A Novel Pneumatic Soft Exoskeleton Rehabilitation Glove for Extension Training to Hand Rehabilitation

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Abstract— **Recently, pneumatic soft robots have been widely applied in hand rehabilitation. This study proposes a pneumatic soft exoskeleton glove for finger extension training. The glove features a multi-air-chamber hip joint airbag design, driving finger extension from the palm's interior to its exterior. The accompanying inflation and deflation system has six outlets for airflow and adjustable pressure. The analytical model of the hand is built for understanding the structure and its motion. In addition, this describes the design and manufacturing method for the airbags. Then, a series of experiments on the output force of the exoskeleton proceeded to verify the exoskeleton. At an airbag pressure of 0.2 Bar, the output force is 3.65N; at 0.3 Bar, the output force increases to 10.46N. Ultimately, the effectiveness of this soft exoskeleton glove for finger extension training is verified through practical evaluation of the actual system.**

Keywords— **Pneumatic soft robots, Finger extension, Soft exoskeleton, Rehabilitation glove.**

I. Introduction

One vital component of the human body is the hand, providing powerful functionality that enables us to perform daily tasks. Unfortunately, stroke is a major contributor to severe and chronic disabilities that impair hand function. This can result in spasticity, abnormal muscle synergy[1], and impaired finger independence[2][1], making it challenging for stroke patients to perform basic activities of daily living(e.g., dressing, eating, and using the toilet). Hand disability can tremendously influence a patient's capacity to accomplish activities of daily living(ADL), which is why hand function rehabilitation is crucial for stroke patients. However, there is a shortage of rehabilitation personnel, and rehabilitation equipment is often complex and expensive. Therefore, designing a lightweight exoskeleton hand for ancillary training can significantly help the stroke-affected population.

In recent years, exoskeletons have become an essential assistive technology for hand rehabilitation, and many institutions have conducted related research[3-13]. For instance, the Hand Extension Robot Orthosis (HERO) Glove uses rope-like artificial tendons to assist finger extension[3]. A biomimetic finger extension mechanism was created by the Korea Advanced Institute of Science and Technology for soft wearable hand rehabilitation devices, which mimicked tendons to extend fingers[4]. Harvard University designed a Cable-Driven Finger Exercise Device With Extension Return Springs for Recreating Standard Therapy Exercises, utilizing cable drives and return springs for rehabilitation exercises[5]. The SMA-Based Soft Exo-Glove, developed by Carlos III University of Madrid, Spain, achieved hand flexion and extension through a tendon-like wiring system[6]. Exo-Glove Poly (EGP) II, developed by Seoul National University, utilized a tendon-driven system to assist hand gripping[7]. Such exoskeleton gloves, utilizing structures similar to ropes or cable[3-7], were capable of both flexion and extension. In terms of extension, these mechanisms typically apply force to the distal phalanges of the fingers, thereby driving the Metacarpophalangeal (*MCP*) Joints through the Interphalangeal (*IP*) joints. However, natural hand movement starts from the Metacarpophalangeal Joints and then moves to the Interphalangeal Joints. These structures do not align with the natural extension characteristics of the human hand, potentially leading to excessive shear stress on the Interphalangeal Joints. Leading to discomfort for the patient and even potentially causing damage to the patient's muscles and joints[8]. This misalignment highlights a crucial aspect of exoskeleton design: the need for a more anatomically accurate and biomechanically sympathetic approach to support the natural movements of the hand.

Air-pneumatic-driven soft exoskeleton devices for hand rehabilitation provide lots of advantages including enhanced security, convenience, and comfort for users. These devices enable a wide range of motion and smooth curves, thanks to their innovative design[9]. These exoskeletons are principally focused on helping users with gripping functions and improving finger flexion capability[10-13]. For example, Seoul National University developed the Exo-Glove PM, a customizable soft pneumatic assistive glove designed to train patients in grasping[10]. ETH Zurich proposed the FWearable Actuated Soft Exoskeleton, which can generate four common types of grasps, enhancing the grasping ability of individuals with hand dysfunction[11]. The National University of Singapore developed a soft exoskeleton for hand assistive and rehabilitation applications using variable stiffness pneumatic actuators, enabling hand grasping and pinching[12]. The "A Soft Robotic Glove for Hand Rehabilitation using Pneumatic Actuators with Jamming Structure," developed by Nanjing

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University of Posts and Telecommunications, featured a design of a soft pneumatic actuator coupled with a granular jamming system. This innovative approach enabled the glove to assist in grasping objects[13]. These types of exoskeletons, when not inflated, can assist in finger extension through their inherent stiffness. However, there is no additional force to drive the Metacarpophalangeal Joints, the force helping finger extension is relatively small and may not achieve full extension effectively.

This study introduces a novel pneumatically-driven soft exoskeleton glove based on silicone airbags. The design fully leverages pneumatically-driven soft exoskeleton devices' flexibility, comfort, and safety for hand rehabilitation. When inflated, the airbags expand from the inside out, pushing the fingers to extend. This applies a uniformly distributed force across the entire length of each finger, aligning with the natural movement characteristics of the fingers. This approach ensures efficient, comfortable, and safe finger extension rehabilitation training, providing a more effective and user-friendly solution than traditional exoskeleton designs.

The remainder of the paper is structured as follows: Section 2 introduces the design requirements for the soft exoskeleton rehabilitation glove. Section 3 describes the design and manufacturing methods of the pneumatic soft exoskeleton glove. Section 4 presents the experimental platform construction and results, respectively. Ultimately, the conclusion is presented in Section 5.

II. DESIGN REQUIREMENTS

A. Skeletal Structure of Human Hands

The skeletal structure of the hand is composed of three main parts: carpal bones, metacarpal bones, and phalanges. The thumb is made up of two phalanges - the proximal and distal phalanges. The other four fingers comprise the proximal, middle, and distal phalanges. Fig.1 displays the skeletal structure of human hands.

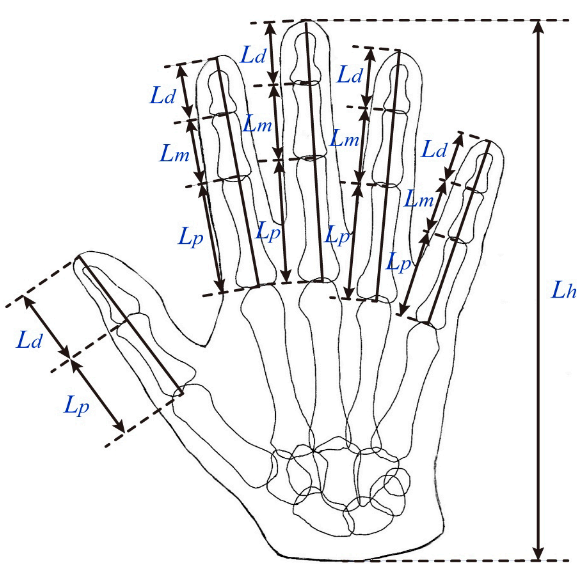

Fig.1. Skeletal Structure of Human Hands

In Fig.1, L_h is the length of the whole Hand, L_f is the length of each finger (thumb, index, middle, ring, small), L_p is the length of the Proximal Phalanges of each finger, L_d is the length of the Distal Phalanges of each finger, L_m is the lengths of the Middle Phalanges of each finger.

It is crucial to know the skeletal structure and dimensions of the hand when designing rehabilitation gloves, as this will help determine the size of both the glove and the driver. Ninety percent or more of individuals have Lengths of Hands (L_h)from 16.8 cm to 20.8 cm[14]. TABLE 1 presents the segmented lengths of each finger.

TABLE 1. SEGMENTED LENGTHS OF EACH FINGER (MODIFIED FROM[15])

	L_p	L_m	L_d
Thumb Finger	$0.251L_h$	/	$0.158L_h$
Index Finger	$0.245L_h$	$0.143L_h$	$0.097L_h$
Middle Finger	$0.266L_h$	$0.170L_h$	$0.108L_h$
Ring Finger	$0.244L_h$	$0.165L_h$	$0.107L_h$
Small Finger	$0.204L_h$	$0.117L_h$	$0.093L_h$

Therefore, the length of each finger can be described as follows:

$$L_f = L_p + L_m + L_d \tag{1}$$

B. Kinematic Analysis of Fingers

The joint between the metacarpal bones and the phalanges is known as the Metacarpophalangeal Joint, while the joints between the phalanges are referred to as the Interphalangeal Joint. The Metacarpophalangeal Joint enables the proximal phalanx Flexion/Extension(*f/e*) and abduction/adduction(*a/a*) movements. The Metacarpophalangeal Joint has two Degrees of Freedom (*DoF*). In contrast, the Interphalangeal Joint has just one Degree of Freedom, allowing the distal phalanx Flexion/Extension motion[16].

TABLE 2 provides the range of motion(*ROM*) for the thumb, and

TABLE 3 lists the range for the other fingers. Fig. 2 shows the flexion angles for each finger. Fig. 3 illustrates the extension angle for the thumb and the extension angles for the other fingers.

In Fig. 2, θ_{PIP} is each finger's angular rotation of the Proximal Interphalangeal Joint(*PIP*), excluding the thumb. θ_{DIP} is each finger's angular rotation of the Digital Interphalangeal Joint(*DIP*), excluding the thumb. θ_{MCP} is each finger's angular rotation of the Metacarpophalangeal Joint, excluding the thumb. $\theta_{IP(T)}$ is the thumb's angular rotation of the Interphalangeal Joint. $\theta_{MCP(T)}$ is the thumb's angular rotation of the Metacarpophalangeal Joint.

TABLE 2. *ROM* OF THUMB JOINT ANGLES(MODIFIED FROM[17])

Joint angular coordinate	Maximum flexion	Maximum extension
$\theta_{IP(T)}$ [°]	90	20
$\theta_{MCP(T)}$[°]	60	20

TABLE 3. ROM OF FINGERS JOINT ANGLES (EXCLUDING THUMB FINGER) (MODIFIED FROM[17])

Joint angular coordinate	Maximum flexion	Maximum extension (passive)
θ_{PIP}[°]	100	0

θ_{DIP} [°]	60	5
θ_{MCP} [°]	90	20(70)

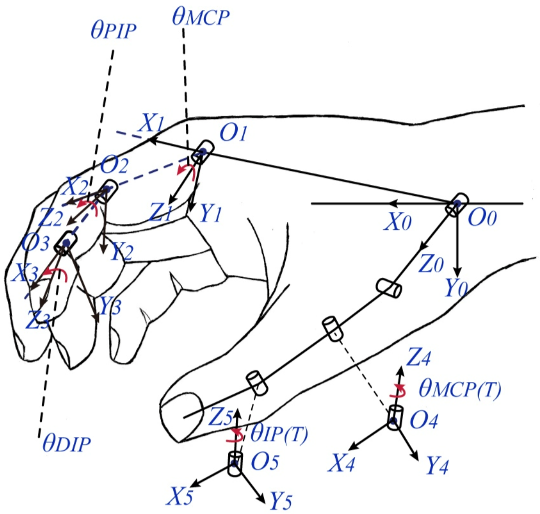

Fig. 2. Flexion angles for each finger

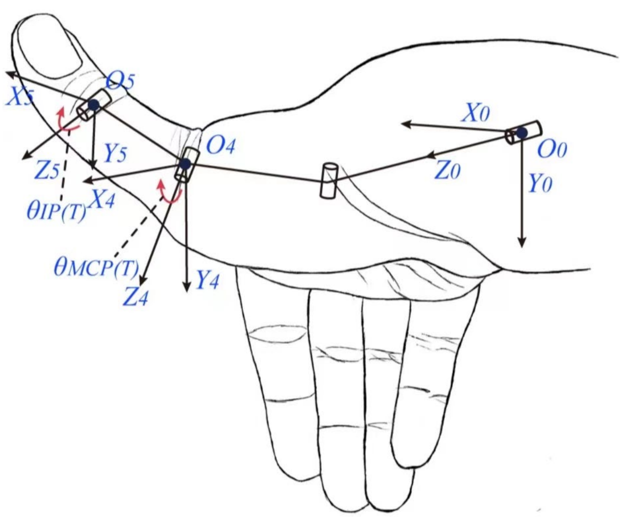

Fig. 3. Extension angle for the thumb

In Fig. 3, $\theta_{IP(T)}$ is the thumb's angular rotation of the Interphalangeal Joint. $\theta_{MCP(T)}$ is the thumb's angular rotation of the Metacarpophalangeal Joint.

In Fig. 4, θ_{PIP} is each finger's angular rotation of the Proximal Interphalangeal Joint, excluding the thumb. θ_{DIP} is each finger's angular rotation of the Digital Interphalangeal Joint, excluding the thumb. θ_{MCP} is each finger's angular rotation of the Metacarpophalangeal Joint, excluding the thumb.

For the Soft Exoskeleton Rehabilitation Glove, two Degrees of Freedom are required at the Metacarpophalangeal Joint, and one Degree of Freedom is necessary at the Interphalangeal Joints. The dimensions of the finger flexion/extension structure in a soft exoskeleton need to be greater than the Lengths of the fingers (*Lf*) to accommodate most users.

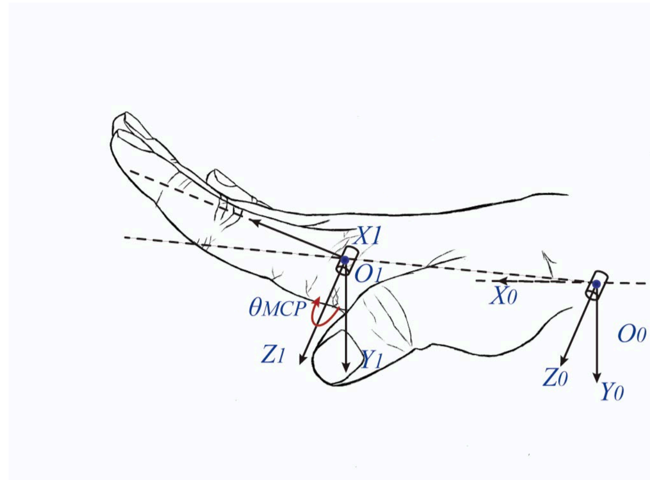

Fig. 4. Extension angles for the other fingers

III. Design and Manufacture of the Exoskeleton Rehabilitation

A. *Design of The Exoskeleton Rehabilitation*

The Computer-Aided Design (*CAD*) model of the soft exoskeleton rehabilitation glove is depicted in Fig. 5. The soft exoskeleton rehabilitation glove consists of seven main modules, which include the glove body (*Module 1*), thumb airbag (*Module 2*), index finger airbag (*Module 3*), middle finger airbag(*Module 4*), ring finger airbag(*Module 5*), small finger airbag(*Module 6*), and palm airbag(*Module 7*). The design of each finger airbag is similar. Interconnected air compartments are included in each finger airbag, enabling overall expansion while constrained by the compartments' walls. This design ensures relative independence in the expansion of each chamber, aligning with the joints between the Metacarpophalangeal and Proximal Interphalangeal Joints, thereby facilitating joint extension. A physical photo of the exosoft glove system is shown in Fig. 6.

The system consists of the exoskeleton gloves and the air pump.

B. *Manufacture of Chamber(Set Middle Finger as an example)*

The finger airbags, serving as the primary actuators of the pneumatic soft exoskeleton glove for finger extension provide the force necessary for finger extension. This section discusses the airbags' structural design and manufacturing methods, which feature a multi-chambered design to facilitate joint movement, using the middle finger airbag as an instance.

The CAD design print of the middle finger airbag is illustrated in

Fig. 7, and the cross-sectional view is shown in Fig. 8. There are a total of four air chambers in the middle finger airbag. The middle finger airbag (Module 4) consists of four air compartments. Chamber 1 covers the distal phalanx of the middle finger, chamber 2 covers the Interphalangeal Joint of the middle finger, champer 3 covers the Proximal Interphalangeal Joint of the middle finger, and chamber 4 covers the Metacarpophalangeal Joint of the middle finger. The size of the chambers is shown in Fig. 8.

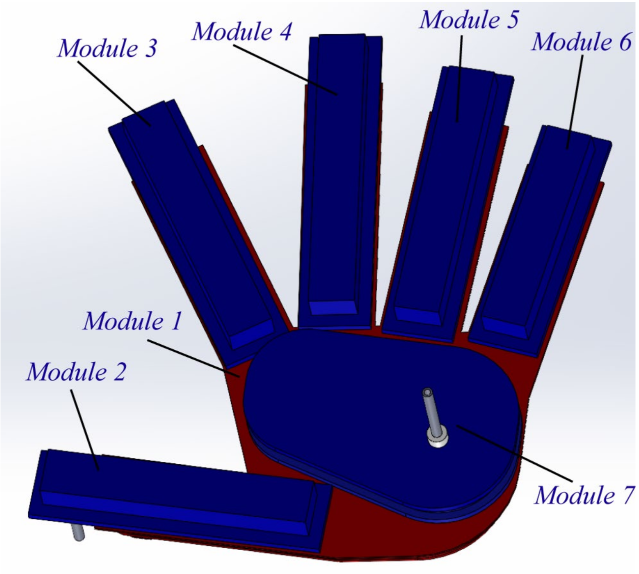

Fig. 5. CAD model of the soft exoskeleton glove

In Fig. 8, L_{c1} is the length of chamber 1, L_{c2} is the length of chamber 2, L_{c3} is the length of chamber 3, and L_{c4} is the length of chamber 4.

To make the chambers fit the joints of the hand, the lengths of the chambers should vary by the changes in the joints. The equations for the lengths are as follows:

$$L_{c1}=20mm+2/3_{Ld} \tag{2}$$

$$L_{c2}=1/3_{Ld}+1/2_{Lm} \tag{3}$$

$$L_{c3}=1/2_{Lm}+1/2_{Lp} \tag{4}$$

$$L_{c4}=1/2_{Lp} \tag{5}$$

3D printing technology has been widely applied in the field of manufacturing rehabilitation aids, including craniofacial repair[18], facial rehabilitation[19], and joint trauma treatment and repair [20]. In the manufacturing process of the soft exoskeleton rehabilitation airbags, the method of 3D-printed silicone molds is also employed, with the specific steps as follows:

- Pour silicone into the mold of the airbag cavity, then allow it to air dry naturally at room temperature (20°C), and finally remove it from the mold.
- Inject silicone into the baseplate mold.
- Place a non-woven fabric cut to fit the mold's dimensions inside. Let it air dry at room temperature (20°C).
- Insert the baseplate into the assembly mold, and add another silicone layer.
- Immediately place the structural part of the airbag on top of it, then let it air dry.

In Fig. 9, shows the manufacturing process of the middle finger airbag.

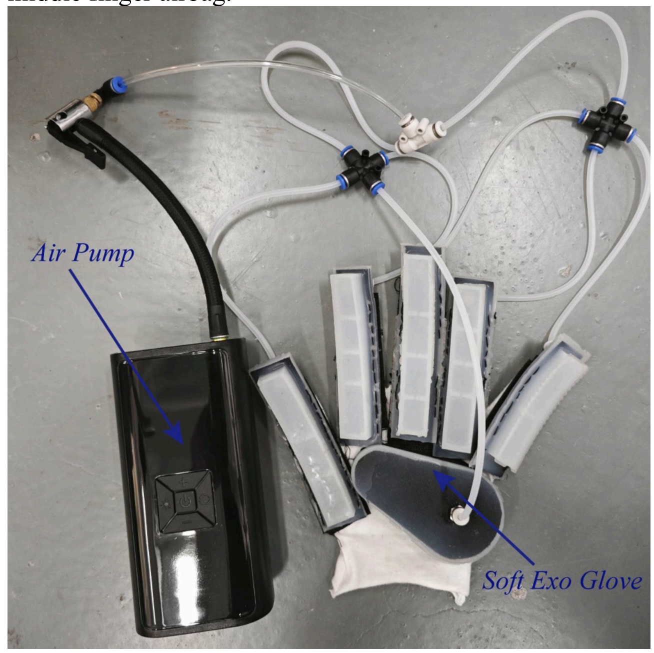

Fig. 6. The soft exoskeleton rehabilitation system

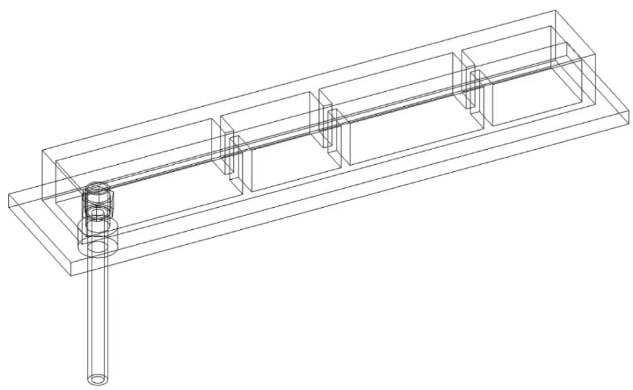

Fig. 7. Middle finger airbag's CAD design

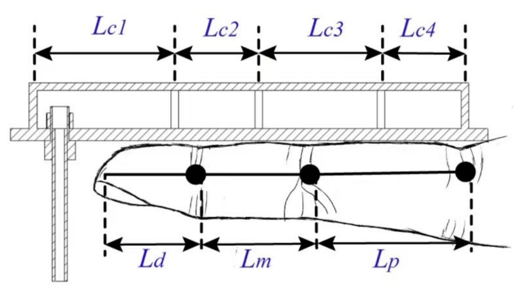

Fig. 8. Cross-sectional view and size of the chambers

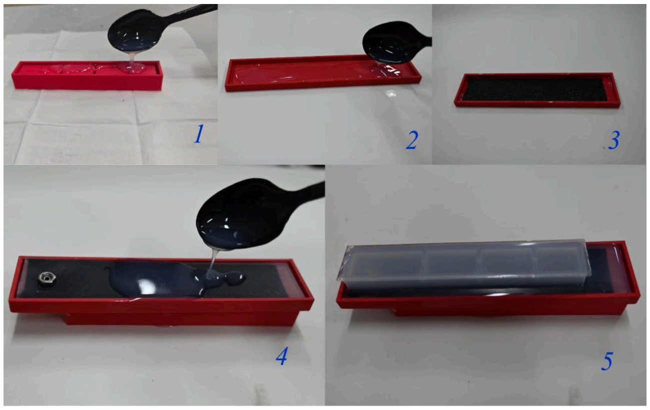

Fig. 9. Manufacturing process of the middle finger airbag

IV. EXPERIMENTS

Two experiments were performed to verify this soft exoskeleton glove's effectiveness. To observe the airbag's deformation, the first experiment involves inflating the chamber with varying pressures without applying external force. The second experiment involves simulating the chamber's application on a finger to evaluate the extent of deformation. The specific force exerted by the chamber on the finger is determined through measurement and calculation.

A. Observation of Balloon Deformation Without External Force

In this experiment, airbags are inflated with pressures of 0.2 Bar, 0.25 Bar, and 0.3 Bar, respectively, to observe the deformation of the airbags under different pressures.

Fig. 10 illustrates the deformation of the exo soft glove middle finger airbag under different air pressures. It is obvious that the more the pressure, the greater the deformation of the airbag, which can apply more force to the of fingers.

Fig. 10 Shape of the airbag at 0.2Bar, 0.25Bar, 0.3Bar

B. Simulation of airbag's Deformation Effect on the Finger

To demonstrate that the pneumatic soft exoskeleton glove can extend the fingers, this experiment conducts a force analysis on the finger airbag and calculates the lifting force exerted on the finger by the airbag under different air pressures. (This experiment uses the middle finger airbag as an example.)

Fig. 11 demonstrates that, given the constraints imposed by the air chamber partitions and the dorsal non-woven fabric, the entire inflated structure can be accurately modeled as a system consisting of four rigid linkages. Since the airbag chambers are interconnected, the internal air pressure is equal, resulting in a uniformly distributed force. The regular forces exerted by the four linkages can be represented as F_{c1}, F_{c2}, F_{c3}, and F_{c4}. When applied to the finger, the Interphalangeal Joints of the finger, which have a limited range of deformability, can be approximated as a rigid body. As shown in Fig. 11 the finger is subjected to a normal force F_e. This model helps understand how the airbag exerts force on the finger, facilitating the design and optimization of the exoskeleton for practical and comfortable finger extension.

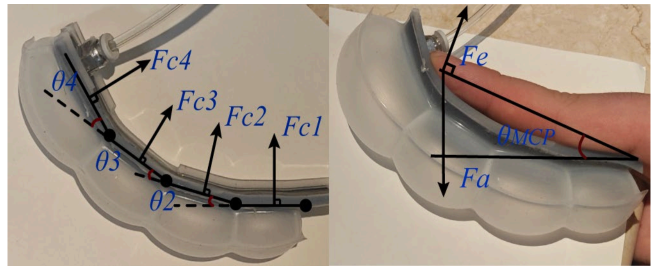

Fig. 11. Force analysis of the finger airbag

The relationship between F_{c1}, F_{c2}, F_{c3}, F_{c4} and F_e is shown by the following equation:

$$F_{c1}+F_{c2}cos\theta_2+F_{c3}cos(\theta_2+\theta_3)F_{c4}cos(\theta_2+\theta_3+\theta_4)$$
$$=F_e cos\theta_{MCP} \quad (6)$$

After the airbag expansion, it can be regarded as four rigid bodies, θ_2, θ_3, and θ^4, which are the angles between the rigid body and the adjacent rigid body respectively. Therefore, the left figure Fig. 11 shows the force the airbag applied on the finger, and the figure represents the approximate force.

To calculate the specific magnitude of F_e, we can determine the vertical component of F_e, labeled F_a, and measure the angle at the Metacarpophalangeal Joint. The equation to calculate F_e is as follows:

$$F_e = F_a / cos\theta_{MCP} \quad (7)$$

TABLE 4 provides the F_a at 0.2 Bar, 0.25 Bar, and 0.3 Bar. The F_a in the table are the results of averaging five measurements. Using equation 8, the specific values of F_e at different air pressures are calculated.

TABLE 4. THE NUMERICAL VALUE OF F_a AND F_e

Air pressure	F_a(N)	θ_{MCP}(°)	F_e(N)
0.2Bar	3.43	20°	3.65
0.25Bar	5.10	30°	5.89
0.3Bar	8.57	35°	10.46

Consequently, with the airbag's air pressure set at 0.2 Bar, the F_e is 3.65N. When the air pressure is increased to 0.25 Bar, the F_e is 5.89N. When the air pressure is increased to 0.3 Bar, F_e rose sharply to 10.46N. Fig. 12 shows the pneumatic exoskeleton glove worn on a participant's hand with an air pressure of 0.25 Bar. From Fig. 12, it is obvious that this pneumatic exoskeleton glove can extend all five fingers of the participant.

Fig. 12. The glove worn on the participant's hand

V. Conclusion

The rehabilitation of hand functions is a long and difficult process. Due to the lack of rehabilitation devices to assist in finger extension, it is challenging for stroke patients to recover finger extension function. This pneumatic soft exoskeleton glove, characterized by its lightweight, portability, and safety, can help stroke patients in training for finger extension. Subsequently, a sequence of experiments focusing on the output force of the exoskeleton was carried out to validate its functionality. With the airbag pressure set at 0.2 Bar, the output force registered at 3.65N; when the air pressure was increased to 0.3 Bar, the output force rose sharply to 10.46N. Finally, an assessment of the real-world system was performed to confirm the effectiveness and practical application of this soft exoskeleton glove in facilitating finger extension training. To precisely determine the variations depending on the varying degrees of participation, we will test the suggested approach on a larger number of patients and healthy subjects in our follow-up studies, improving the rehabilitation efficacy eventually.

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