Research Progress of Exoskeleton for Hand Rehabilitation following stroke

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Abstract. Based on the hand rehabilitation exoskeleton, the research results of three driving modes in recent years, namely cable, connecting rod and pneumatic system, were classified, summarized and analyzed. Through research and analysis, the results of structural dimensions, structural degrees of freedom, drive selection scheme, control strategy and sensor selection scheme which are more suitable for human hand rehabilitation exoskeleton are obtained, which can provide reference for exoskeleton researchers.

1. Introduction
The exoskeleton for hand rehabilitation is a typical human-machine integration device, which is usually fixed on the hands and can drive the finger to achieve flexion and extension movement. The human hand and the exoskeleton have mutual feedback and change of force movement process. In the process of rehabilitation, the portability, comfort and safety of the hand exoskeleton are particularly important. This paper mainly focuses on the rehabilitation effect of the exoskeleton for hands function injury rehabilitation and introduces the current research status and existing problems of the hand exoskeleton in terms of the mechanism as well as driving mode of the hand exoskeleton at home and abroad.

2. Hand rehabilitation requirements and current rehabilitation theories
The current theories for rehabilitation include sensorimotor rehabilitation therapy, constraint induced movement therapy, and robot assisted rehabilitation therapy and other rehabilitation methods. Sensorimotor rehabilitation (SR) therapy is widely used in rehabilitation therapy, including traditional physical therapy, occupational therapy and neuromuscular therapy. Sensorimotor rehabilitation therapy can promote the learning and memory of the brain nervous system through repetitive movement of the affected limb and repairs the nerve control of the affected limb. Constraint-induced movement therapy (CIMT) was proposed by Professor Edward Taud of the University of Alabama. It is mainly to overcome the acquired disuse by restricting the healthy limbs and training the injured limbs, so as to promote the rehabilitation of the injured limbs. Robot-aided rehabilitation therapy (RART) is a kind of treatment method with robot-assisted rehabilitation, which mainly includes continuous passive motion, robot active-assistance exercise, robot progressive resistance exercise and task-oriented virtual environment rehabilitation training.
3. Current research status of hand exoskeleton at home and abroad

Research on the hand exoskeleton began in the 1990s and the hand exoskeleton developed from the industrial manipulator. The typical mass of the hand exoskeleton is about 0.7~5kg [5]. In 2012, the hand exoskeleton developed by the University of Sydney installed the driving part in the forearm through guide rail to reduce the burden on patients' hands [2]. In 2014, the Italian Institute of Technology proposed a series mechanism for the thumb and index finger, which can exert extremely high force on the finger bone vertically [3]. In 2016, the University of Texas proposed a virtual prototype design framework based on simulation design for musculoskeletal analysis as shown in Fig.1. Under this framework, a coupled human exoskeleton model can be developed by means of simulation technology to further promote the development of subsequent exoskeletons [4]. In 2018, the university of Florence adopted series elastic actuator technology, the ring finger side power was driven by toothed belt, the improved four-bar mechanism was adopted for power transmission, and the parameter optimization and objective optimization were carried out [5].

In recent years, the research on hand exoskeleton in China has also made a series of progress, with great progress in the structure, drive and control of the exoskeleton. As shown in Fig.2, in 2014, Harbin Institute of Technology designed a ring driver based on boden cable driver, combined with adaptive exoskeleton, which greatly improved the applicability of exoskeleton to the patients [8]. In 2016, Northeastern University proposed a non-articular tendon-driven structure, which further developed the concept of coupling joints [7]. In 2019, Xi'an Jiaotong University designed the brain-controlled hand exoskeleton based on the combination mechanism of hardness and softness. And the finger fitting part was connected by multiple elastic parts. By measuring the interaction force between the exoskeleton fingertips, the exoskeleton drive force and the fingertip force are further in line with the requirements of the patient's daily life (ADL) [1].

4. Structure and control mode of hand exoskeleton

After the development of the exoskeleton in recent ten years, the general classification of structural mode and drive mode is gradually clear.

Table 1 the advantages and disadvantages between different driving methods

| Drive Mode | Advantages | Disadvantages |
|------------|------------|---------------|
| Linkage    | The ability of self-alignment between the joint of exoskeleton and the corresponding joint of human finger can be realized. | The dislocation of finger joint and exoskeleton may occur and requires compensation mechanism. |
| Cable      | The cable structure reflects the actual finger movement, which helps to maintain the characteristics of light, low inertia structure and independent drive control. | The control system is complex; Elastic deformation. |
| Pneumatic  | High Safety, flexibility, cheap and lightweight. The basic drive unit, which consists of actuating muscles, can simulate human muscle movement and provide more complete driving force. | Pneumatic system produces compression noise and increases the size of the muscle part. |
Similar to other exoskeletons, such as upper limb exoskeleton and lower limb exoskeleton, the drive mode is divided into connecting rod mechanism drive, cable drive and flexible drive. DC motor drive and cable drive are the main power source of hand exoskeleton.

\subsection{Linkage mechanism drive}
Connecting rod transmission mechanism is the most common application structure. Connecting rod mechanism is often used for surface contact connection, its advantages are relatively simple and wear-resistant manufacturing, easy to obtain a higher manufacturing accuracy, at the same time, the connecting rod curve rich, can meet different movement needs. The linkage mechanism can realize the self-alignment ability of the joint of the exoskeleton and the corresponding joint of human fingers, but the interaction force will act on the finger. The disadvantage is that there will be finger joint and exoskeleton dislocation of the safety problem. The actuation of hand exoskeleton can be divided into complete actuation, single degree of freedom actuation and underactuation.

Complete drive means that every joint part has a drive, which can restore the degree of freedom of the finger part to a great extent, but increase the complexity in structure, and can significantly increase the quality of the hand exoskeleton. The hand exoskeleton developed by Turki et al in 1995 is a hand exoskeleton composed of a four-link mechanism driven by a DC motor, which can achieve 14 DOF of human hands, while the exoskeleton developed by Kitada can achieve 20 DOF. The exoskeleton developed by Md Akhlaquor et al. from the University of Technology, Sydney has a drive motor for each joint and uses an l-shaped structure to simulate a spring to provide a constant force for the distal phalanx supporting structure (Fig.3). The basic structural idea of the flexion mechanism comes from the finger flexion splint made by Homecraft Rolyan\cite{2}.

\begin{figure}[h]
\centering
\includegraphics[width=0.4\textwidth]{Fig3.png}
\caption{Exoskeleton developed by the University Of Sydney}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.4\textwidth]{Fig4.png}
\caption{Single DOF drive}
\end{figure}

Single-degree-of-freedom drive refers to the movement of only one joint of the finger, most of which is used to study the way the finger applies force and the size of force (Fig.4). The multi-degree-of-freedom system proposed by the Italian polytechnic university in 2014 consists of a direct-actuated, optimized and under-actuated series mechanism, which can exert extremely high forces on the phalanx vertically and further improves the exoskeleton structure based on the multi-objective optimization algorithm\cite{3, 8}.

Underactuated hand exoskeleton is designed to reduce the control difficulty of hand exoskeleton and the volume and mass of the structure. The number of actuators needs to be reduced. The underactuated hand exoskeleton is designed with actuators less than the degree of freedom of joints, which can meet the requirements of both aspects. Most underactuated finger exoskeletons reduce the number of actuators and reduce multiple actuators for a single finger to one. Santello’s study found that the Angle between the fingers is not completely independent, this suggests that the effective degrees of freedom in one hand, between 5 to 6 only one DOF of exoskeleton diversity affect movement, but does not affect the motion accuracy.

The parallelogram mechanism (Fig.5), proposed by Alessandro in 2014, promoted the development of the optimization process of linkage mechanism\cite{9}. The rotary center is in a fixed position, by adding...
spring and stop the action, and put forward the principle of a seesaw and pulleys, at the same time, under the combination of cable each finger MCP were neglected. In 2016, the mechanical engineering department of Malaga University proposed the coupling theory, designed a single finger underactuation scheme (as shown in Fig.6) and further improved the mechanism by using Malaga mechanism synthesis algorithm (MUMSA) [10]. A series of elastic actuators (SEA [11-12]) with motor proposed by Suin Kim in 2017, in which the spring ACTS as a force sensor, reducing the size and weight of the actuator [13-14]. In 2019, the Korean Defense Development Agency proposed an underactuated wearable exoskeleton for grasping power, which is also underactuated with dynamic elastic characteristics. Its structure involves a rotating mechanism along the longitudinal direction of the operator's hand, and a spherical four-rod mechanism is adopted to solve the problem of power transmission between vertical rotating axes. In 2016, Northeastern University proposed a non-articular tendon driving mechanism (Fig.7 A1 and A2), which was pulled by an actuator through the tendon cord next to each joint, and the ventral tendon cord was pulled by another consistent actuator, which was fixed and arranged in the same way to make the structure compact, such as the tendon driving Glove and the SNU exo-glove [15]. This coupling of the chordae tendineae connection neatly solves the coupling relationship between multiple joints [7]. Suin Kim and others from Ulsan University of Science and Technology in South Korea proposed an exoskeleton driven by a cable mechanism based on the improved linkage structure in 2017, which mainly ACTS on the fingertip (Fig.7 B1 and B2). The SEA structure handexos-beta (HX-beta) proposed by the Institute of advanced bio-robotics, Santa ana, Pisa, Italy in 2019 has the advantage of utilizing bidirectional elastic driving unit to control seven degrees of freedom (Fig.8 C1 and C2), including full DOF and insufficient DOF [16].

4.3 Other driving modes
Other structures and driving modes include pneumatic actuators and steel springs. The exoskeleton design of pneumatic actuators consists of rubber body, strain limiting layer and fiber reinforced threads. It is simple in structure and light in weight, but it will bring compression noise and increase the size and mass of the whole system. In recent years, the development of pneumatic actuators is relatively slow. Compared with other driving methods, they have greater influence on motion error and are less used. In 2019, Xi 'an jiaotong university designed a new type of exoskeleton mechanism with steel spring, which was composed of cable and multi-segment elastic components. Compared with the traditional cable mechanism, its structure was further optimized and its mass was reduced to 0.5kg [1], which further promoted the research and development of flexible exoskeleton in the future (Fig.9).
Fig. 7. Cables drive the exoskeleton

Fig. 8. a. Bending motion generated by the proposed multi-segment mechanism with a spring layer. b. Overview of the hand exoskeleton prototype

The summary table is as follows:

| Research Institution               | Drive Mode          | Innovation Point                                                                 | Figure |
|------------------------------------|---------------------|-----------------------------------------------------------------------------------|--------|
| Sydney University of Technology    | Linear driver, 15DOF.| Left-right mirror mode                                                             |        |
| Harbin Institute of Technology     | Linear driver;      | The nonlinear tensile displacement of the joint can be realized by using the    |        |
|                                    |                     | proposed ring joint composed of spring and parallel sliding mechanism.            |        |
|                                    |                     | Ring joint adjustable device                                                      |        |
| Institution                        | System Description                                                                 | Additional Information                                                                                                                                 |
|-----------------------------------|-------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------|
| Italian Institute of Technology  | The M-DOF system consists of a direct-actuated, optimized, and underactuated series linkage capable of applying extremely high vertical forces to the phalanx. | Multi-objective optimization algorithm with control based on minimal bumpy trajectory generation, based on direct force/torque transfer mechanism. |
| University of Malaga              | Linkage underdrive.                                                                 | Accurate representation of finger motion parameters based on malaga algorithm (MUMSA).                                                                            |
| Northeastern University           | Cable driven. The non-articular tendon drive mechanism is pulled by the actuator by passing through the tendon cord next to each joint, and the ventral tendon cord is pulled by another consistent actuator. | The quadric polynomial coupling curve was used to couple PIP and DIP joint motion.                                                                           |
| University of Texas               | Cable driven.                                                                       | Coupled PIP and DIP joint motion using sinusoidal coupling curve.                                                                                           |
| Northeastern University           | Connecting rod transmission structure and part of the cable drive.                    | The coupling tendon connection between DIP and PIP is implemented by two coupling bars with different radii and two pulleys.                               |
| UNIST                             | The cable drive drive mechanism exerts tension on the fingertip.                      | The instantaneous muscle force was calculated by static optimization method. Maximum durability criterion and sequential quadratic programming (SQP) algorithm are adopted to optimize. |

4. Italian Institute of Technology: The M-DOF system consists of a direct-actuated, optimized, and underactuated series linkage capable of applying extremely high vertical forces to the phalanx. Multi-objective optimization algorithm with control based on minimal bumpy trajectory generation, based on direct force/torque transfer mechanism.

5. University of Malaga: Linkage underdrive. Accurate representation of finger motion parameters based on malaga algorithm (MUMSA).

6. Northeastern University: Cable driven. The non-articular tendon drive mechanism is pulled by the actuator by passing through the tendon cord next to each joint, and the ventral tendon cord is pulled by another consistent actuator. The quadric polynomial coupling curve was used to couple PIP and DIP joint motion.

7. University of Texas: Cable driven. Coupled PIP and DIP joint motion using sinusoidal coupling curve.

8. Northeastern University: Connecting rod transmission structure and part of the cable drive. The coupling tendon connection between DIP and PIP is implemented by two coupling bars with different radii and two pulleys.

9. UNIST: The cable drive drive mechanism exerts tension on the fingertip. The instantaneous muscle force was calculated by static optimization method. Maximum durability criterion and sequential quadratic programming (SQP) algorithm are adopted to optimize.
### 5. Problems and prospects

Using exoskeleton for rehabilitation training has gradually become the mainstream of rehabilitation training\,[22-23]. However, the exoskeleton design requires low complexity, compactness, bidirectional drive, low cost, portability, safe human-machine interaction\,[24] and intuitive control, which further improve the requirements of the exoskeleton in terms of structure, drive, control mode, sensors and so on.
Existing problems as follows:

- The concept of joint coupling for underactuated strategy needs to be perfected. The underactuated strategy couples the joints. The further development of this strategy requires more reasonable mechanism design to achieve the accuracy of movement on the basis of high fit with human hands. Furthermore, exoskeleton flexibility can be developed on the basis of accuracy. Underactuated coupling strategy considers the coupling between individual finger joints, and there is no further research on whether there is coupling between fingers. The text should be set to single line spacing.

- Hand exoskeleton fit problem. Most exoskeletons lack adaptive fine-tuning structure for different hand shape. When the hand shape changes, the remote rotation center of the joint will be offset. At this time, if the center of rotation does not coincide, it will cause secondary injury to the patient.

- Further develop the control theory. The impedance characteristics of human-machine contact and adaptive control need to be further combined to further improve the comfort of the wearer.

- For the hand exoskeleton rehabilitation results did not appear the same criteria, rehabilitation results of the subjective factors have a greater impact, to be further improved.

The rapid development of the hand exoskeleton in the last five years, as well as the introduction of various control modes and novel mechanisms, indicates that the hand exoskeleton is increasingly valued. It is believed that with the progress of science and technology, the hand exoskeleton will continue to improve and become an important medical rehabilitation equipment in the future.

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References
[1] Li M., He B., Liang Z, Zhao C. G., Chen J.Z., Zhuo Y.Y., Xu G.h., Xie J., Althoefer K. (2019) An Attention-Controlled Hand Exoskeleton for the Rehabilitation of Finger Extension and Flexion Using a Rigid-Soft Combined Mechanism. Frontiers in neurorobotics, 13: 34-47.
[2] Md Akhlaquor R., Adel Al-J. (2012) Design and Development of a Hand Exoskeleton for Rehabilitation Following Stroke. Procedia Engineering, 41: 1028-1034.
[3] Jamshed I., Hamza K., Nikos G. Tsagarakis, Darwin G. Caldwell. (2014) A novel exoskeleton robotic system for hand rehabilitation - Conceptualization to prototyping. Biocybernetics and Biomedical Engineering, 61: 69-82.
[4] Agarwal P., Neptune Richard R, Deshpande Ashish D. (2016) A Simulation Framework for Virtual Prototyping of Robotic Exoskeletons. Journal of biomechanical engineering, 138: 061004.1-15.
[5] M. Bianchi, M. Cempini, R. Conti, E. Meli, A. Ridolfi, N. Vitiello, B. Allotta. (2018) Design of a Series Elastic Transmission for hand exoskeletons. Mechatronics, 51: 8-18.
[6] Fuhai Zhang, Lei Hua, Yili Fu, Hongwei Chen, Shuguow Wang. (2014) Design and development of a hand exoskeleton for rehabilitation of hand injuries. Mechanism and Machine Theory, 73: 103-116.
[7] Jianyu Yang, Hualong Xie, Jiashun Shi. (2016) A novel motion-coupling design for a jointless tendon-driven finger exoskeleton for rehabilitation. Mechanism and Machine Theory, 99: 83-102.
[8] Brokaw EB, Black I, Holley RJ, Lum PS. (2011) Hand Spring Operated Movement
Enhancer (HandSOME): a portable, passive hand exoskeleton for stroke rehabilitation. IEEE Trans Neural Syst Rehabil Eng., 19(4):391-399.

[9] Alessandro B. (2015) Kineststatic analysis and design optimization of an n-finger underactuated hand exoskeleton. Mechanism and Machine Theory, 88: 86-104.

[10] A. Bataller, J.A. Cabrera, M. Clavijo, J.J. Castillo. (2016) Evolutionary synthesis of mechanisms applied to the design of an exoskeleton for finger rehabilitation. Mechanism and Machine Theory, 105: 31-43.

[11] Cempini M, Cortese M, Vitiello N. (2015) A powered finger-thumb wearable hand exoskeleton with self-aligning joint axes. IEEE/ASME Trans Mechatronics, 20(2): 705-16.

[12] Jorge AD, Badesa FJ, Blanco A, Garcia N, and Lledo LD. (2018) Hand exoskeleton for rehabilitation therapies with integrated optical force sensor, 10: 1-11.

[13] Suin Kim, Jeongsoo Lee, Joonbum Bae. (2017) Analysis of Finger Muscular Forces using a Wearable Hand Exoskeleton System. Journal of Bionic Engineering, 14(4): 680-691.

[14] Inseong J., Joonbum B. (2017) Design and control of a wearable and force-controllable hand exoskeleton system. Mechatronics, 41: 90-101.

[15] Useok Jeong, Hyun-Ki In, Kyu-Jin Cho. (2013) Implementation of various control algorithms for hand rehabilitation exercise using wearable robotic hand. Intelligent Service Robotics, 6: 181-189.

[16] Dario M., Andrea B., Zach McKinney, Marco Cempini, Simona Crea, Nicola Vitiello. (2019) A novel hand exoskeleton with series elastic actuation for modulated torque transfer. Mechatronics, 61: 69-82.

[17] Wang D., Song M., Naqash A., Zheng Y., Xu W., Zhang Y. (2019) Toward Whole-Hand Kinesthetic Feedback: A Survey of Force Feedback Gloves. IEEE transactions on haptics, 12(2):189-204.

[18] Yeongyu P., Inseong J., Jeongsoo L., Joonbum B. (2018) A Dual-cable Hand Exoskeleton System for Virtual Reality. Mechatronics, 49: 177-186.

[19] Qian Bi, Can-Jun Yang, Xue-Lei Deng, Jing-Chang Fan. (2016) Human finger mechanical impedance modeling: Using multiplicative uncertain model. Proceedings of the Institution of Mechanical Engineers, 230(12): 1978-1986.

[20] Soekadar SR, Witkowski M, Vitiello N, et al. (2015) An EEG/EOG based hybrid brain-neural computer interaction (BNCI) system to control an exoskeleton for the paralyzed hand. Biomed Tech (Berl), 60(3): 199-205.

[21] Knutson J S, Gunzler D D, Wilson R D. (2016) Contralaterally controlled functional electrical stimulation improves hand dexterity in chronic hemiparesis: a randomized trial. Stroke, 47(10): 2596-2602.

[22] Chowdhury A., Nishad S. S., Meena Y. K., Dutta A., Prasad G. (2018) Hand-Exoskeleton Assisted Progressive Neurorehabilitation using Impedance Adaptation based Challenge Level Adjustment Method. IEEE transactions on haptics, 12: 128-140.

[23] Bonikowski M, Hajduk M, Koukolova L, et al. (2016) New trends in the use of robotic devices in motor rehabilitation of upper limbs. Springer International Publishing, New York.

[24] Mohammadhossein S., David C. Long, Ozkan C. (2019) Comparison of Human-Robot Interaction Torque Estimation Methods in a Wrist Rehabilitation Exoskeleton. Journal of Intelligent & Robotic Systems, 94: 565-581.