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A Wearable Soft Device for Assistance in Arm and Hand Rehabilitation

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Abstract: Animal bodies are mainly constructed from highly soft and deformable structures such as muscles, and skin. Such structure permits them to create gentle contact with their surrounding environment and other creatures. Inspired by animal muscle, pneumatic soft actuators that are constructed mainly from soft and deformable materials such as silicone rubbers, and polymers can bend as inflated. Using soft actuators instead of rigid ones such as cylinders, motors, and rigid mechanisms to form mechanisms or devices that interact with humans will bring benefits regarding safety. In this research, we proposed a wearable soft device that is activated by a soft pneumatic actuator for arm and hand rehabilitation support.

Background: The hand rehabilitation glove is equipped with five soft actuators attached to a fabric glove, aligned along the back of each finger. These actuators are at least as long as the fingers themselves. When air is pumped into them, they bend toward the palm, causing the fingers to curl. The elbow rehabilitation system uses two soft actuators arranged in parallel on the back of the elbow. Due to the greater force needed for elbow flexion, a pair of actuators is required. The mechanism works similarly to that of the hand, but since the elbow bends in a V-shape, the actuators are restricted at both ends, about one-third of their length, enabling them to form a V-shape when inflated.

Materials and Methods: The rehabilitation device for supporting arm muscle recovery and hand movements utilizes actuators made from soft, user-friendly materials that are completely safe for the user. The entire device is constructed from rubber, silicone, and fabric. The actuators were fabricated from Dragon Skin 20 silicone rubber. To create the segmented, chambered structure, liquid silicone was mixed in a 1:1 weight ratio of type A and B, then degassed in a vacuum chamber before being poured into a 3D-printed mold. The silicone was cured at room temperature (22°C) for 4 hours. All mold components were designed in SolidWorks and printed using a 3D printer. After curing, the actuator parts were removed from the mold and assembled using silicone epoxy.

Results: A wearable soft rehabilitation device, incorporating pneumatic actuators, was engineered and produced to assist with arm and hand recovery. Its distinct design, featuring a segmented actuator chamber and soft, pliable materials, has demonstrated significant potential in facilitating a variety of rehabilitation tasks, such as grasping, arm flexion, and elbow articulation. Controlled actuation allows for targeted movements while minimizing interference with other natural motions, ensuring that the rehabilitation process remains dynamic and adaptable to user-specific needs.

Conclusion: The soft actuators provided effective assistance across a range of motor tasks, both gross and fine, facilitating arm and hand support while preserving natural movement patterns. The system demonstrated its ability to offer localized support, enabling users to lift loads of up to one kilogram while ensuring optimal comfort and usability.

Key Word: **Soft actuator; Rehabilitation; Wearable device; Soft glove.**

I. Introduction

According to the World Health Organization (WHO), stroke causes 6.2 million deaths annually, more than the combined total of deaths caused by AIDS, tuberculosis, and malaria. In addition to its fatal impact, stroke also results in severe consequences, leading to long-term disabilities such as hemiplegia and impaired motor function in the limbs, including the hands and fingers [1,2,3]. Besides stroke, other conditions such as joint diseases, injuries affecting the nervous system (e.g., brain trauma, spinal cord injuries, brachial plexus injuries, and sensory nerve damage) also cause patients to lose control of their limbs or other muscles in the body, particularly the hands, which are among the most important parts of the human body. The hand plays a crucial role in grasping and performing most daily tasks; therefore, the loss or impairment of hand function significantly affects the patient's quality of life. In addition to surgery, the rehabilitation exercises have a positive impact on patient health[4]. Rehabilitation is a goal-oriented medical solution aimed at helping individuals recover from illness, injury, or surgery. After undergoing the rehabilitation process, patients can regain their physical and mental abilities. Since then, they have been able to enhance their quality of health and reintegrate into their daily normal activities. The rehabilitation process encompasses a wide range of therapeutic interventions designed to restore the functionality of some parts of the human body or the full body. Moreover, the rehabilitation process is not limited to physical recovery but also addresses emotional, psychological, and cognitive aspects to ensure holistic well-being. For the hand functional restoration process, the rehabilitation exercises include simple actions from opening and closing each finger to complicated motions such as grasping various objects and stimulating the muscles and nerves of the hand and fingers to enhance flexibility[5,6]. However, rehabilitation exercises require repetitive processes and the long-term assistance of medical staff, which can lead to money-wasting and time-consuming.

Clinical studies have shown that stroke patients who receive robotic assistance in performing high-intensity repetitive movements experience significant improvements in hand motor functions. Several robotic rehabilitation systems have been developed for hand rehabilitation, including multi-degree-of-freedom exoskeletons. Most of these devices require the biological joints to be aligned with the joints of the exoskeleton, while only a few feature passive degrees of freedom or self-adjusting capabilities. These systems are often expensive and designed for clinical use as they are generally not portable. Additionally, most robotic devices require the supervision of experienced personnel to ensure patient safety. However, their rigid mechanical design makes them reliable devices capable of applying high forces, which are necessary for challenging rehabilitation scenarios. Recently, some hand rehabilitation designs have followed an alternative approach to traditional exoskeletons. These designs incorporate soft gloves with cables connected to the fingers, controlled by motors located away from the hand.

Rehabilitation for individuals recovering from injuries or neurological conditions often requires intensive, repetitive therapy to restore mobility, strength, and coordination. Traditional methods of rehabilitation can be time-consuming and physically demanding for both patients and therapists. To address these challenges, the wearable devices have emerged as a promising solution in the field of rehabilitation technology [7,8,9,10]. These devices are often designed to be lightweight, flexible, and comfortable. Since then, they could provide patients with assistive therapy that supports their arm and hand movements. In recent years, there has been a lot of research focusing on developing these types of devices in different aspects[11,12,13,14,15].

The rest of the paper is organized as followings: Section II describes the material and methods of the research. In Section III, the experimental results of the proposed system are analyzed in-depth via different cases. Finally, Section 5 illustrates the general conclusion.

II. Material and Methods

2.1 The mechanical system design

The rehabilitation device for assisting the movement of arm and hand utilizes soft actuators operated by pneumatic systems. These soft actuators are made from fabric, rubber, or silicone, offering higher user-friendliness and safety compared to traditional rigid mechanical systems. Since the actuators are soft, each structure possesses numerous degrees of freedom, allowing the device to perform a wide range of motions with just a single power source (pneumatic or hydraulic), thus enhancing the device's flexibility. Furthermore, because the device operates on pneumatic or hydraulic systems, it overcomes issues such as motor overload, stepper motor slip, or over-rotation caused by control or actuator failures that could endanger the user. The device consists of two main components: soft rehabilitation glovers, soft rehabilitation elbow sleeve. The elbow movement assistance mechanism is composed of two parallel soft actuators, which increase the load-bearing capacity of the system when the user needs support in carrying heavy objects. The soft actuator designed to assist with elbow flexion is modeled and structurally optimized to meet the requirements for bending the elbow while holding an object weighing up to one kilogram

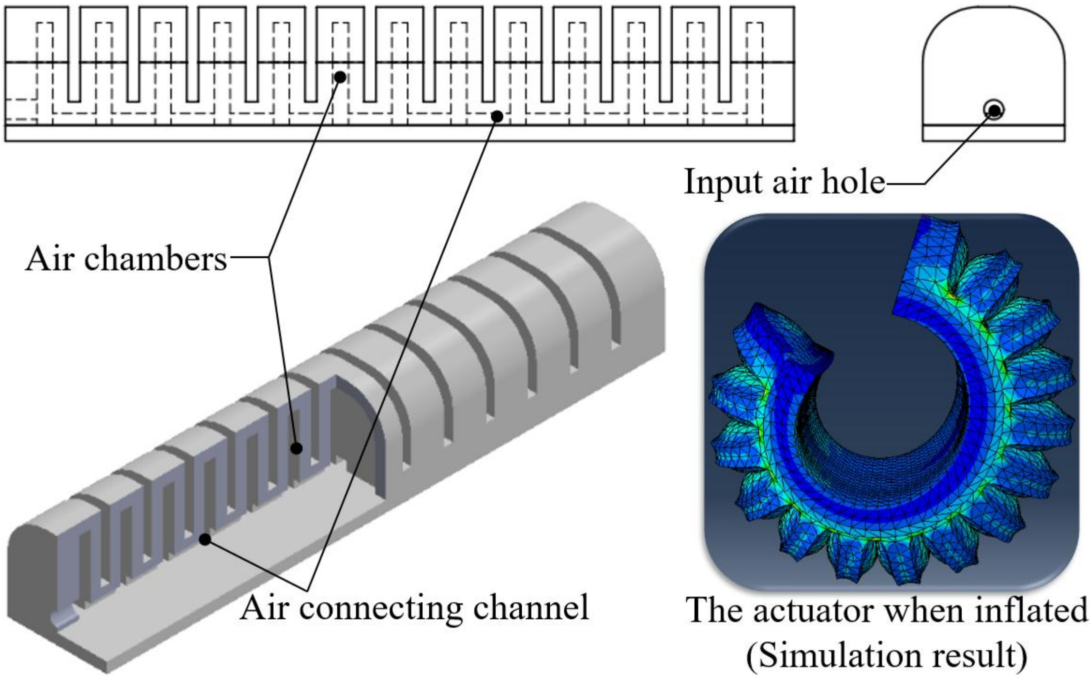

Fig. 1. Design of a pneumatic soft actuator and simulation result.

The soft actuators feature a segmented hollow chamber structure with a non-elastic surface, enabling bending motion in one direction when actuated by pneumatics, mimicking the bending motion of animal muscles. The bendable surface of the soft actuator contains hollow chambers connected by an air channel. The two side walls of the hollow chamber are made thinner than the other walls, allowing for easier deformation. When air is pumped into one end, all the hollow chambers are simultaneously actuated, causing the side walls of the chambers to stretch. Meanwhile, the non-streatchable surface on the opposite side remains unchanged in length. This combination results in the bending motion of the entire soft actuator as shown in Fig. 1 and Fig. 2.

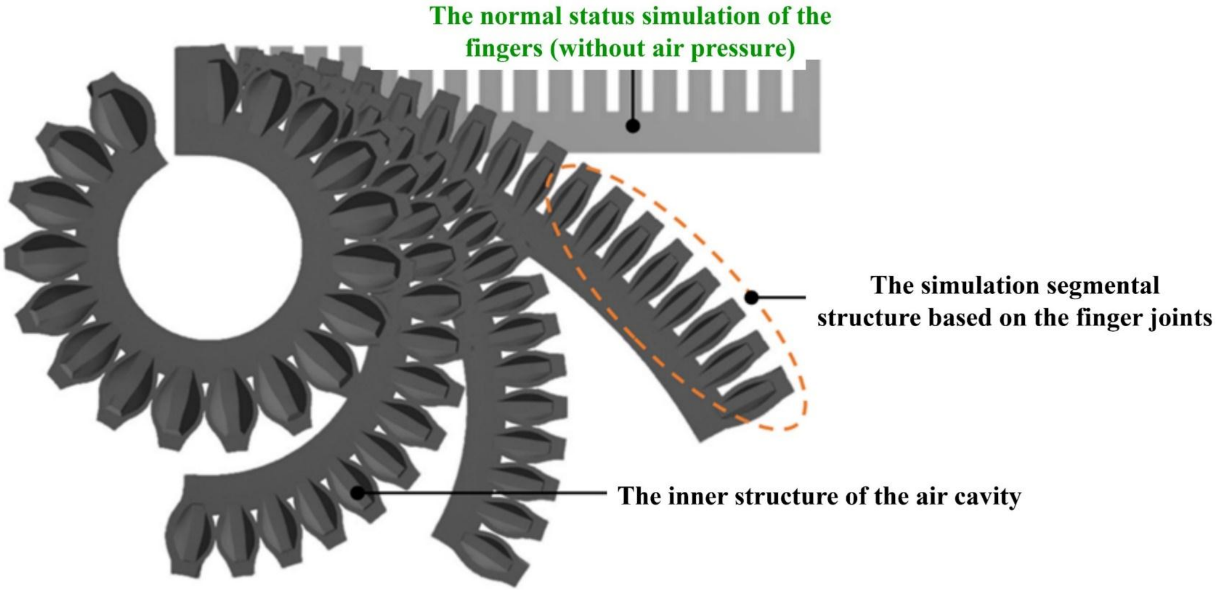

Fig. 2. Pneumatic soft actuator with segmented and chambered structure bending at different pressure

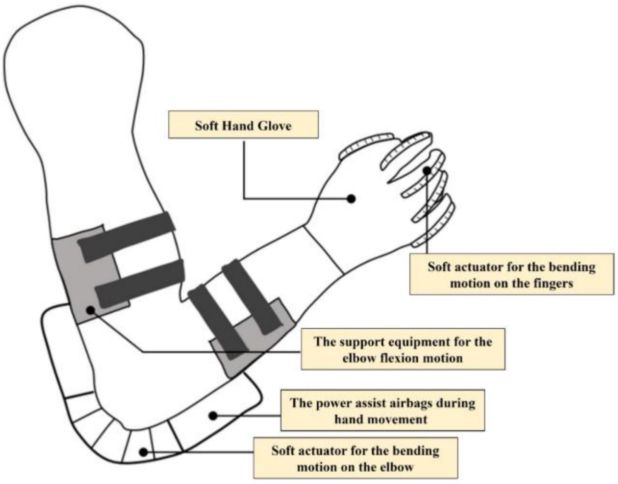

Fig. 3. Schematic of soft wearable device for assistance arm and hand rehabilitation

The degree of bending is determined by the air pressure inside the hollow chambers. Higher air pressure results in greater bending and load capacity. Therefore, controlling the movement of the soft actuators is relatively simple by adjusting a pressure-regulating valve. The hollow chamber structure will be designed to suit the biological characteristics and load requirements of specific body parts, including fingers and elbows. Detailed structures are described in the Fig. 3. The soft rehabilitation glove consists of a glove frame made from appropriate fabric, which can be worn on the wrist to securely attach the glove to the arm. Also, it employs five pneumatic soft actuators supporting the movement of five fingers. The actuators, functioning as fingers, are made of soft materials with reinforcement layers to enhance rigidity. These soft fingers are designed to be fixed to the glove frame and are structured, sized, and shaped to match each finger of users. They are pneumatically actuated through air tubes attached to the glove frame and can be operated independently or synchronously depending on the user's choice. The soft rehabilitation elbow sleeve is made up of two soft actuators placed parallel to each other to increase the load capacity of the mechanism when the user wants to use it to support the carrying of heavy objects. In order to change the curve deformation into a V-shaped deformation simulating the shape of an elbow, the two ends of the mechanism are constrained by a layer of un-stretchable fabric.

Since each finger is composed of phalanges (which do not perform bending motions) connected by joints (which perform bending motions), the soft actuator will be designed to match this structure. The hollow chamber and segmented design will be arranged at positions corresponding to the joints. When air is pumped in, only these locations will bend, while the other parts remain straight. The second method to create localized movements (deformations) as described above involves designing the hollow, segmented structure along the entire length of the soft actuator, then wrapping the non-elastic fabric around the actuator at the positions corresponding to the phalanges. This prevents bending at these points when the actuator is inflated.

2.2 The control system

The compressed air is sourced from a shared pump. The central controller regulates the air supply based on the user’s input by controlling the opening and closing of solenoid valves. Compressed air cannot be continuously pumped into the soft actuator, as this would cause excessive deformation or even damage the structure. Therefore, the air pressure within each actuator is controlled through a pressure-regulating valve. As a result, each air inlet to a soft actuator will have both a pressure-regulating valve and a solenoid valve. The diagram of control system is shown in Fig. 4.

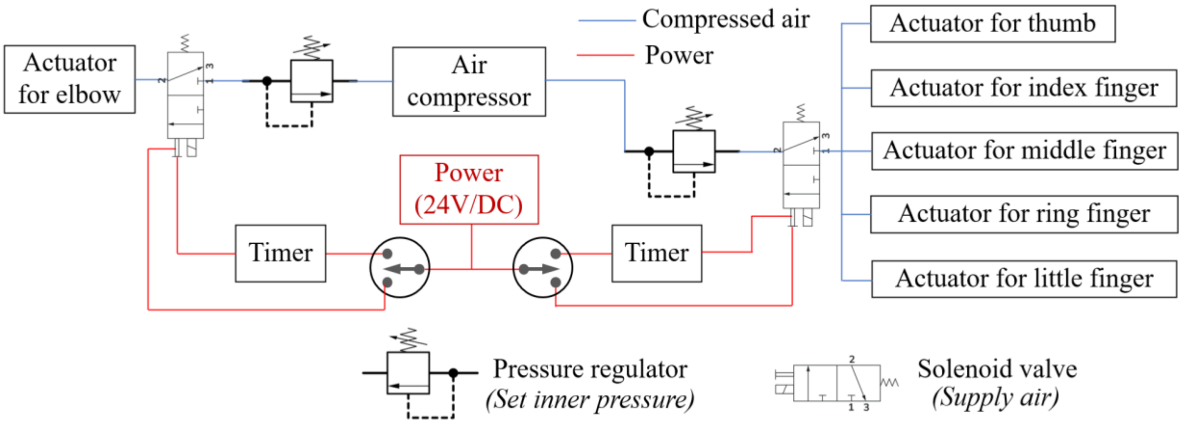

Fig. 4. Diagram of control system of the device

The compressed air is sourced from a shared pump. The central controller regulates the air supply based on the user's input by controlling the opening and closing of solenoid valves. Compressed air cannot be continuously pumped into the soft actuator, as this would cause excessive deformation or even damage the structure. Therefore, the air pressure within each actuator is controlled through a pressure-regulating valve. As a result, each air inlet to a soft actuator will have both a pressure-regulating valve and a solenoid valve. The diagram of control system is shown in Fig. 4.

2.3 The fabrication process

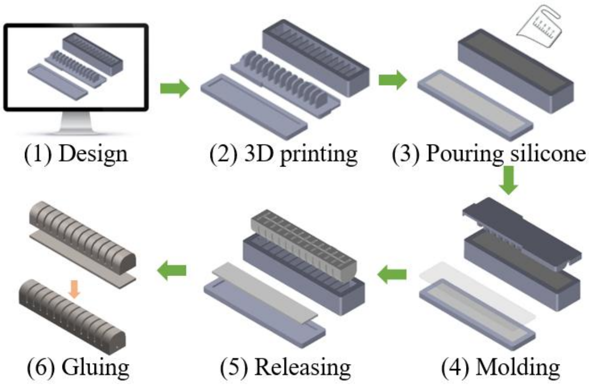

Figure 5. Fabrication process of the soft actuator

The actuators were made from silicone rubber Dragon skin 20 (Smooth-On, Inc., USA). The technical parameters of the silicone rubber Dragon skin 20 are indicated as in Table 1.

Table 1. technical parameters of the silicone rubber Dragon skin 20

No.	Parameter	Unit	Value
1	Mixed Viscosity	cps	20000
2	Specific Gravity	g/cc	1.08
3	Specific Volume	cu.in. /lb.	25.6
4	Pot Life	min	25
5	Cure Time	hour	4
6	Shore A Hardness	A	20
7	Tensile Strength	psi	550
8	100% Modulus	psi	49
9	Elongation at Break	%	620
10	Die B Tear Strength	pli	120
11	Shrinkage	in./in.	< .001

As shown in Figure 5, the fabrication process of the soft actuator consists of six steps in total. To begin with, the design of the soft actuator is established on the Solid Work simulation platform. Based on the designed drawing, the 3D printing procedure for the mold part is implemented. After finishing the printing step, the liquid silicon is poured into a 3D printed mold to form the segmented, chambered structure after mixing types A and B in a ratio of 1:1 in weight and re-gassing in a vacuum chamber. The liquid silicon in situ on the mold is cured at a room temperature of 22 degrees Celsius over 4 hours. After curing, the actuator parts were removed from the mold and glued together using a silicone epoxy (Sil-poxy, Smooth On, Inc., USA). After the fabrication stage, the actuators are assembled in a fabric glove and elbow sleeve to form the rehabilitation system. The finished fabricated system is shown in Fig. 6.

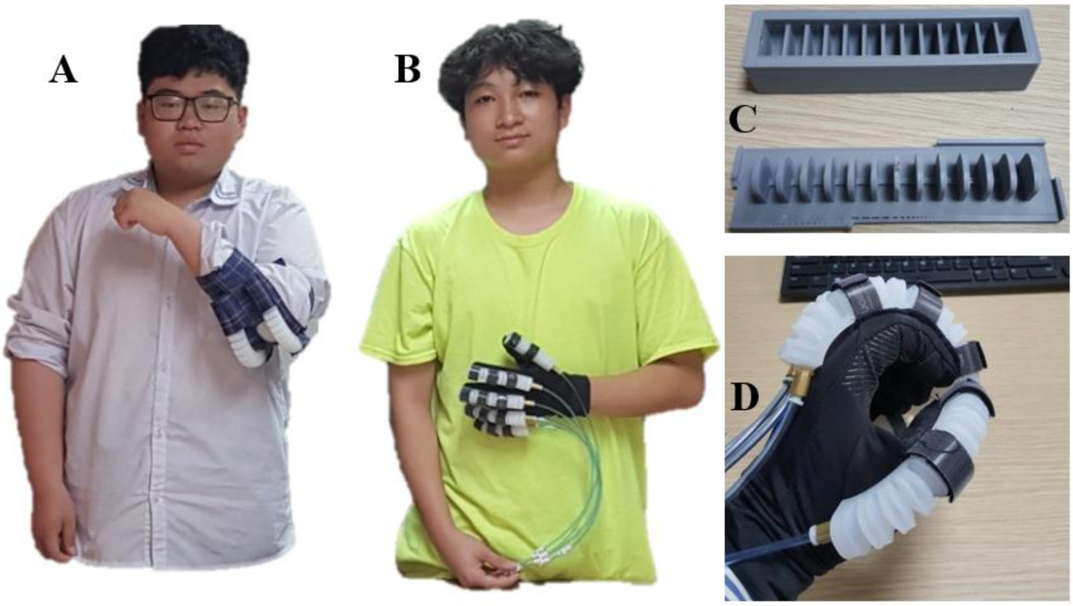

Figure 6. Fabricated device. A – Soft rehabilitation elbow sleeve in working condition. B – Soft rehabilitation glove. C – 3D printed mold. D – Soft rehabilitation glove in working condition.

III. Experimental Results

To evaluate the capability of the soft glove in assisting hand grasping, aiming to support individuals with disabilities, the soft glove was worn on a healthy hand as shown in Fig. 6 (D). Three pressure levels were activated corresponding to three grasping modes set in the control program, while the hand remained fully relaxed in a completely free state. The results indicated that the soft glove could be comfortably worn on the hand and effectively assist the user in grasping movements.

3.1. Elbow Movement Assistance

The first experiment aimed to quantify the elbow sleeve's ability to assist in elbow flexion and extension under passive and active conditions. The soft actuators were fitted onto the user's elbow, and the device was tested under two conditions. The first one is active mode where the user was instructed to voluntarily flex and extend the elbow without any assistance from the device. The elbow joint angles were recorded throughout the movement. The second one is passive mode. In this condition, the actuators were activated in rehabilitation mode, assisting the user in flexing and extending the elbow without any active input from the user. The movement was controlled by a central system regulating the air pressure to the actuators. The angles of elbow flexion and extension were compared between the two conditions to assess the impact of the device in providing support during passive rehabilitation.

Table 2: The bending angles Elbow bend angle at different pressures

No.	Air pressure (kPa)	The time response of the controller system (*ms*)	The bending angle (Degree)
1	0	0	0
2	5	500	10
3	7	500	20
4	9	500	30
5	12	1000	40
6	19	1000	50
7	25	1500	60
8	28	1500	70

Table 3: The bending angle of the thumb finger at different air pressures.

No.	Air pressure (kPa)	The time response of the controller system (*ms*)	The bending angle (Degree)
1	0	0	0
2	3	500	10
3	5	500	20
4	8	500	30
5	10	500	40
6	15	1000	50
7	18	1000	60
8	20	1000	70

3.2. Hand Movement Assistance

The second experiment evaluated the soft glove's ability to assist hand grasping. The glove was fitted onto a healthy participant’s hand (as shown in Figure 6), and three different pneumatic pressure levels were applied to simulate different grasping intensities. The experimental setup was as: (i) The subject was asked to relax their hand completely, leaving the glove to handle the entire grasping process. (ii) Three pressure settings were pre-programmed into the control system, corresponding to three different levels of hand grasping force (low, medium, and high). Each setting was tested sequentially, and the glove's ability to comfortably and effectively close the hand was observed. (iii) The primary metrics for evaluation included the range of grasp motion and the comfort level reported by the user. The glove’s ability to replicate natural grasping movements under varying pressure levels was analyzed.

The experimental results demonstrated that the soft actuators on the proposed system could effectively assisted both elbow and hand movements. In the elbow assistance test, the actuators provided adequate support in passive mode, allowing for smooth flexion and extension comparable to natural movement. Similarly, the glove enabled comfortable and controlled hand grasping, with users reporting minimal discomfort during operation. The load-bearing test confirmed that the actuators could support up to one kilogram of weight without compromising motion or user safety.

IV. Conclusion

In this study, we design a wearable soft device that leverages pneumatic actuators to assist with arm and hand rehabilitation. The device’s unique design, featuring a segmented actuator chamber and soft, flexible materials, has demonstrated its potential to support various rehabilitation tasks such as grasping, arm flexion, and elbow movement. Through controlled actuation, the device allows for specific movements while avoiding restriction of other motions, ensuring that rehabilitation remains dynamic and adaptable to the user's needs.

Experimental results showed that the soft actuators provided meaningful assistance in both gross and fine motor tasks, supporting the arm and hand without impeding natural motion. The system was able to achieve localized assistance, helping users lift up to one kilogram while maintaining comfort and ease of use.

Future work should focus on further optimization of the actuator design to enhance both strength and precision in movement assistance, as well as exploring more advanced control systems for improved user adaptability. This device presents a promising step forward in wearable technologies for rehabilitation, offering a soft and flexible alternative to traditional rigid mechanisms.

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