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Configurable Pneumatic Soft Actuators for Multi-Directional Wrist Rehabilitation

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***Abstract*— Due to their inherent compliance and safe interaction with their environment, soft robots play a significant role in wrist rehabilitation. However, current designs lack bending in multiple directions and have limited payload capacity. This article aims to explore various configurations of pneumatic soft fingers, specifically targeting the different bending directions of the wrist joint. A pair of parallel-connected soft actuators is mounted on the index and ring fingers to achieve extension and flexion movements by simultaneously pressurizing both actuators. Pronation and supination are achieved by activating two diagonally positioned actuators, while radial and ulnar motions are accomplished through two side-connected actuators attached to the little finger and thumb. A nonlinear static analysis based on the Yeoh model is conducted to validate the design while concerning its bending and deflection. A series of experiments is carried out to verify the bending and payload capacity of the pneumatic soft finger. The results show that it achieves a bending angle of 270°, while carrying a payload of 200 g. Moreover, the effectiveness of soft design is validated by bending a 660 g metal frame, which is designed to mimic a human hand, in multiple directions. Finally, four soft fingers were employed to successfully perform flexion deviation on a real human hand. This paper represents the initial phase of utilizing pneumatic soft fingers to achieve multiple wrist-bending movements.**

I. INTRODUCTION

Recently neurological disorders or injuries, such as stroke and spinal cord injuries (SCI), significantly impact the human nervous system, often leading to motor and sensory disabilities [1]. Stroke, one of the leading causes of disability worldwide, commonly results in hemiparesis, affecting the functionality of one side of the body. In Japan, it represents the fourth leading cause of death and requires continuous nursing care, significantly impacting society and the economy [2]. Upper limbs, including the hand and wrist, are particularly affected, with individuals frequently experiencing reduced strength and dexterity, which limits their ability to perform daily tasks [3]. The rehabilitation process is essential for improving hand-motor function and recovering a normal upper limb state [4]. Over the years, significant progress in the field of hand rehabilitation has been developed, including traditional rehabilitation assessments and wearable technologies. However, they still face challenges due to the complexity of hand movements [5].

Inspired by biological appendages, soft robots offer advantages as a rehabilitative device over classical rigid systems, including but not limited to safe interaction with humans, wearability, and enhanced joint alignment. Consequently, soft robotic systems have been widely developed for rehabilitating the hand. However, most of these systems have focused on fingers only, with less concern for the wrist [6]. In [7], a lightweight and soft wearable sleeve for wrist rehabilitation targeting pronation and supination deviations. In [8], [9], a wearable soft robotic hand was introduced for extension/flexion of the wrist. However, they provided a limited range of motion under high operating pressures. In [10], a design of wrist rehabilitation based soft parallel robot was proposed. The robot was able to perform three

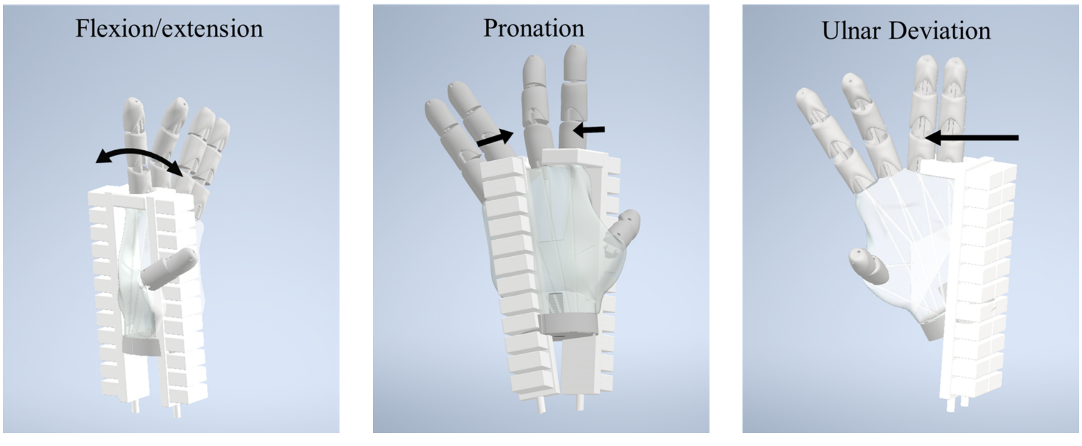

Fig. 1: Soft robotic for wrist rehabilitation

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rotational motions of the wrist, depending on pneumatic artificial muscles (PAMs) and a stepper motor. However, this design requires patients to secure their fingers to a rod, which may be challenging for stroke patients with limited hand functionality. Furthermore, using hybrid actuation increases operational complexity and cost. Pneumatically actuated soft exoskeleton gloves were presented in [11]–[13]. These designs were suited for rehabilitating both the hand fingers and the wrist. However, they were limited to performing only flexion movements. A rehabilitative soft glove-based pneumatic actuation was developed in [14]–[16]. However, they lack payload capability and have a limited bending angle.

It can be concluded that the current robotic systems for wrist rehabilitation focus on flexion and extension movements. Additionally, they have limitations in bending and payload capability. In this regard, this paper is stimulated by the need for developing a soft wearable robot for rehabilitating the wrist joint concerning different bending directions. The contributions of this paper are summarized in the following aspects. (1) Developing configurable pneumatic soft robotic fingers for wrist rehabilitation. The suggested design uses four soft fingers, which are fixed near the base of the index and ring fingers, to the dorsal and palmar sides of the hand as depicted in Fig. 1. The wrist joint can perform flexion and extension by simultaneously pressurizing the top or bottom pair of actuators, respectively. Additionally, activating diagonal actuators results in pronation and supination. On the other hand, the radial and ulnar deviations can be achieved by using two sided-connected pneumatic actuators attached to the base of the little finger and thumb, respectively. (2) Conducting a nonlinear static analysis based on a third-order Yeoh model to verify the proposed design while considering the tensile strength of the soft material and deflection during bending. (3) Estimating the bending shape of the pneumatic finger based on constant curvature approach by using the Inertial Measurement Unit (IMU). (4) Evaluating the design performance by performing a series of experiments, concerning its bending and payload capacity of single soft finger and series-connected fingers. Additionally, the payload capability is validated by successfully lifting a 660 g metal frame designed to mimic a human hand. It is worth noting that this paper represents the initial stage in the development of a wearable soft pneumatic system in different bending directions.

The rest of the paper is organized in the flow diagram shown in Fig. 2. The structural design and fabrication procedure are presented in Section II. Section III introduces the design analysis and modeling approach. Experimental evaluation is elaborated in Section IV. Finally, section V discusses the conclusion and future work.

II. STRUCTURAL DESIGN

Figure 3 illustrates that the proposed soft design is composed of a series of connected chambers. Upon actuation, the design ensures uniform pressure distribution and achieves an approximately circular shape, with nearly all chambers inflating uniformly and exhibiting a nearly constant curvature deformation. The design length is 15 cm and consists of 12 chambers, each with a width of 9 mm and a height of 16.5 mm. It is worth noting that the parameters of soft design are chosen based on real dimensions of adult male as shown in Fig. 3.

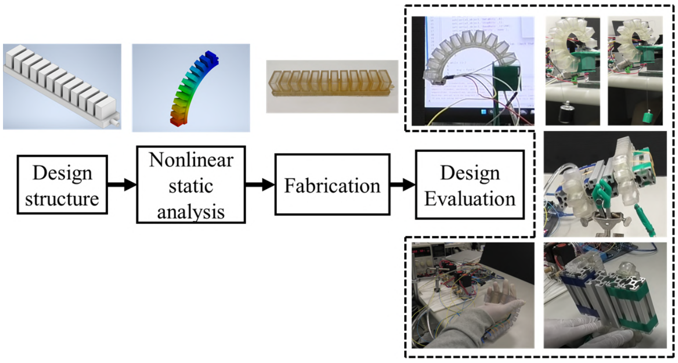


Fig. 2: Schematic diagram of the workflow followed in this study.

A. Fabrication and actuation mechanism

Different fabrication methods are utilized to implement soft material including traditional 3D printer and molding [17]. However, they still lack accuracy and time-consuming. Molding represent one of the famous methods to fabricate soft robot, which starts by constructing the rigid frame, then pouring soft elastomer inside. However, it often involves high costs and subject to defects such air bubbles or uneven curing, which affect the design accuracy [18]. Alternatively, a Form 3 machine, a laser-based 3D printer, which shapes accurate models through Stereo Lithography (SLA) technology. Its accuracy reaches 0.05 mm. It ensures smooth surface finishes and dimensional accuracy which reaches to 0.05 mm, making it ideal for fabricating soft material [19].

Owing to its unique flexibility, Elastic 50A Resin is chosen for fabricating the soft finger as depicted in Fig. 4a. When pressurized, the chambers inflate and press against each other, resulting in a smooth bending as illustrated in Fig. 4.

III. DESIGN ANALYSIS AND KINEMATIC APPROACH

Due to the hyper-elastic properties of soft material, a nonlinear static analysis based on a third order Yeoh model are applied. For simplification, the model coefficients $C_{10} = 0.5234$, $C_{20} = 0$ and $C_{30} = 0.004186$, which were determined for Elastic-50A as presented in [20].The simulation

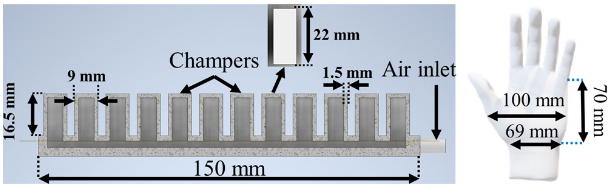


Fig. 3: The design parameters.

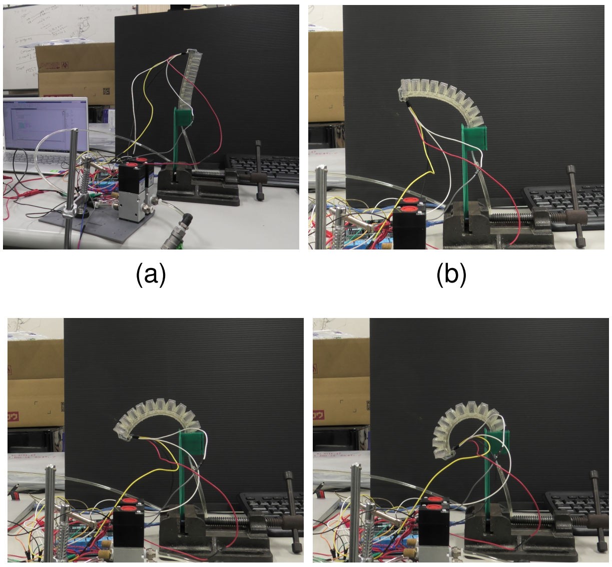

(a) (b) (c) (d)

Fig. 4: Bending of the soft finger upon actuation.

is conducted in Inventor (NASTRAN-2024). The analysis begins by defining the mechanical characteristics of Elastic 50A, which has post curing tensile strength 3.23 MPa. A pressure is applied normal to each internal surface of the design as depicted in Fig. 5. A separation contact is created between every two opposite faces, to avoid penetration. Figure 5, illustrates that the fixed constraint is added to the beginning of the design and the gravity is down.

Figure 6 shows the resulted stress under pressure of 0.1 MPa, 0.15 MPa and 0.234 MPa, respectively. The deflection of the prototype in each coordinate is listed in Table. I. The results show that the design performs bending with reduced deflection along the z-axis while maintaining structural safety under the applied pressure.

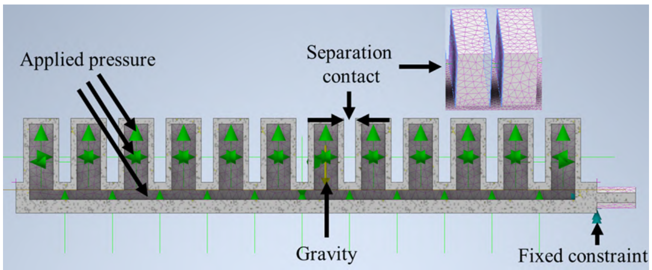
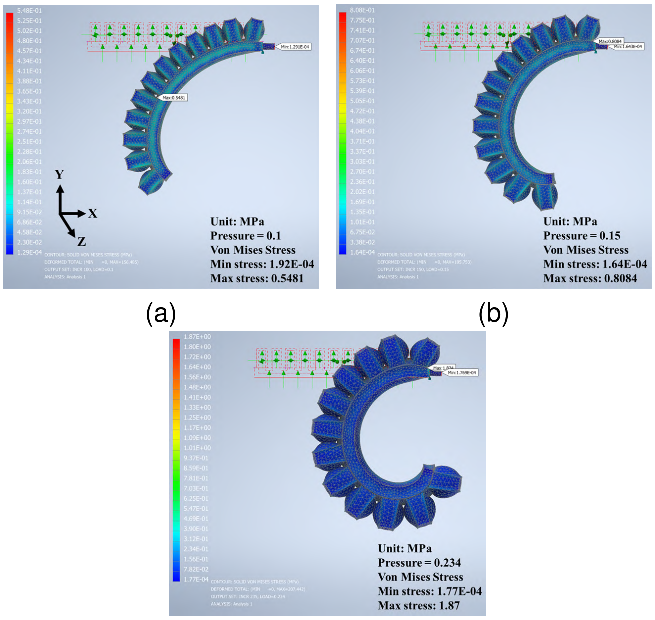


Fig. 5: The nonlinear static analysis of soft pneumatic finger.



(a) (b) (c)

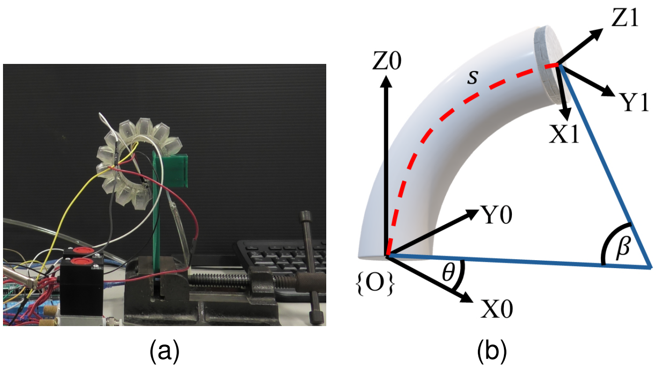
Fig. 6: The stress analysis of design under applied pressure of (a) 0.1 MPa, (b) 0.15 MPa, (c) 0.234 MPa.

TABLE I: The numerical results of nonlinear static analysis.

Pressure [MPa]	Von Mises Stress [MPa]		Displacement [mm]					
	Min	Max	X		Y		Z	
			Min	Max	Min	Max	Min	Max
0.1	1.29E-04	0.5481	-21.52	73	-148.7	5.03	-2.15	2.57
0.15	1.64E-04	0.8084	-27.43	116.20	-162.3	7.52	-3.16	0.3.835
0.234	1.770E-04	1.87	-38.26	176.10	-156.30	13.08	-5.216	5.691

A. *Kinematic modeling*

Based on experimental results, the pneumatic finger can achieve a bending angle of 270°, resembling a circular arc, as shown in Fig. 7a. Regardly, the constant curvature assumption is employed to represent the robot's shape, which is applicable to both pneumatic and cable-driven systems.



(a) (b)

Fig. 7: (a) Bending capability of soft finger, and (b) Schematic diagram of single section soft robot.

The homogeneous transformation matrix T_1^0, which describe the pose of the distal tip relative to its base, is expressed as a function of $\boldsymbol{q} = [S, \theta, \beta]$, as illustrated in Fig. 7b. Where S denotes the arc length, θ is the angle of curvature relative to the +X axis, and β is the bending angle of the arc. It is computed as follows [21]:

$$T_1^0 = \begin{bmatrix} R\left(\boldsymbol{q}\right) & \boldsymbol{P}(\boldsymbol{q}) \\ 0 & 1 \end{bmatrix} \tag{1}$$

where $R\left(\boldsymbol{q}\right) \in \mathbb{R}^{3\times3}$ is the rotation matrix and $\boldsymbol{P}\left(\boldsymbol{q}\right) = [X, Y, Z]^T$ is the robot's tip position. The Inertial Measurement Unit (IMU-9265) is mounted on the distal tip of the soft finger to estimate its real-time orientation in the form of a quaternion vector $\boldsymbol{Q} = [q_w, q_x, q_y, q_z]$. By comparing this measured orientation with the rotation matrix defined in (1), the values of θ and β can be easily computed as follows:

$$\theta = \tan^{-1} \frac{q_y q_z + q_w q_x}{q_x q_z - q_w q_y} \tag{2}$$

$$\beta = \left(1 - 2(q_x^2 - q_y^2)\right) \tag{3}$$

where $[q_w, q_x, q_y, q_z]$ are quaternion parameters derived from the IMU. For simplification, the arc length S is assumed fixed.

IV. Results and Discussion

This section aims to evaluate the design's capability to achieve bending while carrying an external payload. The kinematic modeling approach is validated by comparing the actual bending of the prototype with the simulated motion generated in MATLAB. The performance of the prototype is validated through a series of experiments, including a single finger and two series-connected fingers, focusing on bending behavior under external payloads. Additionally, the design is evaluated using a metal bar that mimics a human hand to assess its ability to achieve wrist movements, including flexion/extension, pronation/supination, and radial/ulnar deviation. Furthermore, four soft fingers are used to achieve the extension of a real human. Figure 8 shows the experimental setup, which is composed of solenoid valves, an Arduino Mega-2560, an IMU-9265, and a power supply. The pump used in the setup is capable of both pressurizing of 0.9 MPa and pressure reduction.

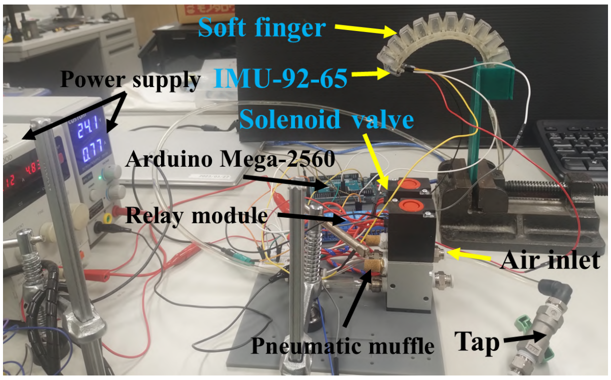


Fig. 8: Experimental setup during actuation of pneumatic soft finger.

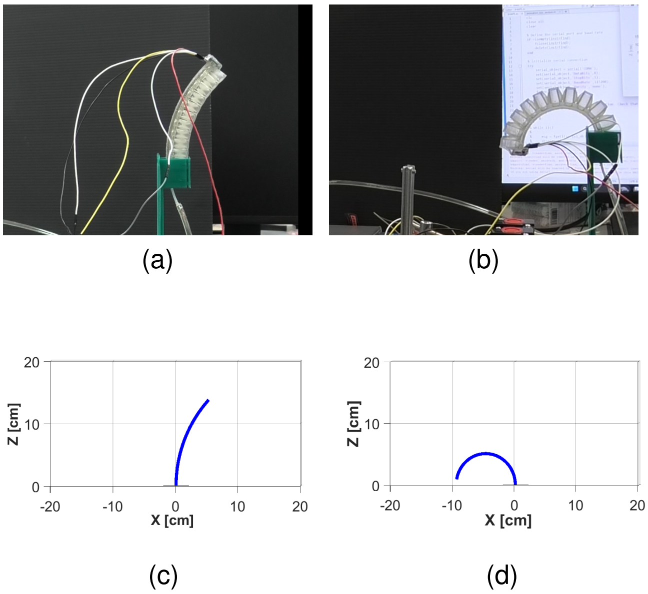


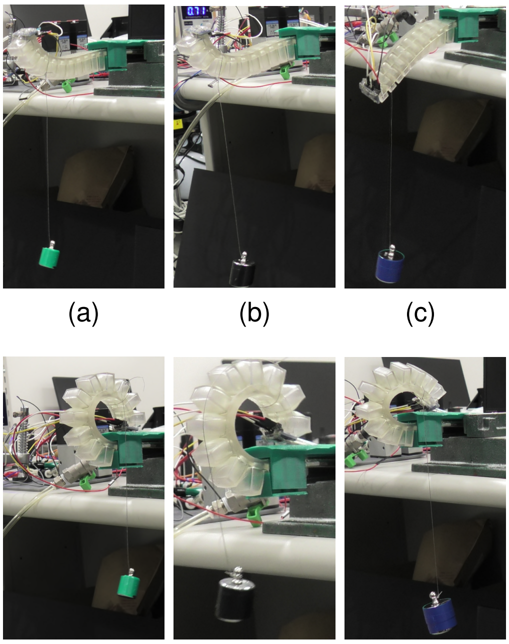
Fig. 9: Bending estimation under (a, c) negative pressure, and (b, d) positive pressure.

A. Shape estimation

This test is used to estimate the maximum bending angles of soft finger during normal and inverse bending, which is obtained by activating pressure or pressure reduction of pneumatic source. The inverse bending is crucial to improve payload capability during rehabilitation. The bending angle β is 48° and 270 ° while supplying or extracting air from the soft finger respectively. Furthermore, the bending shape could be estimated by dividing the finger into a number of points, where the position of each point is computed from (1). Figure 9 illustrates the bending shape in forward and reverse directions. It is worth noting that the IMU sensor works perfectly within angle range 0° to 180°, which is suitable for wrist rehabilitation.

B. Payload capacity

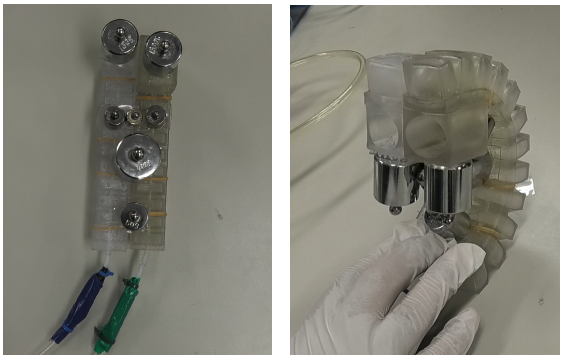
Payload capacity is crucial to validate the prototype's capability to perform bending while carrying weights. In this experiment, external payloads ranging from 10 g to 200 g are anchored to the tip of the soft finger, which is then allowed to bend by 270°. Figure 10 demonstrates that it can bend under payloads of 50 g, 100 g, and 200 g, respectively. To achieve radial/ulnar deviation, it is suggested that two side-connected soft fingers be attached to the bases of the little and thumb fingers, as depicted in Fig. 1c. To perform these movements, a payload of 475 g is applied to two pneumatic fingers as shown in Fig. 11a. Figure 11b exhibits the effectiveness of the prototype to bend under external loads. This finding indicates that the design is suitable for bending a real human hand, which averagely weights around



(a) (b) (c)

(d) (e) (f)

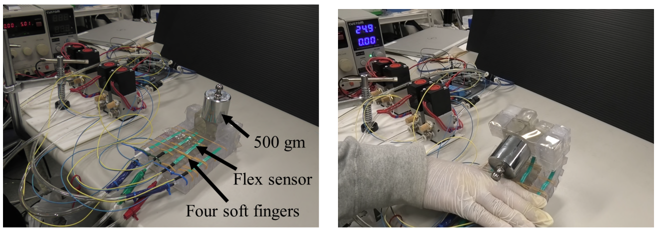
Fig. 10: Bending capability before and after attaching: (a,d) 50 g, (b, e) 100 g, and (c, f) 200 g.



(a) (b)

Fig. 11: Payload capacity of side-connected pneumatic fingers (a) before activation, and (b) under applied pressure.

400 g [22]. Finally, a set of four interconnected soft fingers was utilized to support an external load of 500 g, as shown in Fig.12a. The experimental results confirm that the soft structure can bend under the applied load, as illustrated in Fig. 12b.



(a) (b)

Fig. 12: Effectiveness of four soft fingers to carry external payload of 500 g.

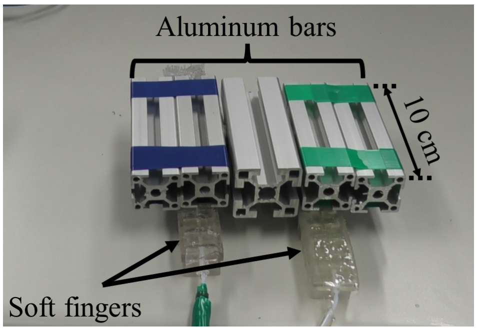


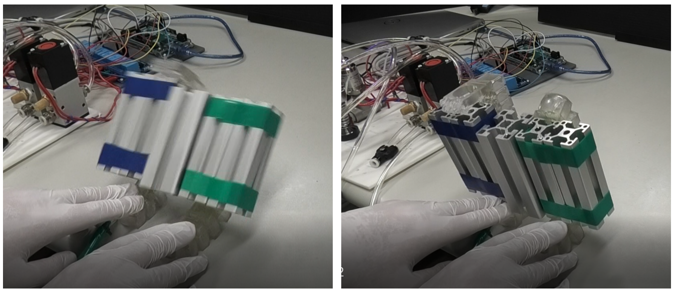
Fig. 13: Experimental setup during actuation of pneumatic soft finger.

C. Bending Capabilities

The performance of the proposed design is evaluated through a series of experiments replicating the wrist joint to achieve various bending directions. In this test, aluminum bars, each with a length of 10 cm and a total weight of 660 g, are utilized to imitate the human hand, as shown in Fig. 13. Figure 13 depicts that two soft actuators are attached to the metal frame to perform flexion/extension movements. When pressurized, they successfully bent the metal bars up to 90°, demonstrating the capability of the system to perform extension and flexion motions, as shown in Fig. 14a and Fig. 14b, respectively.

On the other hand, by pressurizing two opposing soft actuators that are anchored to the index and ring fingers to achieve pronation and supination, as depicted in Fig. 1b. This configuration enables rotational movement of the hand. The actuators are activated simultaneously, resulting in rotational motion of the metal bars, as seen in Figs. 15b and Fig. 15c, respectively.

Conducting the ulnar and radial deviations can be achieved by attaching a pair of side-contacted soft actuators to the little finger and thumb, as illustrated in 1c. As shown in Fig.16a, the soft actuator is attached to one side of the metal frame. Upon simultaneous pressurization of both actuators, the metal frame achieves lateral displacement successfully,



(a) (b)

Fig. 14: Extension capability of two soft robot

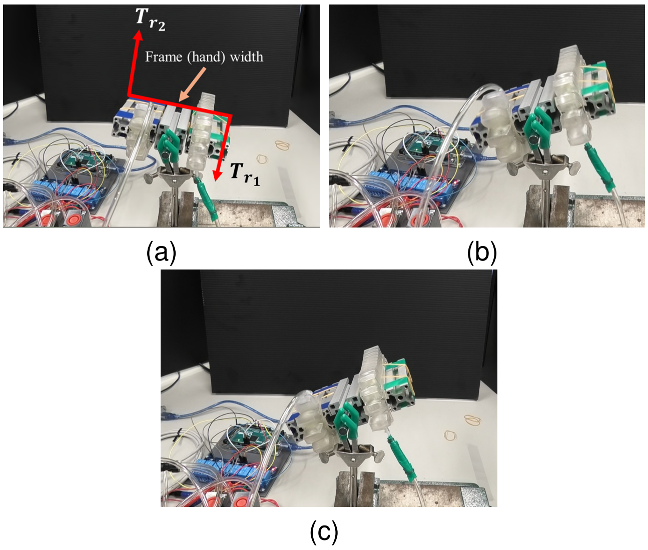


Fig. 15: Demonstration of pronation movement using two soft actuators: (a) initial state, (b–c) deformation after pressure is applied.

as shown in Figs. 16b and Fig. 16c, respectively. Finally, four soft fingers were employed to bend a human hand. Each actuator was equipped with a flex sensor to measure its bending angle, as depicted in Fig. 17a. The air pressure is regulated to achieve bending up to 40°. The results confirm the effectiveness of the soft actuators in bending the human hand as shown in Fig. 17b.

Supplementary material is provided to further illustrate the experimental evaluation of the proposed design, including bending performance, payload capacity, and hand motion capabilities.

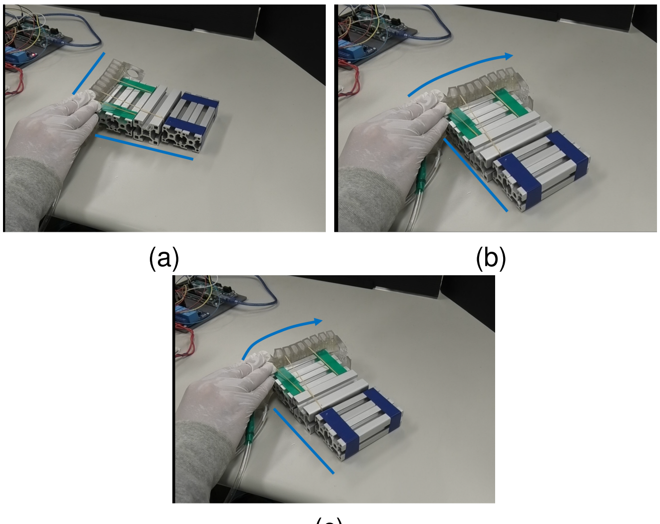


Fig. 16: Conducting ulnar deviation using two sided-connected pneumatic actuators: (a) initial position, and (b-c) displacement under activation.

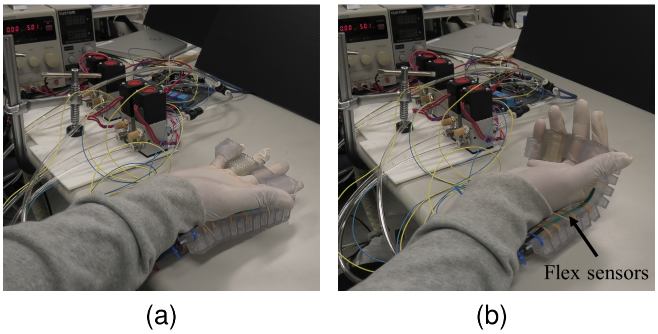


Fig. 17: Banding human hand based on four series connected soft fingers: (a) initial state, and (b) upon pressurizing.

V. CONCLUSION

This paper presents the first phase of designing a configurable pneumatically actuated soft actuator for wrist rehabilitation. The design utilizes two pairs of soft actuators that are fixed near the base of the index and ring fingers to the dorsal and palmar sides of the hand. By simultaneously pressurizing the top or bottom pair of actuators, respectively, the wrist joint is able to perform flexion and extension. The pronation/supination can be achieved by activating diagonal actuators. Furthermore, two-sided connected actuators are anchored to the base of the little finger and thumb to perform radial and ulnar deviations, respectively. A nonlinear static analysis based on the Yeoh model is conducted to simulate the bending performance of the design under the applied pressure. A shape estimation approach of the prototype is developed using IMU-based orientation measurements and the constant curvature assumption.

A series of experiments were conducted to evaluate the bending performance and payload capacity of the pneumatic actuators. The results verify its effectiveness in achieving bending under external payloads. Additionally, the proposed configuration is capable of performing various deviations of a metal frame that is designed to mimic human wrist movements. Furthermore, four series-connected pneumatic actuators are able to bend a real human hand by 40°. This study marks an initial step toward the development of a wearable, compact soft robotic device capable of facilitating complex wrist movements for rehabilitation. Future work will focus on developing a flexible glove equipped with soft actuators to perform rehabilitation tasks.

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