Solution For Improving Wearing Comfort of Hands Exoskeleton

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Abstract. In recent years, with the development of exoskeleton technology, it has been widely applied in the area of rehabilitation. However, in the rehabilitation of neurological diseases such as cerebral stroke, the rehabilitation of hands exists multifaceted difficulties. Long treatment period, choices of therapeutic schedule and costly treatment are common factors that affect the efficiency of rehabilitation. To improve hands exoskeleton's therapeutic effect in the neurological rehabilitation. A considerable number of papers have been studied and the development trend of hands exoskeleton was revealed. This review focuses on the wearing comfort of hands exoskeleton, since wearing comfort is an essential factor when launching arm exoskeleton on the market. This article elaborates on the methods of improving exoskeleton's wearing comfort based on rigid mechanism design and soft or flexible hand exoskeleton design. This article mainly discusses the improving control system and adapted materials, aiming at finding the similarities and differences among various solutions. Pictures concerning each method are also provided for better understanding. Besides, this article provides conclusive perspectives on the existing design and expectations for the further studies.

Keywords: Arm exoskeleton; wearing comfort; design; material.

1. Introduction

Hands exoskeleton has been evolved for decades. Researchers improved its wearing comfort by multiple measures. Some focus on the mechanical design of hands exoskeleton. Wang et al. designed an exoskeleton based on linear motor and connecting rod chute structure [1]. This research adopted both kinetic examinations and mechanical mechanism designs of connecting rod. The translation and rotation about the hands with multiple degrees of freedom can be supported by this exoskeleton under the condition of less driving force. And with the light structure, the wearing comfort of patients was improved. Daniele et al. examined an electromyography (EMG)-driven hand exoskeleton for improving the efficiency during rehabilitation [2]. This device is adaptive to patient's hands with free-palm and free-fingertip design. Others assess users' wearing comfort by establishing evaluation model. LI et al. designed a comfort evaluation index system which is established concerning four aspects: ease of operation, motion matching, force uniformity and shape adaptability [3]. Choosing the appropriate material is also an important part of improving wearing comfort since the inside of exoskeleton is the part that makes direct contact with hands. In material science, many insightful methods have been taken into study. Fabric-based material has been proved effective in improving wearing comfort and in the designs of SNU Exo-Glove it was taken into practical examination [4]. A newly-designed silicone actuator applied both elastic fabric and inelastic materials. A thermoplastic elastomer (TPE) part was implemented to function. Its structure is different from ordinary silicone actuator. Elastomeric materials are adopted and fill in the 3D printed molds of the actuator [5].

This paper aims at illustrating methods of improving wearing comfort from two aspects: rigid mechanism design and soft or flexible hand exoskeleton design. Finally, summary about the shortages of current methods for improving wearing comfort on hand exoskeleton is given. Besides, the developing trend of these two main methods based on research results in recent years is concluded.

2. Rigid Mechanism Design

2.1. Bowden Cable Driven Mechanism Design.

In previous studies, adopting bowden cable to improve wearing comfort is common. Plessis et al. designed a hand exoskeleton using shell-liked structure on the phalanges [6]. This structure distributed the force applied on the hand to improve wearing comfort. Bowden cable actuates the hands remotely to decrease the inertia and the entire weight. Chiri et al. adopted a bowden cables transmission system as a remote underactuation solution [7]. In his study, the application of bowden cables was helpful in locating the bulky actuation, thus the entire inertia of that parts was reduced.

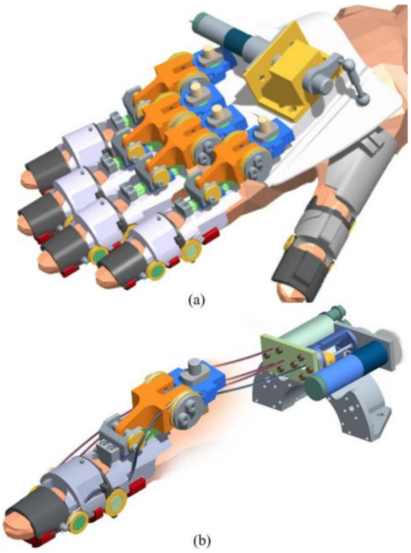

Fig. 1 (a) Five independent finger modules [7]; (b) Specific information of the finger part [7].

A light and soft hand exoskeleton driven by cables constructed with a prototype of that upper limb system was designed by Didier [8]. In this study, a man-machine interaction simulation experiment was conducted. Bowden cables transmitted the power of the motor. It can bend and extend the arm. The result showed positive effects of bowden cables on the improvement of exoskeleton' wearing comfort since less active forces were required and the flexibility of forearm was also improved.A EMG-Driven hand exoskeleton called Maestro was designed to mainly focus on the improvement of wearing comfort of users[9]. This design adopted electric motors, including a pulley on the motor shaft. The actuation mechanism was remotely actuated by bowden cables, which reduced the weight and made the mechanism compliant. To reduce the amount of friction during using, compression springs were introduced at the joint. The whole system was placed on a glove.

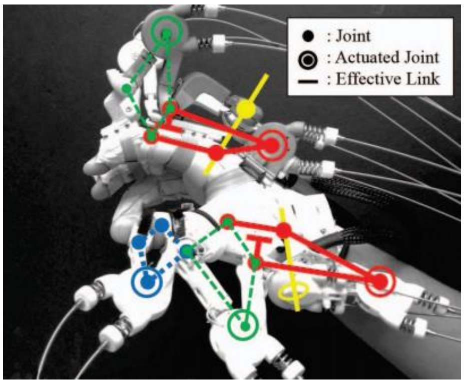

Fig. 2 Maestro's multiple four-bar mechanisms [9].

Wege et al. invented a hand exoskeleton prototype and a control algorithm to improve the wearing experience [10]. In current design, full range of motion was allowed due to its link lengths. The application of two bowden-driven cables realized a newly-designed mechanism of four degrees of freedom functioning bidirectional. A pulley was placed on each end of the lever. On that structure, the bowden cable was fixed on the two ends. By organizing the angles of the hall sensors, the position accuracy could be further fixed. Due to the flexibility and durability provided by the bowden cables. The system was able to synchronize with the patient and altered the speed trajectory automatically, allowing the improvement on wearing comfort feasible.

Fig. 3 Prototype of the exoskeleton. Hall sensor and Actuator unit [10].

2.2. Underactuated Design.

By adopting underactuated design, one actuator can actuate several DOF and improve hands' flexibility. Underactuated system also decreases the weight as Bowden cable. It is also a design, which improves the wearing comfort of hand exoskeleton.

A control plan was proposed by Popescu et al [11]. An exoskeleton with underactuated fingers, aiming at improving the capacity of control. To maximize the feasibility of this system, an Intelligent Haptic Robot-Glove (IHRG) was designed. It has low mass and inertia, improving the wearing comfort.

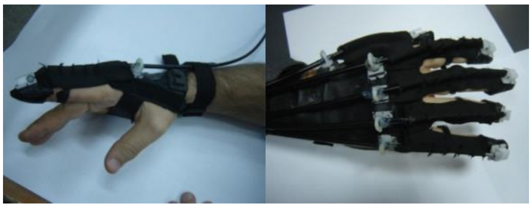

Fig. 4 Robotic glove [11].

Sarac presented a underactuation-driven hand exoskeleton [12]. Potentiometer was installed additionally to figure up the angle and the applying force on the joint. The device only transmits the normal movement of force acting on the phalanges, thus the pressure on the fingers was alleviated and the user can wear it in a comfortable manner.

Fig. 5 The grasping tasks conducted by the multi-finger hand exoskeleton [12]

An Exo-Glove was proposed based on the underactuation mechanism [13]. This novel mechanism was proposed to fulfill the requirement of adaptive grasping. A U-shaped tubes tube was installed at the end of the index. Other tubes were applied on the middle fingers. When human's hand makes contact with even or uneven surfaces, this mechanism enables the Exo-Glove to provide adaptation, distributing the force applied on the hands. Using this novel underactuation improved the wearing experience and simplify the implement process.

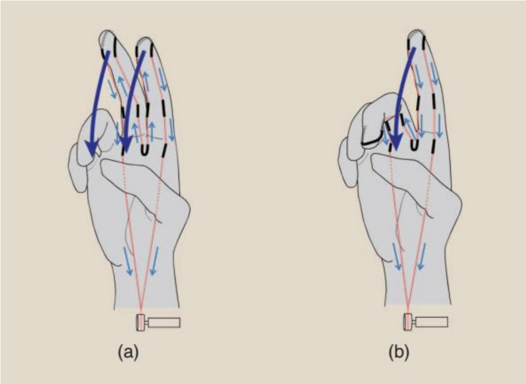

Fig. 6 The movement in the Exo-Glove: (a) Identical two fingers movement [13]; (b) The index finger moves when the middle finger is remaining stable [13].

Gabardi et al. designed and evaluated an underactuated exoskeleton with five degrees of freedom [14]. It is allowable for natural movement. This exoskeleton was actuated by only one actuator. But it could maintain four dofs mobility. Since fasteners on the device around the finger were less tight than other designs, which was effective in loading the thumbs phalanges. This adaptability to various hand sizes was designed based on an open kinematic design, which improved the wearing comfort.

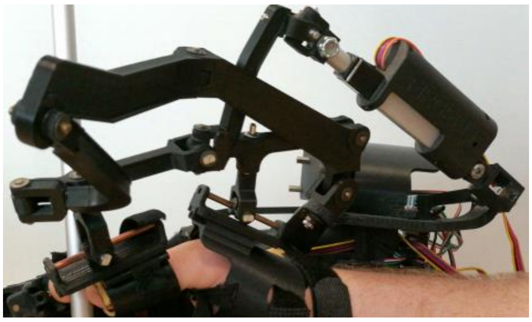

Fig. 7 The exoskeleton prototype [14].

3. Soft or Flexible Hand Exoskeleton Design

The materials of hand exoskeletons are mostly divided into 3D printing and flexible materials. Soft wearable gloves provide a novel concept in improving wearing comfort and feasibility. They are mainly designed by fabric, plastic materials. Some apply a novel silicon-based materials. Fabric material application is common and has been studied for years. Traditional rigid exoskeleton is easy to cause pressure on users' hands and is not suitable to wear, so soft exoskeleton gloves are born. Soft exoskeleton gloves are divided into soft pneumatic actuators and hydraulic actuators. Silicone actuator with enhanced fiber is an elastic material. It poured in a 3D printed mold, which can be bent, extended and twisted, and configured as a single actuator.Many traditional exoskeleton robots adopt rigid actuators, which can accurately transmit motion. However, human muscle tissue is flexible, flexible robots can better meet people's needs for comfort and complex movement. Scientific researchers put forward a series of elastic actuator, SEA. Ashish et al. proposed SEA for small robots, and designed LC-SEA and HT-SEA respectively. Its structure diagram is shown in Figure 10 and Figure 11. Because of its light size and compact structure. Therefore, the wearing weight is low and the wearing comfort is improved [15].

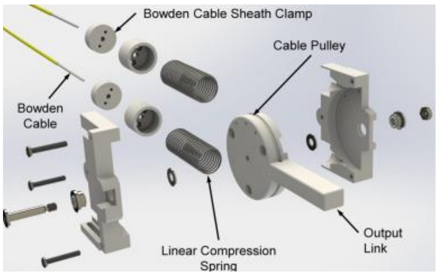

Fig. 8 The structure of the SEA structure [15].

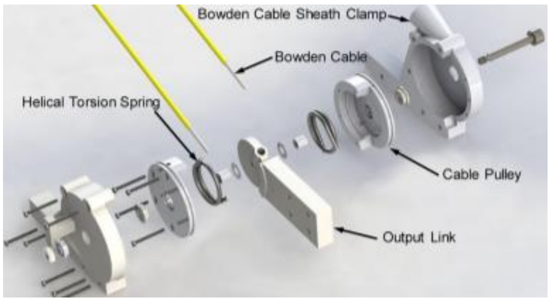

Fig. 9 The structure of SEA structure [15].

Yang et al. used a finger rehabilitation robot designed by serial elastic actuators to realize the MP1, PIP and DIP flexed and extended their movements of four fingers except the thumb, and the execution part adopted the way of rope transmission. Part of the actuator uses a series elastic actuator, which is characterized by low impedance, small volume, high energy density, stable force output and good buffering of external impact load [16]. And, the hand robot model was shown in the Figure 12.

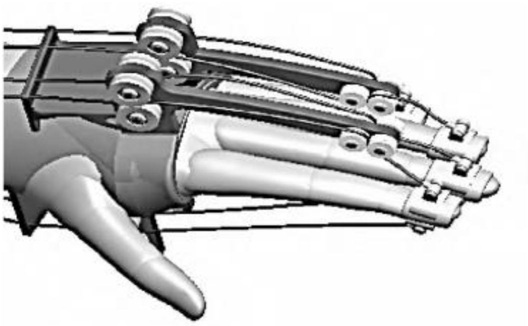

Fig. 10 The hand robot model [16].

Because the rigid exoskeleton is heavy and inconvenient to wear, the flexible exoskeleton is comfortable to wear, but it is difficult to control. Therefore, Lin et al. designed a hand exoskeleton with both rigidity and flexibility, and adopted a sliding spring mechanism consist of three different layers (TLSS) [17]. Through analysis of the length, width and thickness. The spring was optimized, the flexibility of movement was enhanced, the wearing weight was reduced, the mechanism was simplified, and it could be customized with the change of the user's hand type, which improved the comfort of hand wearing. Through experiments, the angle of hand exoskeleton joint approaches to the natural extension and bending of human hand, so the design is effective. Figure 13 presented the three-layer sliding spring mechanism.

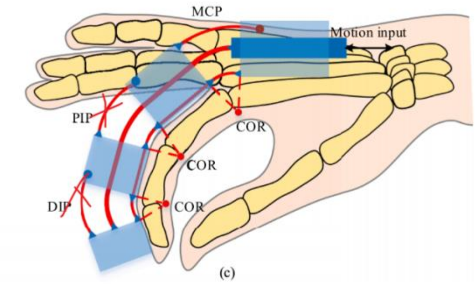

Fig. 11 The three-layer sliding spring mechanism [17].

Bützer et al. put forward an actuation on soft hand exoskeleton relay exoskeleton, which gathers the advantages of rigid mechanism and flexible mechanism, and reduces the degree of freedom of the hand to three in order to simplify the mechanism design [18]. Reduce the total weight of hand exoskeleton. But it can still satisfy 80% of daily grabbing activities. Figure 14 is the finished design of hand exoskeleton. The backpack control system includes a motor and a battery, and the hand exoskeleton is connected with the backpack control system through a cable.Transferring the control system from the hands to the back can reduce the pressure on the hands and improve the wearing comfort. In order to make the exoskeleton of the hand better in the adaptation of the size and movement about the hand, a set of parameters are constructed, and the tester can obtain the appropriate size by measuring. This increases the control and flexibility of the hand. Experiments show that this method is effective, but the control of grasping force needs to be further optimized.

Fig. 12 RELab tenoexo consists of hand exoskeleton and backpack control system [18].

4. Discussion

This study has analyzed the methods for improving wearing comfort from two types of hand exoskeletons. In the following part, their advantages and disadvantages will be further discussed.

4.1. Bowden cable driven mechanism design.

Bowden cable is able to transfer the force applied on the force to the fingers by its rigid structure. It can simplify the structure of hand exoskeleton. By using bowden cables, the actuating devices can be placed distal, which decreased the weight of the hand exoskeleton when wearing it. Some investigated the effectiveness of using bowden cables to reduce the inertia.

4.2. Underactuated design.

Underactuated system is widely adopted in the design of exoskeleton. It uses fewer actuators to actuate the fingers and it has less weight than full actuated system. Underactuation mechanism enables the transmission of force applied on the hands adaptively adjusted.

4.3. Soft or flexible hand exoskeleton design

The development and improvement of the silicone-based actuators face several problems. After analysis of previous tests. The period of that is longer than that of the textile actuators. However, better dimensional accuracy revealed on that material.

The construction using pleated textile as their main exposure materials shows promising result compared to ordinary materials, which benefits the rehabilitation effects of hands exoskeleton.

Fiber-Reinforced Silicone Actuator is more accurate than soft fabric-reinforced pneumatic actuator, but they take longer to make, while soft fabric-reinforced pneumatic actuator is lighter, more convenient, and shorter in making time.

SEA can sense the mutual force between exoskeleton and the outside world, and enhance the robot's ability to deal with complex environment. ESEA device reduces the bandwidth of zero motion force of the mechanical system, and cannot avoid the oscillation phenomenon. in order to obtain continuous output force, DSEA needs the motor to continuously input energy to the system. Therefore, it is seldom used in robots.

5. Conclusion

Current development of hands exoskeleton is rapid. Many researchers have conducted enormous experiment in improving the wearing comfort. In this paper, four methods for improving wearing comfort of hands exoskeleton are listed. The hands exoskeleton was classified into two main types: Rigid mechanism design and Soft or flexible mechanism design.

In rigid mechanism design, existing methods concerning bowden cables and underactuation mechanism are analyzed. Bowden cables show its advantages in ability in reducing the weight of the exoskeleton and the inertia of using the device. Bowden cables improve the wearing comfort by improving the structure of the exoskeleton and reducing the burden on the hands. Underactuated design focuses on improving the assistance provided when grasping objects. It creates a more flexible using experience. Underactuated design also decreases the total wearing weight as it requires less actuator.

In soft or flexible mechanism design, both two types of actuators present the ability to meet the fundamental criteria of wearing during rehabilitation. Specifically, the textile actuator makes the construction of hands exoskeleton lighter as it effectively reduces the size of the device. Besides air pump can further optimize that effect and it requires less power to function well. Additionally, these actuators simplify the process of wearing and reduce the cost for maintenance as it is more durable than rigid hand exoskeleton. The cost for manufacturing is also reduced since the replacement frequency for actuators is decreased. The raw materials are inexpensive and their purchasing methods are stable. So, it is more recommended for textile actuators than silicone actuators were identified.

SEA is passive and compliant, which can protect the robot from the impact of the outside world. The robot based on SEA can decouple the motor from the end effector by using elastic or damping devices, and absorb or buffer the impact of the robot from the outside world.

It can be concluded that the existing shortage of methods for improving wearing comfort. In rigid mechanism design, most of the methods are currently only conducted in the laboratory. There is a long way to go before entering the market. Besides, most of the designs do not reduce the cost of the exoskeletons. Since many of them require anthropometric measuring to fit different hands.

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