Design of a Soft Exoskeleton with Motion Perception Network for Hand Function Rehabilitation

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Abstract. Hand dysfunction seriously affects patients' activities of daily life. Rehabilitation exoskeleton can effectively improve the hand function of patients and reduce the burden of their families. However, most of the existing exoskeletons lack the ability to detect the state of hands during rehabilitation, which is a potential safety risk for rehabilitation. In order to improve the safety of hand function rehabilitation training, we proposed a soft wearable exoskeleton equipped with motion perception network. The soft exoskeleton is composed of guided bending bellows actuators, and has good mechanical properties. Besides, the soft bending sensor used to build the perception network has high measurement accuracy. The results showed that the soft exoskeleton with motion perception network not only realizes the full range of finger motion, but also measures the angle of each joint during the movement process. Therefore, this device can improve the rehabilitation effect, avoid secondary injury during rehabilitation training, and meet the rehabilitation needs of patients with hand dysfunction.

Keywords: Soft exoskeleton · Motion perception network · Soft actuator · Bending sensor · Hand function rehabilitation

1 Introduction

Whether at work or in daily life, hands participate in various activities, such as perception, movement, holding, manipulation, etc. Almost all survival activities are inseparable from hand function, so hands play a vital role in human life [1]. However, many neurological diseases or injuries cause hand dysfunctions, such as stroke, cerebral palsy, spinal cord injury, hand trauma, and central nervous system injury [2]. The traditional approach to hand functional rehabilitation relies heavily on the experience of therapists and requires their significant physical effort and strength to perform manual interventions [3]. As a result, the traditional treatment is difficult to cope with the surge of patients and the strict

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requirements of rehabilitation training on intensity, duration and consistency. In order to solve these problems, with the development of soft robotic technology in recent years [2, 4], the field of rehabilitation medicine has embraced wearable robots as a common practice. Wearable exoskeleton, for instance, are frequently employed in hand functional rehabilitation to encourage the re-establishment of connections between damaged central nervous system and patients' hand.

In the past few decades, the development of soft robotics technology has provided a solid guarantee for the safety requirements of wearable exoskeleton rehabilitation robots [5, 6]. In terms of structures, the trend is from the traditional series link hinge mechanism of rigid robots to innovative mechanisms by utilizing advancements in power transmission technology and exploring new materials, such as cable-driven exoskeleton gloves and pneumatic artificial muscle exoskeleton gloves. In a previous study, we designed a pneumatically guided binding bellows actuators, and developed the wearable rehabilitation gloves, which not only meet the mechanical needs of rehabilitation training, but also ensure safety during the rehabilitation process [7].

In robot-assisted hand function rehabilitation, the reliability and safety of the devices are crucial to avoid causing secondary harm to patients [8, 9]. Even though the soft robot has the natural characteristics of high safety, it would be better to monitor the training process in order to further enhance the safety of rehabilitation [10, 11]. For the existing soft exoskeletons, most of them lack the ability to monitor the motion state, due to no sensors embedded [12]. Therefore, the integration of sensing technology into the soft exoskeleton to achieve motion monitoring has important application value for clinical rehabilitation.

This study aims to develop a soft exoskeleton with motion perception network to monitor the hand motion and enhance safety during hand function rehabilitation process. We used the flexible bending sensors to establish a motion perception network, and then combine it with the rehabilitation glove based on guided binding bellows actuators to design a soft exoskeleton with perceptive function. The actuators and sensors in the exoskeleton were measured to evaluate the performance of the exoskeleton for hand function rehabilitation.

2 Methodology

2.1 Mechanical Structures

The design of the execution mechanism for hand function rehabilitation is inseparable from the rehabilitation requirements, including passive techniques like muscle and joint relaxation in the initial phase, followed by active training in the intermediate phase, and additional training in daily activities during the later phase [5, 13]. In size, the hand joints are small with high motion complexity, it is not suitable to use rigid active exoskeleton structures as the hand function rehabilitation exoskeleton robots. In addition, the power and transmission of rigid mechanical structures require large space, and it is difficult to accomplish wearing comfort and fit, which will increase the burden on the hands, and even cause secondary injuries [14]. In conclusion, the soft wearable hand function rehabilitation device is a more appropriate choice. Considering that the rehabilitation training requires bi-directional force for the joints, we choose fluidic driving instead of cable. Because the weight of the rehabilitation exoskeleton should be borne by the participants in training, the pneumatic driving is finally selected in order to reduce the weight of exoskeleton as much as possible comparing to the hydraulic driving mode.

In this study, we used a kind of pneumatic actuator called guided bending bellows actuators (GBBAs) as the driving mechanism of the rehabilitation glove [7], which can obviously provide bidirectional mechanical output and reduce the weight of the patient's hand compared to other flexible actuators. As shown in Fig. 1, at each finger joint, an independent actuator is configured to provide the force to make the finger joint bend. Connected to the glove through two fixed plates, the output force of the pneumatic actuator can be transmitted to the joints on both sides. When the internal output of the actuator is positive pressure, the output force at both ends acts as thrust, driving the finger to flexion, while the internal output of the actuator is negative pressure, the output force at both ends acts as pulling force, driving the finger to extension.

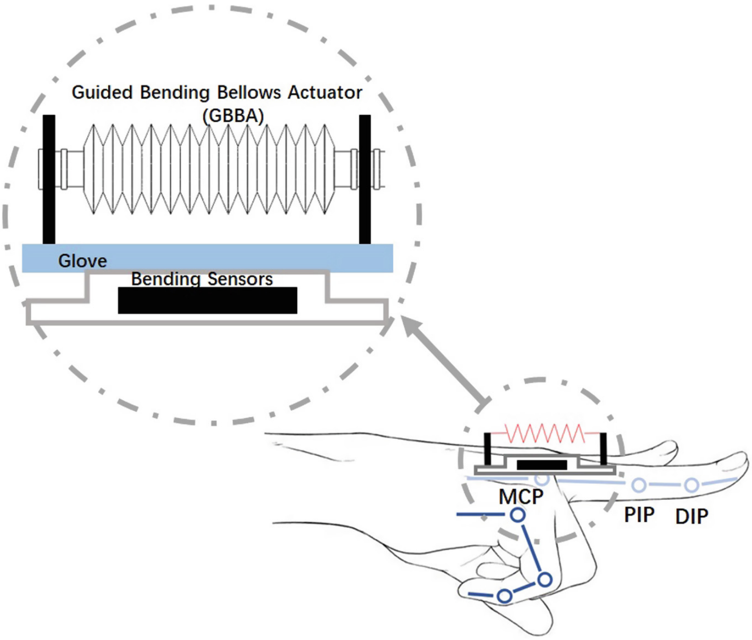

Fig. 1. Schematic diagram of the working principle of the soft exoskeleton with bending sensors.

In order to establish a motion perception network, we placed the bending sensors on the finger joints, including the interphalangeal (IP) and metacarpophalangeal (MCP) joints of thumb and the distal interphalangeal (DIP), proximal interphalangeal (PIP) and MCP joints of the other four fingers, as shown in Fig. 1. These sensors are constructed with a novel material that functions as an electrical semiconducting tape. This material is made of soft and flexible ethylene propylene rubber (Scotch Electrical Semi-Conducting Tape 13, 3M), and its impedance changes in response to bending. The effectiveness of this material as a bending sensor has been evaluated in our previous works [15, 16].

During hand function rehabilitation training, the pneumatic actuator provides pushing or pulling force at both ends according to the change of internal pressure. These output forces are transmitted to the fingers on both sides of the knuckle through the fixed plate to drive the joint to rotate. The flexible film bending sensor embedded in the glove follows the finger motion to generate corresponding bending changes, thus obtaining real-time data on the knuckle bending.

2.2 Working Principles of Control System

The control system of the soft rehabilitation glove can perform both open-loop control by setting the rehabilitation intensity, and closed-loop control based on the feedback provided by the sensor network in the system. The entire control system can be categorized into three distinct routes, including the information route, the electric circuit route and the gas route. These routes correspond to the transmission of control signals, electric energy and gas flow direction in the system, respectively. Figure 2 depicts the physical diagram of the lower controller and gas drive system based on the three schematic routes.

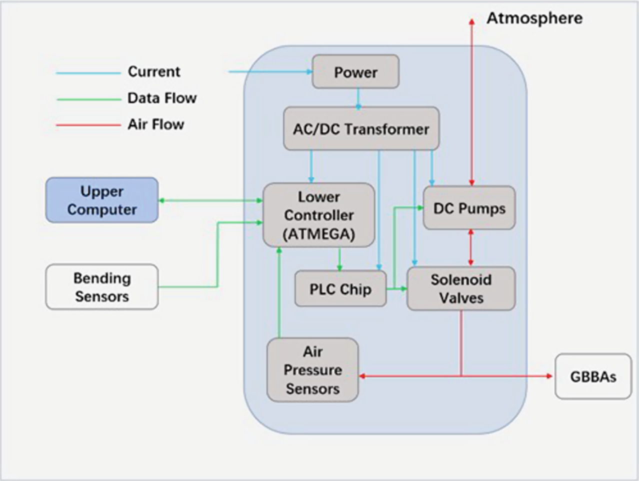

Fig. 2. Schematic diagram of control system.

The open-loop control system functions by transmitting control signals from the upper computer to the lower controller (AT-MEGA328P-AU) via the serial port. The lower controller then sends the processed analog signals to the PLC drive chip (Macrowis, 4 WAYs), which activates the pneumatic components, including drive pumps (Chaofei, ES-3910, DC24V) and solenoid valves (OST Solenoid 2/2 NC, 24V). The system's air pressure sensors and bending sensors directly send signals to the lower controller for collection. To power the system, the AC power supply (JC Power, 24V 72W) converts electrical energy into 24V DC power, which is used by the PLC chip module, DC pumps and solenoid valves. The compressed or vacuum gas is transferred from the compression and vacuum pump to the main gas route via two parallel solenoid valves. A manual flow valve is located after the solenoid valves to maintain stable flow rates in the gas circuit. Ultimately, the control instructions issued by the upper computer are carried out by passing compressed or vacuum gas through GBBAs with the cooperation of the control system's modules.

In the closed-loop system, the self-developed soft bending sensor network mentioned above mainly provides rehabilitation state awareness. By detecting the real-time angle of the corresponding knuckles through the bending sensor, the angle change trend of each knuckle can be calculated [17, 18], and compared with the input command of the pneumatic system, the patient's motion trend can be obtained. The input signal of the pneumatic generating system (input air pressure, duration, etc.) will be passively adjusted according to the patient's motion trend [4, 19], which not only prevents secondary damage to the patient's knuckles by the rehabilitation equipment, but also improves the recovery efficiency.

3 Results

In order to test the performance of a single GBBA, we measured its displacement changes during inflation and extraction. The results are shown in Fig. 3. Considering the original length of GBBA, it is clear that its elongation ratio exceeds 200%. This elongation ratio ensures that the fingers can move in a large range driven by the soft exoskeleton. Then we evaluated the measurement characteristics of a single bending sensor. As shown in Fig. 4, bending sensor has high measurement accuracy, with mean absolute error (MAE) of 2.99°. It is acceptable for the measurement of hand motion.

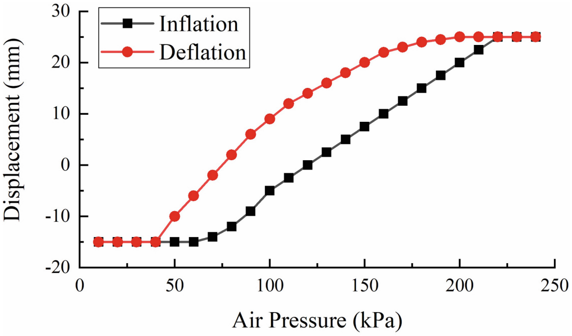

Fig. 3. The displacement change of GBBA during inflation and deflation.

Through the measurement of a single actuator and sensor, it is believed that the soft exoskeleton made up of these components would have good performance. In order to evaluate the performance of the soft exoskeleton, we designed a bionic finger model with three joints [7], and its total range of motion is 270°. We use soft exoskeleton to drive the finger model, and record the air pressure and motion amplitude. The result is shown in Fig. 5. It is obvious that the soft exoskeleton can achieve full range of motion. Due to the measurement error of the bending sensors, there may be an obvious error on

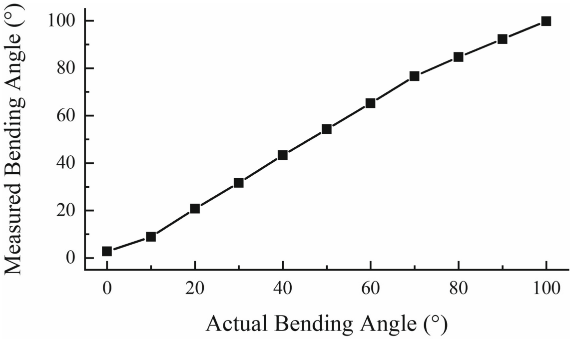

Fig. 4. Performance test of bending sensor.

angle measurement when the movement amplitude is large. However, there is no doubt that with motion perception network, the motion angle of each joint can be measured in real time, so as to estimate the motion state of the hand.

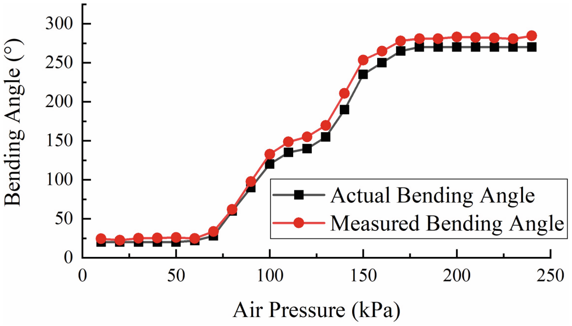

Fig. 5. Flexion of a finger model under soft exoskeleton.

4 Conclusions

In this study, we proposed a soft exoskeleton integrating bending sensor array as a perception network. At each knuckle, the exoskeleton is equipped with a pneumatic guided bending bellows actuator as the driving mechanism and a soft membrane bending sensor to collect motion information. As a novel wearable hand functional rehabilitation device with motion perception system, our exoskeleton not only provides patients with active rehabilitation training, but also obtains the motion trend during the training process and adjust the input signals of the pneumatic control system in time. The real-time detection of motion state and trends during rehabilitation training can both effectively avoid secondary injuries to patients and greatly improve rehabilitation efficiency.

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