finger joints were further studied. According to the aforementioned target parameters and finger dimensions, the size of the pneumatic actuator was determined. Subsequently, mold design

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was completed, silicone materials were selected, and the actuator fabrication process was optimized. To establish the actuator's kinematics model, each micro-segment was treated as a rigid component, simplified using a piecewise constant curvature model to obtain end-effector poses. Based on the Yeoh strain energy density function model for hyperelastic materials, the relationship between input pressure and bending angle was derived. Material parameters were determined through theoretical calculations and tensile tests. ABAQUS software validated cross-section rationality, static model accuracy, and optimized key dimensional parameters. A control system for the soft pneumatic actuator was designed, including driving execution and control units. Two training modes were provided: passive training and active assistive training. Pneumatic circuits were designed, and calibration with curve fitting was performed for bending angle sensors and thin-film pressure sensors. Using PID control algorithms, experiments on maximum bending angle and thumb MP joint motion of the designed hand rehabilitation robot verified the accuracy of the static model.

Research from Hefei University of Technology described the development of a finger rehabilitation robot (FRR) for both active and passive training to meet different rehabilitation stages [8]. Pneumatic muscles (PMs) were arranged as antagonistic pairs to provide bidirectional forces for passive training, while controllable magnetorheological (MR) dampers supplied resistive forces for active training. Multiple active-passive training experiments were conducted to evaluate the FRR prototype, confirming the system's feasibility and stability.

A soft pneumatic glove developed by Tianjin University features five segmented pneumatic networks per finger [9]. This pneumatic device, made of soft materials and attached to a glove, transmits power through inflation and deflation via pneumatic tubes to drive finger flexion-extension movements. The metacarpophalangeal (MCP) and distal interphalangeal (DIP) joint chambers adopt trapezoidal side profiles to enhance backward bending capability, effectively expanding the range of hand rehabilitation motions. The robot integrates finger rehabilitation and grasping functions, employing a segmented design with three independent pneumatic tubes controlling DIP, PIP, and MCP joint motions respectively.

Research from Université de Lille, France proposed a pneumatically actuated soft exoskeleton system providing coordinated assistance for hand and wrist joints via PD feedback control [10]. Results demonstrate the system's potential for flexion/extension rehabilitation and task-oriented training. The study confirmed that PD control ensures precise tracking of target angle trajectories and angular velocities. Successful tests in full-assist and semi-assist modes verified the system's adaptability to varying degrees of impairment.

3. Rigid Linkage-Based

Rigid linkage-based mechanisms are widely used in food engineering machinery, medical rehabilitation equipment, and textile machinery due to their simple mechanical structure and flexible power transmission characteristics. They are also the mainstream configuration for finger rehabilitation robots. Based on differences in kinematic pairs within planar linkage mechanisms, they can be primarily classified into hinged four-bar linkages and crank-slider mechanisms. The entire rehabilitation device can be summarized as a drive-linkage-execution mechanism form [11].

A robotic index finger exoskeleton rehabilitation mechanism developed by the Institute of Automation, Chinese Academy of Sciences achieves independent joint motion of the index finger through an automatic drive system, enabling finger flexion-extension and lateral oscillation [12]. This mechanism connects finger joints to the drive unit via knitted fabric, resulting in a lightweight structure; the drive unit is positioned above the forearm, effectively reducing patient burden and improving rehabilitation efficiency.

An early representative hand exoskeleton was developed jointly by Vanderbilt University and the University of Kentucky for NASA. Researchers proposed a design using scissors mechanisms with remote centers of rotation (RCR), enabling dynamic alignment between the mechanism's axis and the hand joint's rotation center. This concept has been widely adopted in hand rehabilitation exoskeleton development [13].

The hand rehabilitation robot HEXOSYS developed by Iqbal et al., adopts a planar three-link underactuated configuration. Its design integrates finger kinematic characteristics and optimizes the structure based on mechanism dexterity, isotropy, and vertical human-robot interaction forces [14].

The hand rehabilitation robot ExoFing developed by Carbone et al., utilizes a single-joint four-bar linkage drive, providing two active degrees of freedom per finger. Its metacarpophalangeal (MCP) and proximal interphalangeal (PIP) joints are connected through a four-bar linkage. This independent actuation of uncoupled joints enhances mechanism flexibility, enabling patients to perform diverse motion training patterns [15].

Similarly employing single-joint four-bar linkage drives is the ASSISTON-FINGER hand exoskeleton developed by Ertas et al. Its design philosophy equates human grasping motion to: first, MCP joint flexion until the proximal phalanx contacts an obstacle; followed by PIP joint flexion until complete object grip. A key feature is that a properly constrained closed-chain human-robot system forms only when the patient wears the device; here, the hand joints become part of the mechanism, exhibiting inherent axis alignment characteristics [16].

4. Cable Driven

Cable-driven finger rehabilitation robots utilize flexible cables as transmission media to convert the rotational motion of remotely placed motors into linear traction for finger joints. Through precise guiding path design, sensor feedback, and advanced control algorithms, they enable safe, compliant, and customizable rehabilitation training modes including passive, active-assistive, and active-resistive exercises. Their lightweight nature, excellent compliance, and strong adaptability offer significant advantages in clinical rehabilitation applications, though challenges remain in friction control, elastic compensation, and bidirectional drive design.

Research from Chongqing University of Technology developed a compact, real-time controlled exoskeletal wearable finger rehabilitation robot based on cable-driven principles, capable of passive and mirror therapy modes. To achieve large-angle finger rotation and smooth force transmission, finger physiological structures and degrees of freedom were analyzed, followed by drive mechanism design. Based on this, the exoskeleton execution mechanism, Bowden cable transmission system, and cable-driven mechanism were configured, analyzed, and designed. Kinematic and dynamic models were established and simulated. A control system was designed for multi-environment rehabilitation needs, alongside a human-machine interface. Prototype fabrication and experimental platform setup were completed, conducting mirror therapy, passive training, and task-oriented grasping tests were conducted. Finally, device performance was evaluated using the Analytic Hierarchy Process (AHP), verifying feasibility and reliability [17].

Tianjin University of Technology and Education designed a cable-driven hand rehabilitation robot system for patients with hand dysfunction, assisting finger flexion-extension and grasping training. The system comprises three parts: the lower computer, the upper computer, and the control system. The lower computer receives and parses commands via serial port to execute rehabilitation motions; the upper computer collects and processes finger flexion data to characterize hand motion states with visualization. To ensure stability, a position-velocity dual closed-loop PID control strategy was implemented, achieving rapid response while suppressing overshoot for precise finger positioning [18].

Southeast University proposed an external tendon structure design to address traditional transmission systems' insufficient compactness and low force efficiency. Using biomimetic technology, they developed a cable-driven external tendon finger rehabilitation robot. Six cables enable thumb flexion/extension, abduction/adduction, and index finger flexion/extension. Furthermore, to overcome traditional robots' difficulty in adaptive grasping of irregular objects, an underactuated concept was introduced. Differential mechanisms and multi-pulley cabling achieved adaptive grasping [19].

The National University of Singapore developed the cable-driven HandCARE rehabilitation robot. This system uses motorized cable loops for individual finger force/position control—single motor rotation trains single-finger flexion/extension. Three training modes are provided: Fixed mode locks drive gears to maintain finger position for isometric force training; Free mode allows gears to rotate freely for unconstrained finger movement; Active mode engages motors to apply torque directly. Biomechanically measured designs adapt to various hand sizes and finger lengths. An engaging VR game interface facilitates training for hemiplegic patients at home or in clinics [20].

The Catholic University of America developed BiomHED, a biomimetic hand exotendon device for post-stroke recovery. Using a limited number of actuators to drive external tendons (cables), it assists patients in performing complex hand motions. Resembling a glove with side zippers for easy wear, its cable system mimics human hand tendons: four fingers driven by one cable each, the thumb by two cables. Experiments confirmed improved kinematic performance in fingertip-pressing tasks and significantly reduced thumb-to-fingertip distance, supporting efficient task-oriented rehabilitation [21].

5. Conclusion

This paper systematically reviews the design principles, technical characteristics, and research progress of actuation mechanisms for finger rehabilitation robots. Facing the severe reality of rising incidence of hand dysfunction caused by stroke, occupational injuries, and other factors—along with the significant limitations of traditional manual rehabilitation in efficiency, cost, and compliance—finger rehabilitation technologies represented by pneumatic actuation, rigid-link drives, and cable-driven systems offer new approaches for hand dysfunction recovery. However, finger rehabilitation robotics remains in its early R&D stage, with numerous defects preventing widespread adoption.

First is the safety risk issue. Most existing devices rely on rigid-link mechanisms to drive complex hand joint systems, posing potential secondary injury risks. While softer alternatives like pneumatically actuated robots offer better

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safety, they struggle to match the precision of rigid-link structures in rehabilitation outcomes.

Second is the high cost challenge. Complex device structures, high-level technical integration, expensive high-performance materials, and substantial R&D investments result in prohibitively high end-user prices. Future efforts must explore cheaper materials and simpler mechanisms.

Finally, human-robot interaction and adaptability problems persist. Current devices are often bulky, poorly portable, and lack adequate hand conformity, restricting patient mobility and confining usage to specific settings rather than integrating into daily high-frequency routines. Future designs should prioritize ergonomic optimization, adopting lightweight flexible materials and enhancing elastic/flexible actuation systems to reduce patients' awareness of the device during daily use.

This paper concludes that future development of finger rehabilitation robots will rely on multidisciplinary integration. Advances in materials science, electronic engineering, mechanical engineering, and related fields will address existing shortcomings—poor safety, high costs, and suboptimal human-robot interaction—enabling widespread adoption and ultimately replacing traditional manual rehabilitation methods.

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