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Development Report:

Soft Robotic Gripper Based on Multi-Layers of Dielectric Elastomer Actuators

Witchuda Thongking[*,], Ardi Wiranata[*], Ayato Minaminosono[*], Zebing Mao[*], and Shingo Maeda[*]**

[*]Department of Functional Control System, Shibaura Institute of Technology
3-7-5 Toyosu, Koto-ku, Tokyo 135-8548, Japan
E-mail: nb21107@shibaura-it.ac.jp
[**]Biomedical Innovation Engineering, Suranaree University of Technology
111 University Avenue, Muang District, Nakhon Ratchasima 30000, Thailand
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Dielectric elastomer actuators (DEAs) are a promising technology for soft robotics. The use of DEAs has many advantages, including light weight, resilience, and fast response for its applications, such as grippers, artificial muscles, and heel strike generators. Grippers are commonly used as grasping devices. In this study, we focus on DEA applications and propose a technology to expand the applicability of a soft gripper. The advantages of gripper-based DEAs include light weight, fast response, and low cost. We fabricated soft grippers using multiple DEA layers. The grippers successfully held or gripped an object, and we investigated the response time of the grippers and their angle characteristics. We studied the relationship between the number of DEA layers and the performance of our grippers. Our experimental results show that the multi-layered DEAs have the potential to be strong grippers.

Keywords: soft gripper, multi-layer of dielectric elastomer actuators, dielectric elastomer actuator

1. Introduction

The human musculoskeletal system is marvelous. It provides movement, stability, and support to the body [1]. Muscles and internal skeletal systems are indispensable for movements. Human handscans handle and grip an object and move it wherever they wish to place it [2]. Some researchers developed rigid robots to achieve these functions by mimicking human hand movements [3]. Precise, powerful, and fast movements are the advantages of rigid robotics [4]. However, conventional robots include heavy and hard components, which are unsafe for human-robot interactions [5]. Therefore, soft robots have been developed to increase the adaptability of robots to humans [6, 7].

Recently, various types of soft robots have been developed based on different principles, such as chemical, pneumatic, and electrical methods [7–12]. Among these methods, the pneumatic method requires an air compressor and several solenoid-controlled valves [9, 11]. In the chemical method, the robot system has to be repeatedly filled with chemicals such that the entire system can work continuously [13]. To address these problems, we used an electrical method that provides lightweight and easy to fabricate robots [14, 15]. The materials for these robots can be mainly divided into two groups: shape memory alloys and electroactive polymers (EAPs) [14–16]. We focused on EAPs because these soft actuator parts were available with the electrical method, unique materials, and artificial muscles. Principally, EAPs change their size or shape when they are activated by an electric field. Dielectric elastomer actuators (DEAs) are a type of EAP [8, 17]. DEA produces force, motion, and a large strain through Maxwell stress. When we apply a voltage through the passive elastomer film of a soft material, the soft material produces large strains from charges between two compliant electrodes. However, DEA expands and bends to release large strains [18, 19]. We propose a simple method to create DEAs by simply brushing a carbon nanotube (CNT) powder to an elastomer film [20]. Previous researchers have studied one layer of DEA and the basic characteristics of the actuation [21]. The study indicates that the force is generated by a single layer of DEA, which is smaller than multi-layers of DEAs. We observed that a one-layer DEA cannot produce a higher actuation force [22], and to overcome this problem, we introduced a multi-layer DEA fabrication process for gripper applications. We observed that multi-layer DEAs had high resistance strain and large deformation when a high voltage was applied [23]. Therefore, we propose a new gripper using multi-stacked layers of DEAs. Our soft gripper has finger structures that replicate a human hand. Our research aims to build a soft gripper composed of a DEA that mimics the human fingers and to investigate the operating characteristics of the soft gripper. We examined the characteristics of the joint angle and applied voltage to the soft gripper. We evaluated the performance of the soft gripper holding the object.

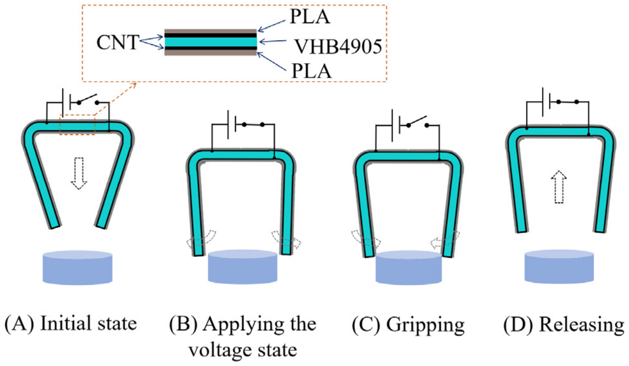


Fig. 1. Mechanism of soft gripper using dielectric elastomer actuator, (A) initial state of the soft gripper, (B) applying the voltage state (3 kV) to the DEA of the soft gripper that expands DEA and affect the opening finger structure, (C) turning off the voltage to grip the object, (D) releasing the object.

2. Mechanism

The human finger and muscles inspired us to build a soft gripper. We developed a soft gripper based on multi-stacked layers of DEAs. Each soft gripper layer included a polypropylene (PP) frame. The thickness of the polypropylene frame was 1 mm. The frame was resilient and could bend under stress. The soft gripper was fabricated using a 0.033-mm thick pre-stretched elastomer film of VHB 4905. Then, we brushed the CNT powder between the elastomer membrane layers. We added six layers. The final process of DEA gripper fabrication involved fixing the gripper shape using a 2-mm thick polylactic acid (PLA) frame. The important elements of the soft gripper include both multi-stacked layers of DEAs and an appropriate gripper frame. We designed the gripper frame by imitating the thumb and index finger functions (**Fig. 1(A)**) to realize the gripping process. The gripper design included two-finger-shaped structures and a beam and hinge joint for connecting them, as depicted in **Fig. 1**.

The width of the gripper tip was 60 mm. The overall length of the gripper frame was 110 mm, and the beam dimensions were 20 mm, as demonstrated in **Fig. 2(A)**. The mechanism of the soft gripper involved DEA conductivity combined with the hinge joint of the gripper frame. When a voltage was applied to the actuator, the soft gripper expanded the finger structure. The soft gripper could hold an object, as shown in **Fig. 1**. The gripping process of the soft gripper involved four steps. First, the soft gripper was in its initial state. It was moved to the object position, as shown in **Fig. 1(A)**. Second, voltages were applied to the soft gripper to open the finger structure, as illustrated in **Fig. 1(B)**, at an appropriate angle. Third, the voltage of the soft gripper was turned off. Consequently, the finger structure could grip the object, as demonstrated in **Fig. 1(C)**. Fourth, the soft gripper was moved to the terminal position. When the object was released, voltages were applied to the soft gripper to open the finger structure again. Thus, the soft gripper released the object, as shown in **Fig. 1(D)**.

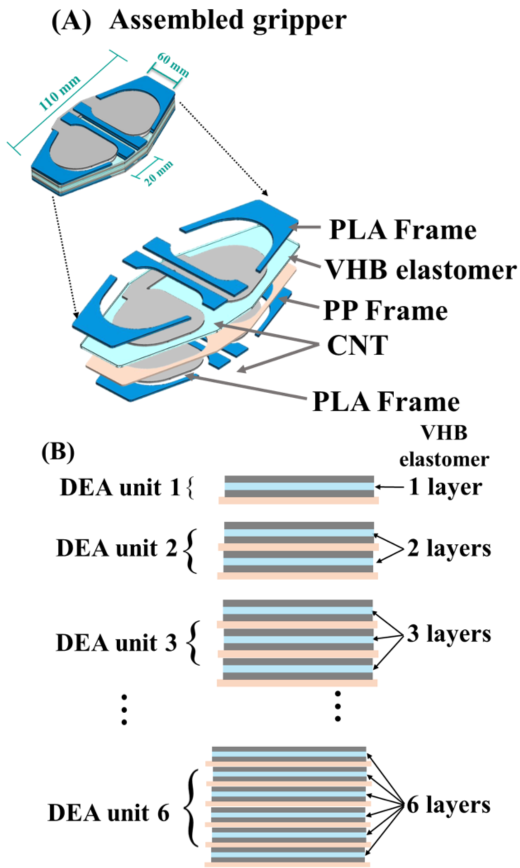


Fig. 2. Schematics of DEA units of the soft gripper. We designed different units of DEAs for six devices. (A) Assembled soft gripper and dimension. (B) Cross-sectional view of soft gripper including DEA units in each soft gripper device.

3. Design and Fabrication

We tested the soft gripper from the following three aspects: angle characteristics and the response time of the finger structure when we apply voltages to the soft gripper, the releasing time when we turn off the voltages of the soft gripper, and the ability to hold the object of the soft gripper. In the experiments, we applied three voltages (1, 2, and 3 kV) to the gripper. We prepared six devices with different numbers of DEA layers, as demonstrated in **Fig. 2**. We performed the experiments three times.

The fabrication of our soft gripper included seven processes: designing the soft gripper, cutting the frame of the soft gripper, pre-stretching elastomer films, brushing the CNT powder, assembling layers of DEAs, removing bubbles in the soft gripper, and adjustment of the soft gripper structures. First, we designed a soft gripper by imitating the gripping movement of the human hand. We designed the frame for the gripper structure. The gripper frame had a two-finger structure that was connected by a beam structure. The beam structure, which played an important role, was the base of the finger. It avoided an electrical breakdown when a voltage was applied to the soft gripper, as depicted in **Fig. 3(A)** [20, 21]. Another advantage of the beam was that it was designed to

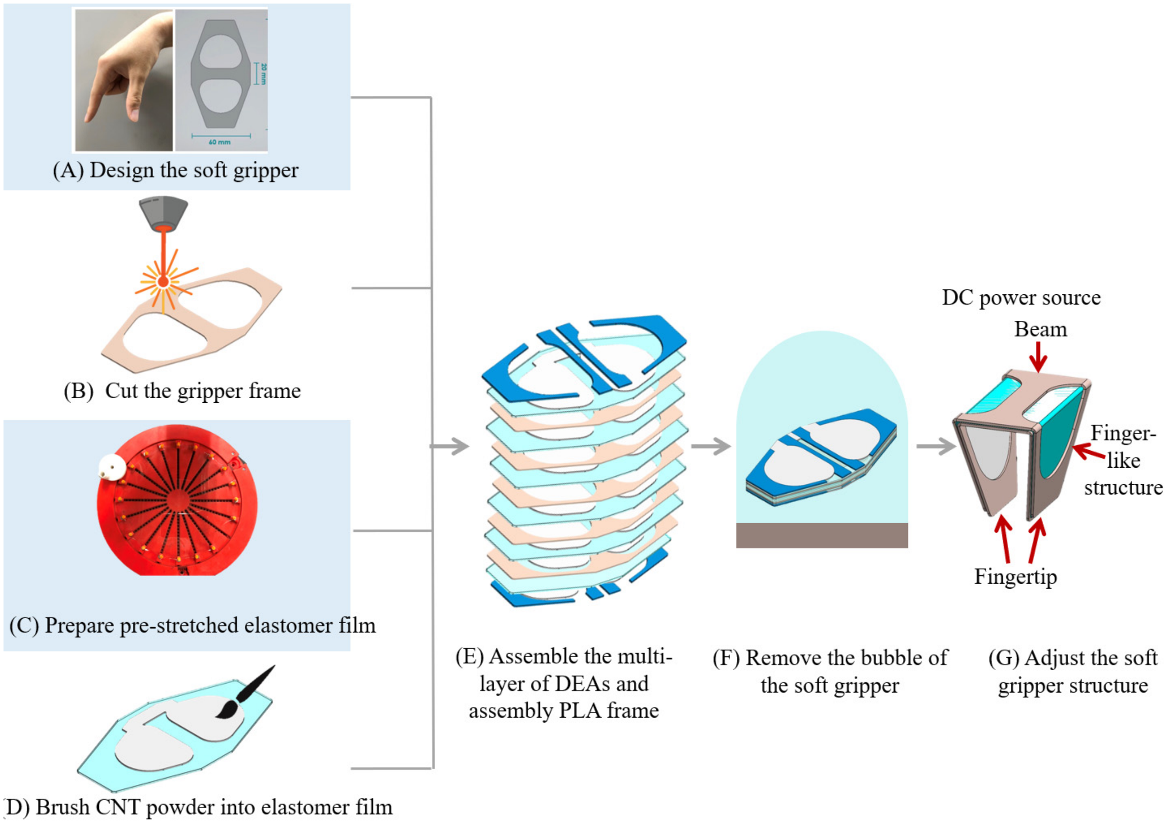


Fig. 3. Design and fabrication of the soft gripper based on the dielectric elastomer actuator, (A) design the soft gripper, (B) cut the gripper frame, (C) prepare the pre-stretched elastomer film, (D) brush CNT powder into elastomer film, (E) assemble the multi-layers of DEAs and the PLA frame, (F) remove the bubble of the soft gripper, and (G) adjust the soft gripper structure.

be 20 mm wide to prevent the twisting of the finger. The second process involved cutting the gripper frame. A cutting laser machine (TROTEC Speedy 100) was used to cut the gripper frame, as shown in **Fig. 3(B)**. The gripper frame was made of polypropylene (PP). The PP material is thin and flexible. The resilient material property is neither extremely soft nor extremely hard. If the gripper frame is made of a soft material, it cannot have a resistant elastomer adhesion force. However, if the gripper frame is made of a hard material, it cannot move the finger structure. Therefore, we must carefully select an appropriate material frame. Hence, we selected PP as the material for the gripper frame. The third process involved pre-stretching the elastomer films. The elastomer used was VHB 4905. The initial thickness of the VHB 4905 elastomer was 0.5 mm. Therefore, we prepared a pre-stretched VHB elastomer using a circular pre-stretched machine, as shown in **Fig. 3(C)**. A 300% pre-stretched elastomer, which is the ultimate performance of the pre-stretched elastomer, is desirable. It is one of the thinnest layers of the VHB elastomer and resists a large strain of electrical voltage [15]. Therefore, we prepared a pre-stretched VHB elastomer using a circular pre-stretched machine. The thickness of the single layer of the VHB elastomer was changed from 0.5 mm to 0.033 mm after the stretching process. Then, we assembled the pre-stretched VHB elastomer and fitted it to the gripper frame. The fourth process involved brushing the CNT powder [18]. Before brushing the CNT powder to the VHB elastomer, a marking tap was used to locate the brushing area. The CNT powder was then brushed to the elastomer membrane layers, as depicted in **Fig. 3(D)**. The fifth process involved assembling the layers of the DEAs. We repeated the previous four processes until we obtained six layers of DEAs, as demonstrated in **Fig. 3(E)**. After assembling the six DEA layers fabricated using the aforementioned five processes, we obtained a multi-layered soft gripper. This process could easily cause bubbles in the multi-layer structures of DEAs. Therefore, it had to be removed in the next process. The sixth process was the gripper persistence process. Polylactic acid (PLA) was used to create a PLA frame. A 3D printing technology was used to create a 2-mm thick PLA rigid frame. The PLA frame plays an important role in stabilizing the soft gripper for a long time. Multiple DEA layers were assembled with a PLA frame, as illustrated in **Fig. 3(E)**. The next step was to remove bubbles from the soft gripper. A vacuum machine was used to remove bubbles, as shown in **Fig. 3(F)**. This process took approximately two hours. The importance of the process was to reduce the electrical breakdown when voltages were applied to the soft gripper. The final process involved adjusting the soft gripper structure. We adjusted the hinge joint of the finger structures, as depicted in **Fig. 3(G)**.

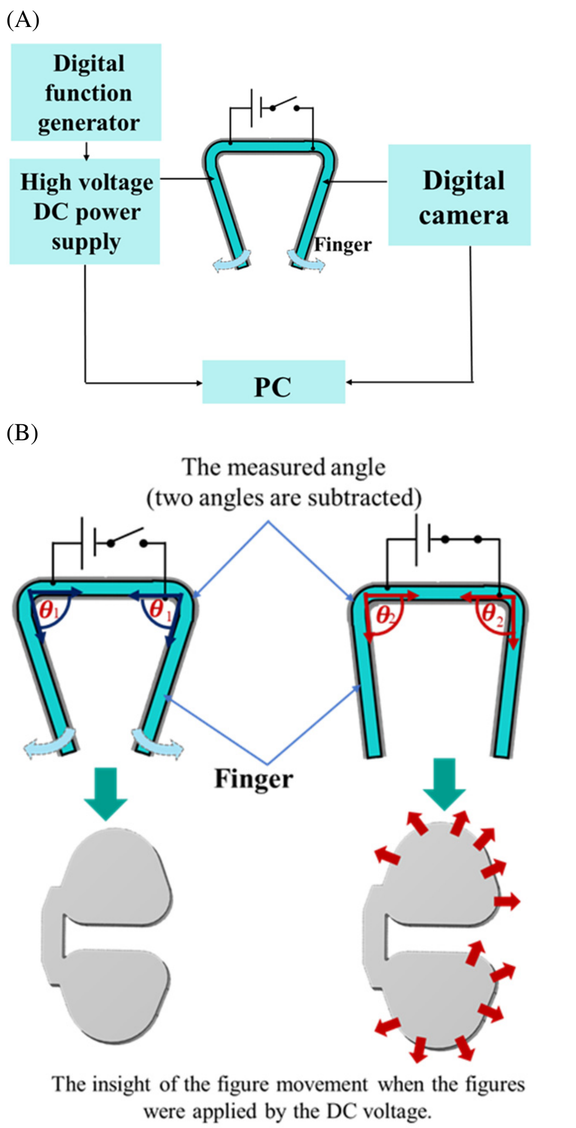


Fig. 4. Schematics of the experimental setup. (A) Experimental setup of the soft gripper and (B) angle characteristics of the finger structure (angle result $\theta_3 = \theta_2 - \theta_1$).

4. Experimental Setups

Figure 4(A) demonstrates our experimental setup. We used a DC voltage amplifier (HEOPT-20B10-LS, Matsusada Precision Inc.) combined with a function generator (eK-FGJ, Matsusada Precision Inc.) to power up and control soft gripper actuation. The actuation of the gripper was captured using a video camera (EOS M6 Mark II, Canon Inc.). Then, the captured video was further processed using ImageJ to analyze the angle characteristics of the soft gripper.

Figure 4(B) illustrates the movement of the gripper when a voltage is applied. First, we measured the initial angle θ_1 when the voltage was not applied to the soft gripper. Second, when the voltage was applied to the soft gripper, it bent to another angle θ_2. Finally, we obtained angle θ_3 by subtracting θ_1 from θ_2.

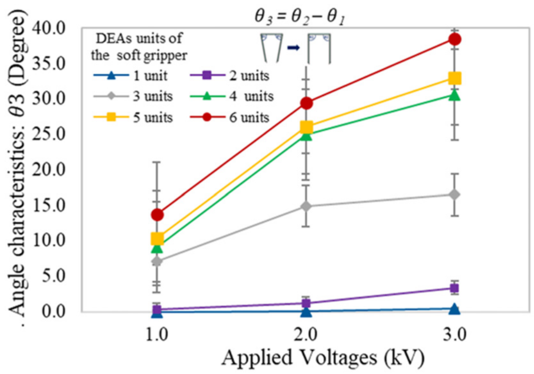


Fig. 5. Angle characteristics of the soft gripper as a function of applied voltages in terms of different DEA units.

5. Results and Discussion

5.1. Angle Characteristics

Figure 5 illustrates the relationship between the angle characteristics and the applied voltages of the soft gripper. We prepared six devices with different numbers of DEA layers in this experiment. The angle characteristics depended on the applied voltage and the number of DEA layers. When we adjusted the voltages from 1.0 kV to 3.0 kV, as shown in **Fig. 5**, the angles of the soft gripper with one layer of DEA increased from 13.84° (1 kV) to 38.53° (3 kV). This was because higher voltages caused the gripper to generate larger forces and then expanded the angle of the gripper. In addition, the device with six layers provided the gripper with a stronger force than other devices [23]. Meanwhile, the PLA frame is an important supporter that maintains the finger structure and prevents twisting the fingers. We observed that the soft gripper generated 0.45° (one layer) and 38.53° (six layers) under 3 kV. This might be because more layers could resist contractile deformation and induce larger expansion if the number of layers was less than a certain value [22, 24]. Overall, the maximum angle was 38.53° because the gripper was designed with six layers and operated at 3.0 kV.

5.2. Opening and Releasing Time

We investigated the opening time when the gripper was actuated by applied voltages and the releasing time at which the gripper returned to its original position when the voltages were turned off. **Fig. 6(A)** shows the relationship between the opening and releasing times of the gripper with different numbers of DEA layers. We observed that the opening time was longer than the releasing time, irrespective of the number of DEA layers. In these experiments, we used the DEA elastomer (VHB 4905). The viscoelastic and adhesion properties of VHB 4905 resist the opening response of the gripper and maintain its balance [25]. This influenced the opening time of the gripper. The six-layer gripper took 6.68 s to open and 4.79 s to release when it was applied with 3 kV. In addition, both the opening and releasing times slightly increased as the

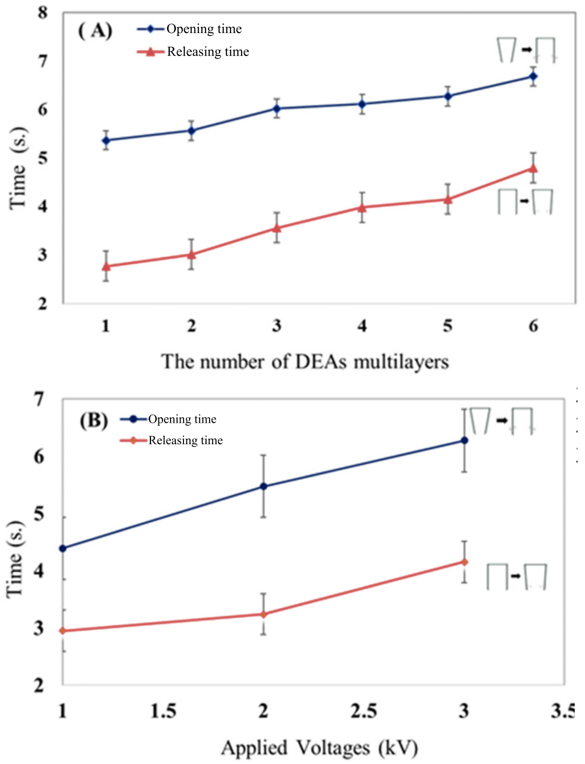
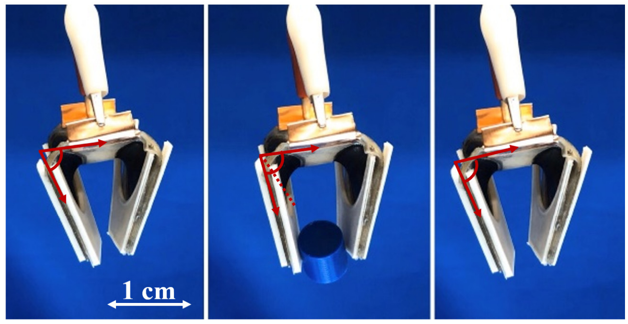


Fig. 6. (A) Relationship between the opening and releasing time of the gripper with different numbers of DEA layers, and (B) relationship between the opening and releasing time of the gripper at different voltages.

number of DEA layers increased. This was because an increase in the number of DEA layers enhanced the tensile strength and viscoelastic properties and required a longer opening time of the gripper. However, the releasing time was influenced by the adhesion property of VHB 4905. The adhesion property reduced the releasing time, and therefore, the releasing time was shorter than the opening time.

Figure 6(B) demonstrates the relationship between the opening and releasing times of the gripper (six layers) at different voltages. The highest voltage was 3 kV that produced a larger force than the other voltages and provided higher angles. The opening times of the six DEA layers were 4.39 s, 5.47 s, and 6.27 s, and the releasing times were 2.95 s, 3.24 s, and 4.15 s.



(A) Initial state **(B) Applying the voltage state and gripping** **(C) Releasing object**

Fig. 7. Demonstration of operating the soft gripper.

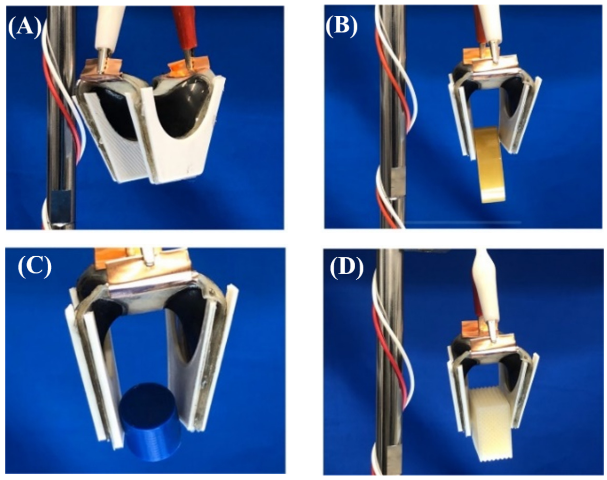


Fig. 8. Ability of the soft gripper to hold the object, (A) gripper from a lateral view, (B) clear tape (17 g), (C) ABS tube (2 g), and (D) square spongy (7 g).

Table 1. Ability to hold the object of the soft gripper.

Quantities of DEAs layers	Force of the soft gripper [N]	Object weight [g]
4	137.20	14.00
5	147.00	15.00
6	166.66	17.00

5.3. Applications

We examined the ability to hold an object by measuring the object weight using the soft grippers with 4–6 layers. We weighed the object using electronic weighing scales (accuracy 1 mg). We tested the ability to hold the object by applying a voltage of 3 kV.

The soft gripper could perform purely 2-dimensional movements (gripping and releasing), as demonstrated in **Fig. 7**. In the gripping mechanism, the soft gripper required three states. The first state was the initial state (0 kV), as shown in **Fig. 7(A)**. The second state is shown in **Fig. 7(B)**. DC voltages (3 kV) were applied to the soft gripper. The soft gripper bent the finger structures. Then, we turned off the voltages. The gripper held the object at a voltage of 0 kV. The final state was the release of the object. The DC voltage had to be applied again to open the gripper, as depicted in **Fig. 7(C)**. **Fig. 8** demonstrated the ability to hold the different shapes of an object such as clear tap, ABS tube, and square spongy.

Table 1 presents the ability of the soft gripper, including the force of the soft gripper and object weights that a different number of DEA layers can hold. The force in each of the different numbers of DEA layers was 137.20, 147.00, and 166.66 N. The holding ability of the soft gripper was 14.00, 15.00, and 17.00 g for the four-layer, five-layer, six-layer devices, respectively. Therefore, our device could hold the object with the maximum force and weight of 166.66 N and 17.00 g, respectively. The overall weight of the gripper was 5.45 g. This implied that the soft gripper could hold an object with a weight that was almost three times its weight.

6. Conclusion

In this study, we propose a new soft gripper using multi-layered DEAs. We evaluated the opening and releasing times of the soft gripper. We examined the angle characteristics of the soft gripper. We also examined the number of DEA layers to assess actuation performance. We conducted experiments to investigate the performance of the soft gripper by applying DC voltages. We applied the multi-DEA layers to a soft gripper to grip an object with a maximum weight of 17.0 g and the largest angle of 38°. Thus, this study shows that multi-layered DEAs can be a strong gripper. We believe that the new soft gripper can be incorporated into other soft robotics.

Acknowledgements

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Name:
Witchuda Thongking

Affiliation:
Smart Materials Laboratory, Department of Functional Control System, Shibaura Institute of Technology
Biomedical Innovation Engineering, Suranaree University of Technology

Address:
3-7-5 Toyosu, Koto-ku, Tokyo 135-8548, Japan
111 University Avenue, Muang District, Nakhon Ratchasima 30000, Thailand

Brief Biographical History:
2019-2021 Graduated Student, Biomedical Innovation Engineering, Suranaree University of Technology
2021- Ph.D. Student, Smart Materials Laboratory, Department of Functional Control System, Shibaura Institute of Technology

Main Works:
• "Analysis and Classification of Abnormal Vertebral Column by Convolutional Neural Network Algorithm," Suranaree J. of Social Science, Vol.16, No.1, 2021.

Name:
Ardi Wiranata

Affiliation:
Smart Materials Laboratory, Engineering Science and Mechanics, Shibaura Institute of Technology

Address:
3-7-5 Toyosu, Koto-ku, Tokyo 135-8548, Japan

Brief Biographical History:
2019- Ph.D. Student, Smart Material Laboratory, Department of Engineering Science and Mechanics, Shibaura Institute of Technology

Main Works:
• "Simple and Reliable Fabrication Method for Polydimethylsiloxane Dielectric Elastomer Actuators Using Carbon Nanotube Powder Electrodes," Advanced Engineering Material, Vol.23, 2001181, 2021.

Name:
Ayato Minaminosono

Affiliation:
Smart Materials Laboratory, Engineering Science and Mechanics, Shibaura Institute of Technology

Address:
3-7-5 Toyosu, Koto-ku, Tokyo 135-8548, Japan

Brief Biographical History:
2014-2018 Bachelor Course Student, Department of Engineering Science and Mechanics, Shibaura Institute of Technology
2018-2020 Master Course Student, Department of Mechanical engineering, Shibaura Institute of Technology
2020- Ph.D. Student, Department of Functional Control System, Shibaura Institute of Technology

Main Works:
• "Untethered rotational system with a stacked dielectric elastomer actuator," Smart Materials and Structures, Vol.30, pp. 065007-1-065007-11, 2021.
• "A deformable motor driven by dielectric elastomer actuators and flexible mechanisms," Frontiers in robotics and AI, Vol.6, 1, 2019.

Membership in Academic Societies:
• The Japan Society of Mechanical Engineers (JSME)

Name:
Zebing Mao

Affiliation:
Smart Materials Laboratory, Engineering Science and Mechanics, Shibaura Institute of Technology

Address:
3-7-5 Toyosu, Koto-ku, Tokyo 135-8548, Japan

Brief Biographical History:
2020- Postdoc Researcher, Shibaura institute of technology
2021- Assistant Professor, Shibaura institute of technology

Main Works:
• Z. Mao et al., "Contraction waves in self-oscillating polymer gels," Extreme Mechanics Letters, Vol.39, 100830, 2020.

Membership in Academic Societies:
• The Japan Society of Mechanical Engineers (JSME)

Name:
Shingo Maeda

Affiliation:
Smart Materials Laboratory, Shibaura Institute of Technology

Address:
3-7-5 Toyosu, Koto-ku, Tokyo 135-8548, Japan

Brief Biographical History:
2008 Received Ph.D. from Waseda University
2005-2008 Research Assistant, Waseda University
2008-2009 Assistant, Waseda University
2009-2011 Assistant Professor, Waseda University
2011-2014 Assistant Professor, Shibaura Institute of Technology
2014-2019 Associate Professor, Shibaura Institute of Technology
2015-2016 Visiting Professor, The Bio Robotics Institute, Scuola Superiore Sant'Anna
2021- Professor, Shibaura Institute of Technology

Main Works:
• "Autonomous oil flow generated by self-oscillating polymer gels," Scientific Reports, Vol.10, 12834, 2020.
• "Stretchable pumps for soft machines," Nature, Vol.572, pp. 516-519, 2019.
• "Stretchable Suction Cup with Electroadhesion," Advanced Materials Technologies, Vol.4, No.1, 1800304, 2019.

Membership in Academic Societies:
• The Institute of Electrical and Electronics Engineers (IEEE)
• The Robotics Society of Japan (RSJ)
• The Japan Society of Mechanical Engineers (JSME)