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An Electrostatic/Gecko-Inspired Adhesives Soft Robotic Gripper

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***Abstract*— Compared to traditional grippers, soft grippers can typically grasp a wider range of objects, including ones that are soft, fragile, or irregularly shaped, but at the cost of a relatively low gripping force. To increase gripping force for soft grippers, this research presents a gripper with an integrated electrostatic and gecko-inspired adhesive. Synthetic gecko-inspired, microstructured adhesives are controllable (i.e. they can be turned on and off) and work on a wide range of substrates and materials; however, they are not typically effective on rough surfaces. In contrast, electrostatic adhesives, also controllable, have a higher tolerance to rough surfaces. By combining the two, it is possible to create an adhesive that is effective on a wider range of materials and roughness, including fabric. To increase the gripping force, parameters that affect electrostatic adhesion, including the electrode gap, electrode width, relative permittivity of gecko-inspired layer, and air gap between the adhesive and substrate were studied with Comsol Multiphysics software and experimentally validated. Results show that adding the two adhesives improves the gripping capabilities across acrylic, Tyvek fabric, and Kapton hemispheres of different diameters on an average of 100, 39, and 168%, respectively.**

I. Introduction and Background

Grasping and manipulating objects is a demanding problem in robotics. Most conventional rigid grippers have low flexibility, which limits their ability to grip a variety of objects. Underactuated adaptive grasping is one solution to this issue that can fixture an object to the fingers without requiring control or prior knowledge of object geometry [1]. Another solution is to employ controllers and add sensors to detect the target's position, shape, and material, but this can be expensive and complicated. Alternatively, one can use soft materials for the gripper, which minimizes the need for expensive control systems and sensors [2].

Soft grippers can adapt to irregular surfaces, making it possible to grasp and handle objects with different shapes, sizes, and materials. The grippers are typically fabricated from compliant materials, such as elastomers, that distribute forces uniformly, which can also be advantageous from a safety perspective if the gripper must physically interact with humans. However, this compliance typically comes at the cost of a relatively lower gripping force. To address this shortcoming, this paper describes a soft gripper with embedded electrostatic and gecko-inspired adhesives technologies that increase the gripping force (see Fig. 1).

Fig. 1. An electrostatic/gecko-inspired adhesive soft gripper picks up and handles a wine glass, a soccer ball, an orange, and a lamp. The contributions of electrostatic/gecko-inspired adhesives are important to grasp steadily the wine glass, orange, and soccer ball.

Gripping force is a function the gripper's stiffness as well as friction and adhesion between the gripper and object. The last two parameters play a crucial role when objects are not caged completely with soft fingers. The friction force depends on the normal force and friction coefficient at the points of contact. The adhesion force is a function of the contact area, which is related to the normal force and stiffness of the gripper's fingers and objects as well as the work of adhesion between gripper's finger and objects. Compared to rigid grippers, soft grippers have lower friction force due to lower normal interaction force, but have greater adhesion from a larger contact area.

Researchers have used several methods, such as particle jamming [3] or variable stiffness [4] to tune stiffness and normal force between a soft gripper and an object. Meanwhile, electrostatic adhesion [5], [6], [7] and gecko-inspired

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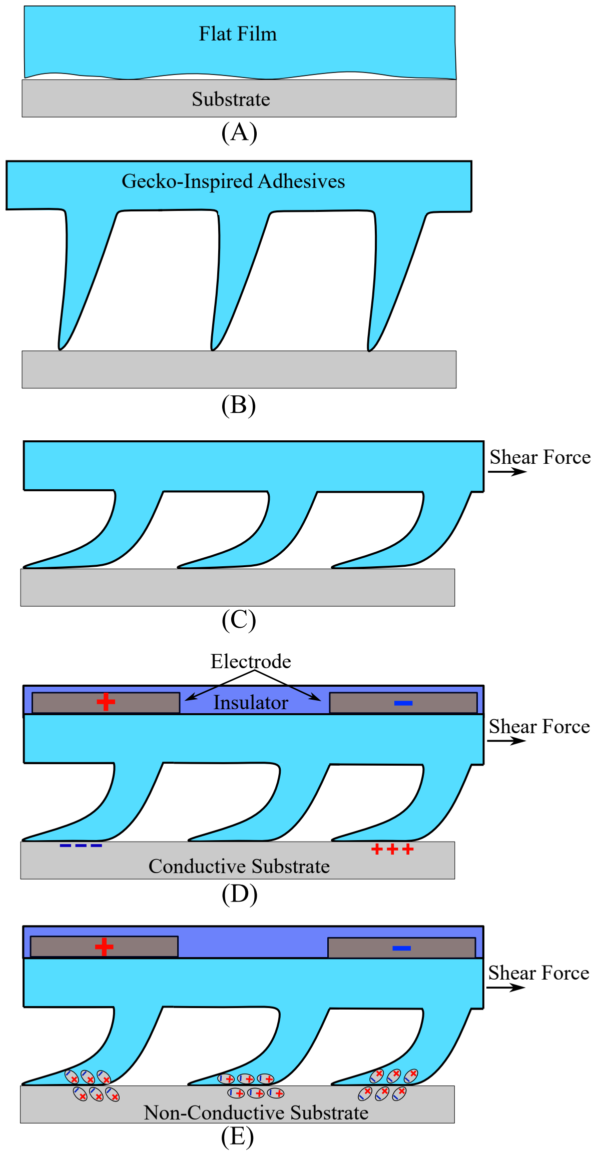

Fig. 2. Cross-sectional view of A) A flat film on a substrate demonstrating a small contact area. B) Unloaded directional gecko-inspired adhesives. C) Directional gecko-inspired adhesives loaded in shear. D) Electrostatic/directional gecko-inspired adhesives loaded in shear on a conductive substrate. E) Electrostatic/directional gecko-inspired adhesives loaded in shear on a non-conductive substrate. The contact area between the microstructures and substrate in C is greater than A and B. Contact area in D and E is greater than C.

adhesives [8], [9], [10], [11], [12] have also been used in soft and rigid grippers to control adhesion. However, electrostatic and gecko-inspired adhesives have not previously been simultaneously combined with a soft gripper, and the two together offer some unique advantages, as described below.

Gecko-inspired microstructures generate adhesion via van der Waals forces by creating a large contact area between its microstructures and the substrate [13] (see Fig. 2C). In electrostatic adhesion, the embedded interdigital electrodes generate electric fields that create a set of capacitors on conductive substrates (see Fig. 2D) and polarize non-conductive substrates (see Fig. 2E) and create adhesion [14]. By combining the two adhesives, the electrostatic element increases preload on the microstructures of the gecko-inspired adhesives, which results in a larger real contact area and, subsequently, greater adhesion. In return, the gecko-inspired adhesives bring the electrostatic adhesives closer to the surface of the object, leading to a deeper electric field penetration and higher electrostatic adhesion (see Fig. 2). The combination of electrostatic adhesives and gecko-inspired adhesives can, at times, provide an adhesive that is greater than the sum of its parts through this positive feedback cycle.

Electrostatic/gecko-inspired adhesives can be effective on a wide range of materials, including fabrics and rough surfaces [14]. Furthermore, although these technologies can be used in almost any environment, they have special promise in space applications since the technologies are all space-compatible [15], [16], [17]. These include grasping and manipulating objects [15], perching astronaut assistance tools such as Astrobee [18], and collecting orbital debris [17].

This paper presents a soft robotic gripper that utilizes electrostatic and gecko-inspired adhesives. Parameters that affect electrostatic adhesion including the electrode gap, electrode width, relative permittivity of the gecko-inspired layer, and the air gap between the adhesive and object were studied using Comsol Multiphysics, a finite element analysis, solver, and simulation software, and experimentally verified. The experimental results characterizing the gripper show that adding gecko-inspired and electrostatic adhesives to the soft gripper improves its gripping capabilities for acrylic, Tyvek fabric, and Kapton across objects with a variety of curvatures.

The paper is organized as follows: Section II describes the fabrication processes for the soft tendon-driven gripper and electrostatic/gecko-inspired pads. Section III explains the testing procedures. Section IV details the results of simulations and tests designed to evaluate electrostatic adhesion and gripping force. Section V provides concluding remarks.

II. Fabrication

This section outlines the fabrication processes for the gripper, electrostatic pads, and gecko-inspired adhesives.

A. Soft Tendon-Based Gripper

The gripper consists of two fingers and a main body. The fingers are comprised of two tendons to actuate the fingers, two rubber tubes the tendons slide through, and a rigid piece that connects the finger to the main body of the gripper.

The compliant fingers are fabricated by molding silicone rubber (Mold Star 30, Smooth-On, Inc.) in a 3D-printed mold (see Fig. 3, step 1). Each finger has five sections, four of which can be used to grasp objects. The fifth is connected to a rigid “finger holder” with three screws.

A tendon (⌀36 mm) threaded through silicone rubber tubing (inner ⌀0.76 mm, outer ⌀1.65 mm) is used to actuate the fingers. The tubes are mounted in the mold before pouring the silicone (see Fig. 3, step 2). Then, the silicone is degassed inside the mold (see Fig. 3, step 3) and cured at

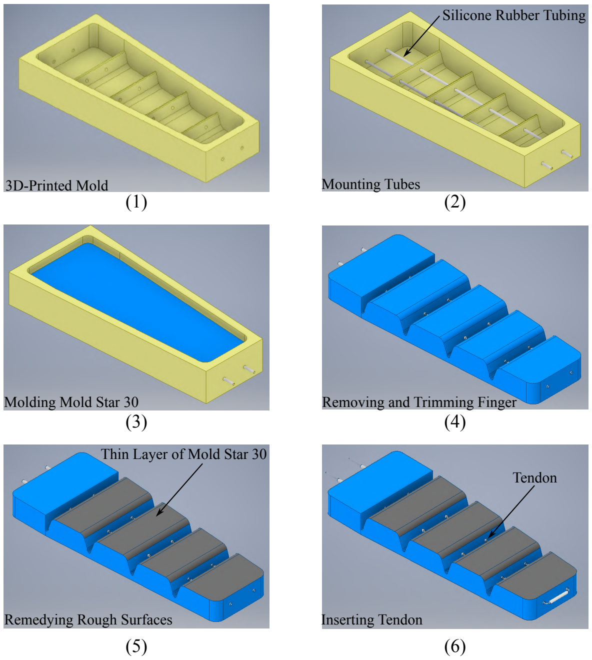

Fig. 3. Soft finger fabrication process. The thin layer of Mold Star 30 in steps 5 and 6 is highlighted gray for clarity.

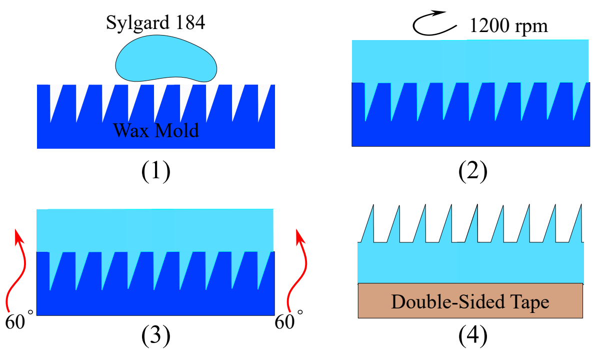

Fig. 4. Casting Sylgard 184 in a negative wax mold to create the gecko-inspired microwedges.

80 °C for 60 min. The finger is removed from the mold and carefully trimmed (see Fig. 3, step 4).

The electrostatic/gecko-inspired adhesives need a smooth surface to which to attach; however, due to imperfections in the 3D-printed mold, the surface of the fingers are rough. To remedy this, a thin layer of Mold Star is added on the surface and air cured (see gray layer in Fig. 3, step 5). Finally, the tendon is inserted through the tubing (see Fig. 3, step 6).

The 3D-printed main gripper body consists of a 320 N mm servo, a 3D printed spool, an electronic circuit with potentiometer to actuate the soft fingers, and a high voltage amplifier (EMCO, AG series) for electrostatic adhesion.

B. Gecko-Inspired Adhesives

The gecko-inspired adhesives used in this work are *directional*, meaning there is no adhesion when they are loaded solely in the normal direction (adhesion is off), but they can

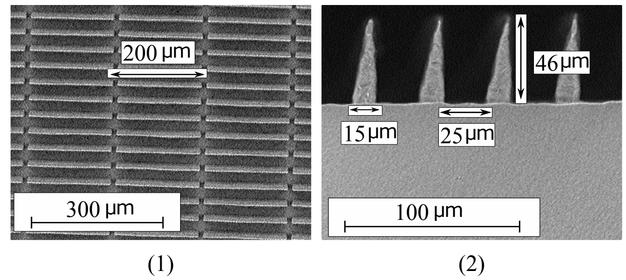

Fig. 5. SEM pictures of top (1) and cross sectional (2) views of the gecko-inspired adhesives.

sustain adhesion in the normal direction when first loaded in the shear direction (adhesion is on) [19]. To fabricate the gecko-inspired adhesives, we used Sylgard 184 (Dow Corning) due to its high work of separation, high elastic modulus, and low work of adhesion. Prior work has shown that these properties yield a gecko-inspired adhesive with high shear strength and low adhesion to dust [20].

For fabrication, Sylgard 184 is prepared per the manufacturer's instructions and degassed in a vacuum chamber. The mixture is poured into a negative wax mold of the gecko-inspired adhesive wedges [21] (see Fig. 4, step 1) and spun for 40 s at 1200 rpm (see Fig. 4, step 2). The mixture is degassed again until no bubbles appears and cured at 60 °C for 2 h (see Fig. 4, step 3). Double sided tape (100 µm thick, 3M) is used to detach the gecko-inspired adhesives from the mold (see Fig. 4, step 4). The microstructures are then fully cured at 120 °C for 30 min (see Fig. 5).

C. Electrostatic Adhesives

Electrostatic adhesives were fabricated both in-house and purchased from Pioneer Circuits, Inc. The fabricated adhesives were used on the gripper, and the purchased adhesives were used in characterization and testing of electroadhesion alone. Generally, the fabricated adhesives cannot be made with gaps smaller than 300 µm due to an increased risk of a spark, and the purchased adhesives must have a constant pitch (electrode width plus gap width) of 700 µm with an electrode gap and width that can vary in 100 µm increments because of manufacturing limitations. We have seen no discernible difference in their performance.

To fabricate an electrostatic adhesive pad [22], an interdigital pattern with 700 µm wide electrodes and 300 µm wide gaps is printed on toner transfer paper and laminated to the 9 µm-thick copper side of a 25 µm-thick Kapton sheet (see Fig. 6, step 1). Bare copper is removed by etching in a ferric chloride bath for approximately 15 min after which acetone is used to remove the ink covering the electrode pattern (see Fig. 6, step 2). A layer of DYMAX Multi-Cure 9-20557 resin insulates the electrodes. To reduce the risk of a spark forming, the resin is degassed in a vacuum chamber and a layer of 13 µm Kapton (*LF*7001, Dupont) is placed on top of the resin and laminated. The resin is cured in an oven at 100 °C for 2 h (see Fig. 6, step 3).

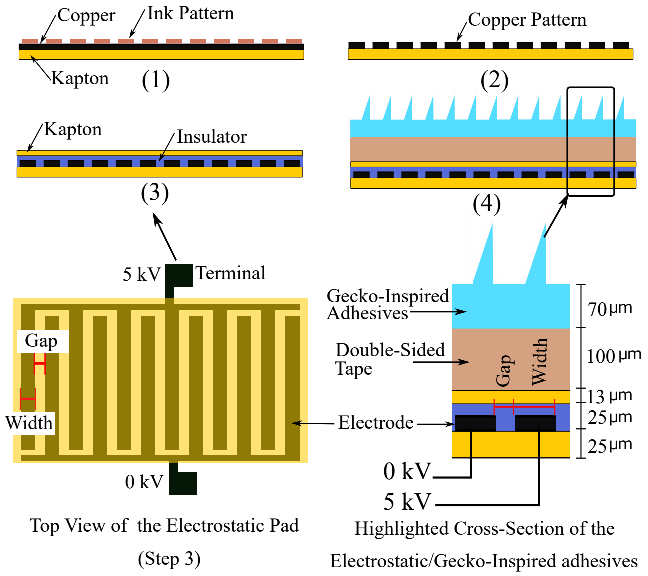

Fig. 6. The electrostatic pad fabrication and its combination with the gecko-inspired adhesives. Step 1) The electrode pattern is laminated to the copper side of a Kapton sheet. Step 2) A ferric chloride bath removes exposed copper. Step 3) Resin and a second layer of Kapton (*LF*7001) are added. Step 4) The electrostatic pad is attached to the gecko-inspired adhesives with double-sided tape. The bottom-left image shows a top-down view of the electrostatic pad in step 3. The bottom-right shows a cross-sectional view of electrostatic gecko-inspired adhesive. While electrostatic adhesion is on, one set of electrodes is grounded and the other has a 5 kV potential. Note that for clarity, elements are not drawn to scale.

D. Soft Electrostatic/Gecko-Inspired Adhesives Gripper

The other side of the double sided tape (3M) that was used to detach the gecko-inspired adhesives from the mold is used to attach the gecko-inspired adhesives to the electrostatic adhesive (see Fig. 6, step 4). To attach the complete electrostatic/gecko-inspired pads to soft fingers, another piece of 100 µm double sided tape (3M) is used. Electrostatic terminals and wires to high voltage amplifier are fixed on the two sides of soft fingers (see Fig. 7).

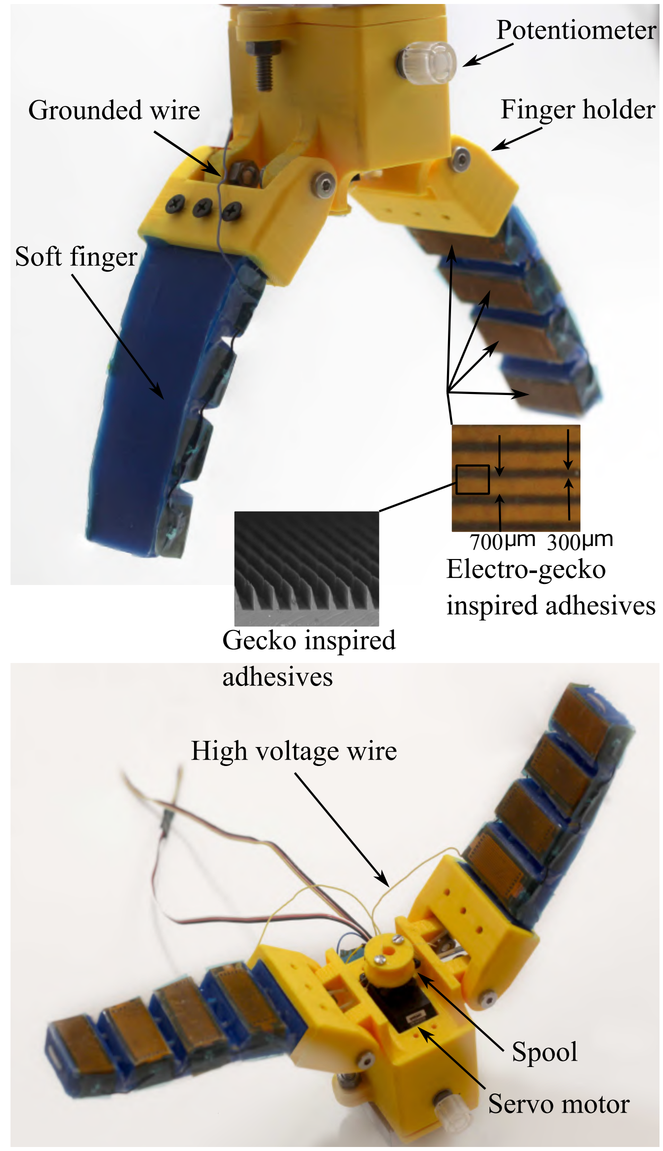

Fig. 7. The tendon-based soft gripper with electrostatic/gecko inspired adhesives.

III. Experimental Platform and Testing Procedure

To maximize adhesion, a parameter study was performed that included varying electrode gap, electrode width, air gap, and the gecko-inspired adhesive's dielectric constant.

The initial tests used six different electrostatic pad designs with electrode width and gap dimensions as follows: 600 µm/100 µm, 500 µm/200 µm, 400 µm/300 µm, 300 µm/400 µm, 200 µm/500 µm, and 100 µm/600 µm, respectively. Electrostatic adhesion was measured on a glass substrate using an Instron-5542 tensile tester and a static 50 N load cell with a holder moving at 50 mm min^{-1} (see Fig. 8 A). When electrostatic adhesion is on, one set of electrodes is grounded and another one has a 5 kV potential. To ensure a uniform load distribution, a thin foam backing is used and the glass substrate is attached on a leveled micro stage.

To confirm the experimental results, the six pads were modeled in Comsol Multiphysics with varying air gaps between the electrostatic pad and glass substrate (see Fig. 8 B). After confirming that the simulation matches the experimental results, the software was used to find the best electrode gap and width as a function of air gap and gecko-inspired adhesive dielectric constant. The gecko-inspired adhesives are assumed to be a thin, solid layer to simplify the simulation. As such, one 100 µm layer of simulated double-sided tape and one 110 µm layer of simulated gecko-inspired adhesive was added to model shown in Fig. 8 B. The relative permittivity of Kapton, the insulator, double-sided tape, and the substrate are assumed to be 3.7, 3.0, 3.2, and 5.0, respectively

Finally, the gripper's grasping force was measured using an Instron-5542 tensile tester (see Fig. 9). Grasping tests were performed under three conditions: 1) the soft gripper with no adhesives, 2) the soft gripper with electrostatic

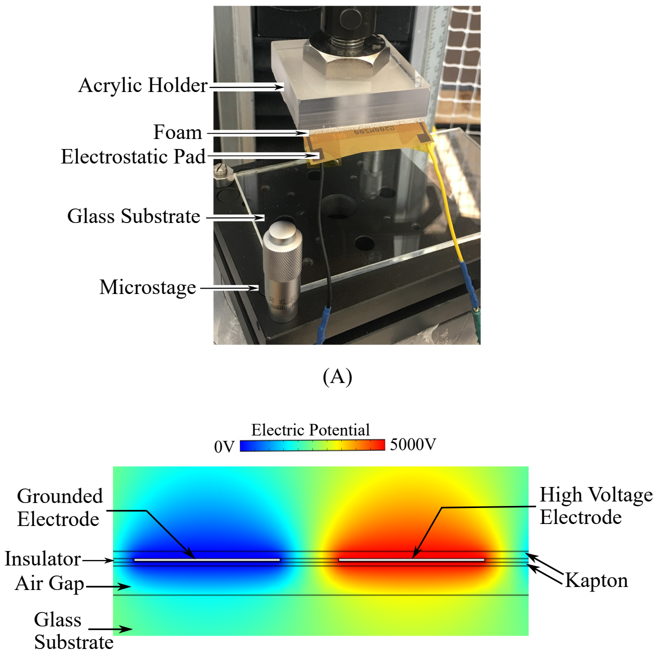

Fig. 8. A) Normal adhesion test of electrostatic pads. B) Electrostatic adhesion simulation in Comsol Multiphysics.

gecko-inspired adhesives (electrostatic adhesion is off), and 3) the soft gripper with electrostatic gecko-inspired adhesives (electrostatic adhesion is on). When electrostatic adhesion is on, one set of electrodes is grounded and another one has a 5 kV potential. Tests were done on hemispheres of three different diameters (203, 254, and 305 mm) and three different materials (acrylic, Tyvek fabric, and Kapton).

IV. Results and Discussion

A. Electrode Width and Gap Effect on Electrostatic Adhesion

Blue bars in Fig. 10 show the experimental results of the normal adhesion test for electrostatic pads with different electrode gaps and widths while the pitch remains a constant 700 µm. The electrostatic pad with 600 µm width and a 100 µm gap has the highest adhesion, and adhesion decreases as electrode width decreases. The latter is because a wider electrode results in a larger polarized area on the glass substrate and higher adhesion force.

Despite our best efforts to create a uniform load distribution, we know that an imperfect contact area will lead to some non-uniformity in the load, which will lead to stress concentrations and crack propagation as the adhesive releases from the substrate. In other words, even though we expect the experiment to have an air gap smaller than 5 µm [23], we know that we use a larger air gap value in the simulation to account for these imperfections.

In previous work to simulate electrostatic adhesion, the air gap was chosen based on the substrate's surface roughness [14], [24]. Here, we go further to identify the proper air

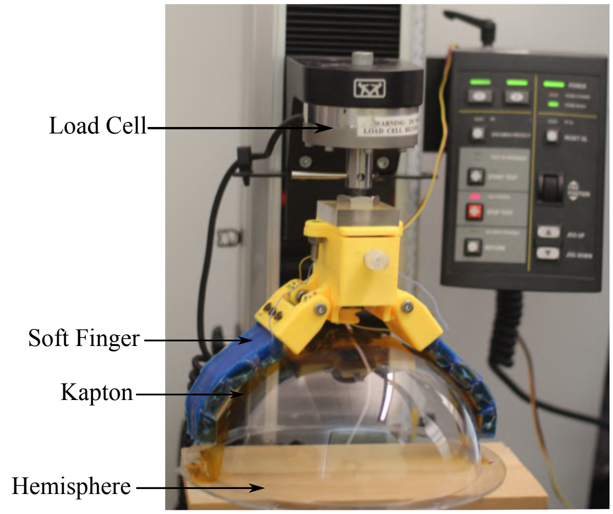

Fig. 9. Measuring griping force of electrostatic/gecko-inspired adhesives soft gripper while gripping an hemisphere covered with Kapton.

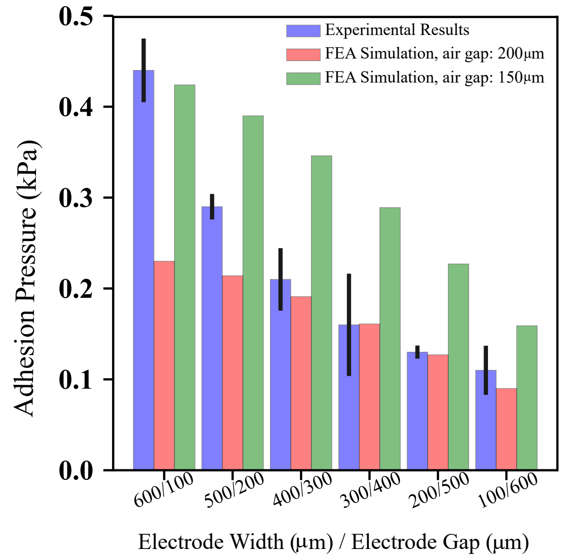

Fig. 10. Experimental and Comsol simulations of normal adhesion test with electrostatic adhesive pads on a glass substrate (see figure 8).

gap needed to demonstrate the effect of the aforementioned imperfections. This is illustrated in the red and green bars in Fig. 10, which show the Comsol Multiphysics simulation normal adhesion results with an air gap between the simulated glass substrate and electrostatic pad of 200 µm and 150 µm (see Fig. 8). The 200 µm air gap results matches the experimental results for electrostatic pads with 400 µm/300 µm, 300 µm/400 µm, 200 µm/500 µm, and 100 µm/600 µm electrode width and gap. The 150 µm air gap results matches with the experimental results for electrostatic pads with a 600 µm/100 µm electrode width and gap.

When adding the gecko-like adhesives to the simulation, note that they will take up some of the space of the air gap; thus, we simulated three smaller air gaps: 100 µm, 50 µm,

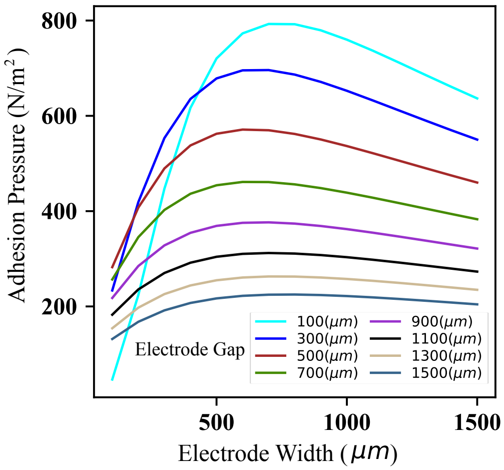

Fig. 11. Simulation results of electrostatic adhesion pressure versus electrode width for different electrode gaps (air gap is 10 μm, and relative permittivity of the gecko-inspired adhesive is 3).

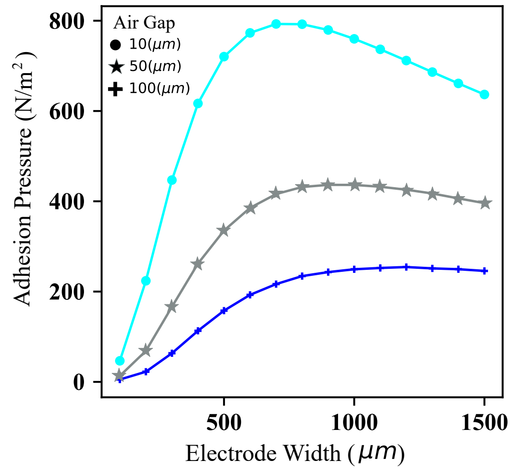

Fig. 13. Simulation results of electrostatic adhesion pressure versus electrode width for three different air gaps when electrode gap is 500 μm (relative permittivity of gecko inspired adhesives is 3).

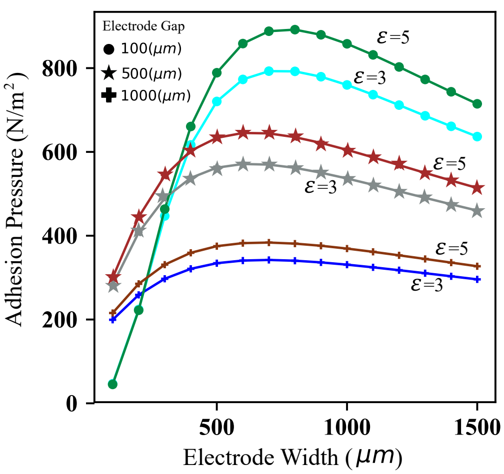

Fig. 12. Simulation results of electrostatic adhesion pressure versus electrode width for three different electrode gaps when relative permittivity (ε) of the gecko-inspired layer is either 3 or 5.

TABLE I

SIMULATION RESULTS SHOWING HIGHEST ELECTROSTATIC ADHESION PRESSURE VERSUS ELECTRODE GAP AND WIDTH FOR DIFFERENT AIR GAPS AND GECKO ADHESIVE RELATIVE PERMITTIVITY.

Air Gap (μm)	Relative Permittivity	Electrode Gap (μm)	Electrode Width (μm)	Adhesion Pressure (N/m^2)
100	5	100	1200	267
100	5	200	1100	262
100	5	300	1100	252
100	3	100	1200	254
100	3	200	1100	249
100	3	300	1100	238
50	5	100	1000	469
50	5	200	900	454
50	5	300	900	432
50	3	100	900	436
50	3	200	900	422
50	3	300	800	399
10	5	100	800	891
10	5	200	700	849
10	5	300	700	786
10	3	100	700	792
10	3	200	700	754
10	3	300	700	696

and 10 μm. Fig. 11 shows those simulation results with a dielectric constant of the gecko-inspired adhesives layer of 3. When the electrode gap is constant, increasing electrode width increases electrostatic adhesion until it reaches an optimum value and the rate of changes slows down for wider electrode gaps. The results show that there is an optimum gap and width to maximize electrostatic adhesion, trends that match previous work [24].

Fig. 12 shows that increasing the relative permittivity of the gecko-inspired layer increases electrostatic adhesion. Prior work has shown that adding Copper(II) Phthalocyanine to Sylgard 184 can tune the relative permittivity of the gecko-inspired adhesives [25].

Fig. 13 shows the air gap effect on electrostatic adhesion as a function of electrode width for three different air gaps when electrode gap is 500 μm. As can be seen, decreasing the air gap can improve electrostatic adhesion.

Table I shows the best electrode gaps and widths for electrostatic/gecko-inspired adhesives as a function of the air gap and relative permittivity of the gecko-inspired adhesive. Since the relative permittivity of Sylgard 184 is 2.7–3 and the soft gripper is tested on smooth materials, the results for a 10 μm air gap with a relative permittivity of 3 should yield the best results for the gripper (700 μm/100 μm width/gap). As mentioned earlier, due to limitations in the accuracy of printing the electrode pattern and etching of our fabrication method, we could not fabricate a gap less than 300 μm. Thus, an electrostatic adhesive with an electrode width of 700 μm

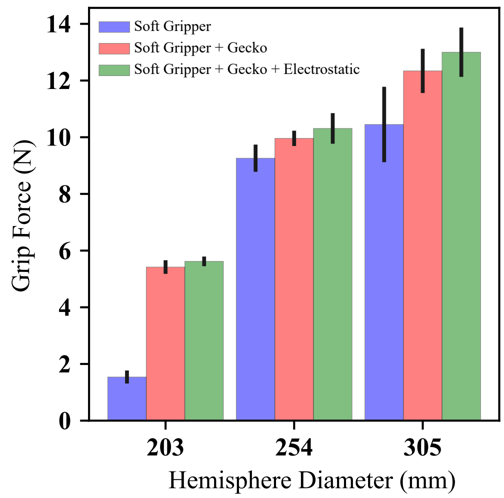

Fig. 14. Grip force for three hemisphere diameters when substrate is Acrylic. Error bars represent the standard deviation.

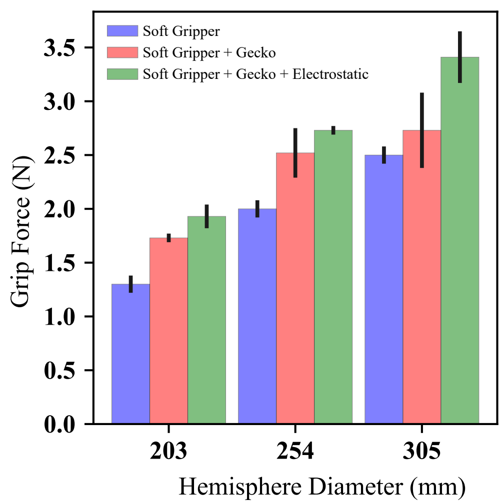

Fig. 15. Grip force for three hemisphere diameters when substrate is Tyvek. Error bars represent the standard deviation.

and a electrode gap of 300 µm was ultimately used (see Table I) in the gripper (see Fig. 7).

B. Soft Gripper Results

Figures 14, 15, and 16 show that electrostatic and gecko inspired adhesives significantly improve the gripping force of the soft gripper across a variety of materials, including Acrylic, Tyvek fabric, and Kapton, and substrate with curvatures of 203, 254, and 305 mm. Adding gecko-inspired adhesives to the soft gripper increases its gripping force for different curvatures an average of 92% (2.15 N), 21% (0.36 N), and 103% (3.60 N) for Acrylic, Tyvek fabric, and Kapton, respectively. Most of improvement occurs for smallest curvature (203 mm), where gripping force without the gecko-inspired adhesives is very low, and smooth materials (Acrylic and Kapton).

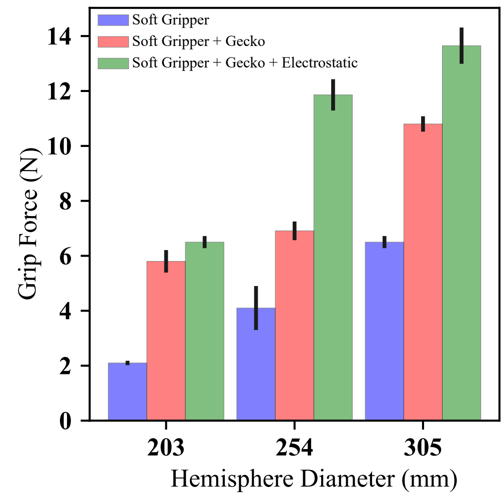

Fig. 16. Grip force for three hemisphere diameters when substrate is Kapton. Error bars represent the standard deviation.

Acrylic has a relative permittivity of ≈ 2.6. Tyvek is a lightweight, durable, and water-resistant synthetic material made from polyethylene fibers with a ≈ 2.4 relative permittivity. Kapton is a polyimide film with a relative permittivity of ≈ 3.7. Electrostatic adhesion is proportional to the relative permittivity of the material such that gripping force improvement should be highest in the Kapton, followed by Acrylic and Tyvek fabric.

Experimental results show that electrostatic adhesion increases the gripping force 4% (0.4 N), 15% (0.38 N), and 36% (2.83 N) for Acrylic, Tyvek, and Kapton, respectively. The gripping force increase is about the same for acrylic and Tyvek since their relative permittivities are close. However, the percent increase for Tyvek is higher due to its lower overall gripping force. Finally, for all three substrates, a larger hemisphere diameter increases gripping force, which is due to larger contact area between the gripper and substrate. Microscopic contact areas between the gripper and object for the soft gripper, soft gripper with gecko-inspired adhesives, and soft gripper with electrostatic/gecko-inspired adhesives are shown in Fig. 2 A, C, and E, respectively. Note that all three materials tested are non-conductive.

To improve electrostatic adhesion on all materials, including those with low relative permittivity, the gecko-inspired adhesives can be fabricated from high relative permittivity materials [25] (see Fig. 12) or electrodes could be brought closer to the surface (e.g. casting gecko-inspired adhesives directly on the surface of electrostatic pads, without using double sided tape [22]). Last, the gripper design could be improved to have larger contact area by adding more sections or fingers.

V. Conclusions

In this research, the gripping force of a soft gripper is improved by utilizing a gecko-inspired and electrostatic adhesive. Simulations in Comsol Multiphysics informed us of the proper geometry for the electrodes in the electrostatic adhesion portion of the adhesion. Experimental results show an improved grasping force on hemispheres of different diameters across three different materials. The gripper may prove useful in space applications because the underlying technologies are all space compatible.

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