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Development of a gecko-like robotic gripper using Scott–Russell mechanisms

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SUMMARY
This paper describes the development of a gecko-inspired robotic gripper for grasping flat objects using Scott–Russell mechanisms. Compared to previously reported grippers that utilize gecko-like adhesives, the one presented here produces higher normal adhesion and has robustness and controllability advantages. To verify the applicability of proposed gripper, a mechanical model and experimental results on a variety of substrates are presented. The experimental results demonstrated a 19.6% and 50% increase in normal adhesion using a preload of <15 and <30 N, respectively, compared to previously reported results under similar testing parameters and conditions.

KEYWORDS: Gecko-like adhesion; Scott–Russell mechanism; Robotic gripper.

1. Introduction

Automated flat panel handling systems are used in manufacturing operations for transporting discrete flat parts from one processing machine to another or packing final products. These systems are typically designed for a particular process and/or to take advantage of the material properties of the object being handled (e.g., using an electromagnetic gripper to manipulate ferromagnetic materials). This paper describes a robotic manipulator gripper that utilizes gecko-like adhesives to be used in such systems (see Fig. 1a).

In recent years, gecko-like dry adhesives have been introduced as a new approach for manipulating flat objects in robotic grippers.[1–7] The method has several advantages over other, more traditional, gripping methods such as lower power consumption compared to suction-based systems[8] or the ability to handle non-magnetic materials.[9,10] Controllability, or the ability to turn the adhesive on and off, arises from the use of *directional* gecko-like adhesives (see Fig. 1b). When these adhesives are loaded solely in the normal direction, only the tips of the gecko-like structures contact the substrate, creating little to no adhesion. However, when the adhesives are first loaded in shear, the gecko-like structures bend over to create a large real area of contact with the substrate, subsequently creating a large normal adhesion pressure.[2] In general, the more shear load that is applied to the adhesives, the more allowable normal adhesion is generated (up to a limit). Thus, by controlling the shear load, one can subsequently turn the normal adhesion 'on' or 'off.'

Recent gecko-inspired grippers with directional adhesives have utilized tendons to transmit force from a centralized actuator and generate a shear load in the adhesives.[8,10,11] Tendon-based grippers have several advantages: they are compact, easy to fabricate, and distribute loads evenly across multiple adhesive pads. However, tendon-based grippers have difficulty finely controlling the applied load, and they tend to loosen over time, creating reliability and robustness issues. While the latter may be non-issues for prototypes in laboratory environments, it can create challenges in real-world

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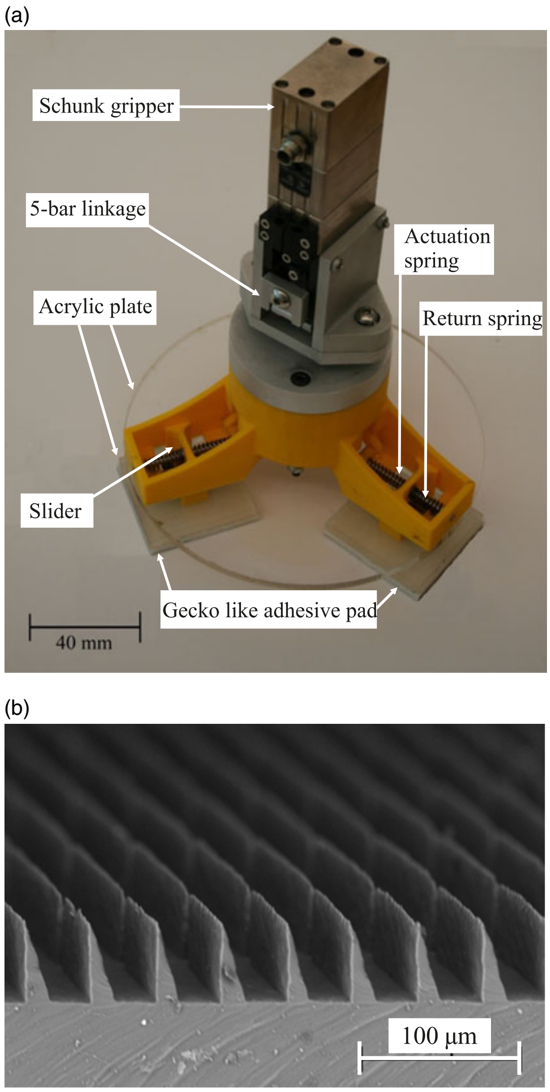

Fig. 1. (a) A gecko-like robotic gripper that utilizes a Scott–Russell mechanism to transmit load from a central actuator to three gecko-like adhesive pads and (b) a scanning electron microscope picture of the synthetic, directional gecko-like adhesives used in this work.

manufacturing environments. To address these issues, a shape memory alloy-actuated gecko-inspired robotic gripper was presented in ref. [12], but the proposed gripper had a relatively high power consumption and low response time (due to the shape memory alloy wire cooling time) in comparison to similar grippers. Moreover, the shape memory allows wires, similar to tendons, loosen over time, thus requiring the gripper to be periodically re-calibrated.

In response, this paper introduces a robotic gripper for directional gecko-like adhesives that utilizes three Scott–Russell mechanisms to transmit loads from a central actuator to multiple adhesive pads (see Figs. 1 and 2). Scott–Russell mechanisms are relatively simple and have the advantage of amplifying displacement orthogonal to the input motion vector. The gripper is designed to be mounted on a robotic manipulator to perform pick-and-place operations. The result is a gripper that is more robust and reliable than previous tendon-based grippers.

The paper is organized as follows. Section 2 outlines the design of the gripper, presents a lumped-parameter model of the system, and discusses the gripper's fabrication. Section 3 describes the experimental set-up used to characterize the gripper. Section 4 provides results. Finally, Section 5 presents concluding remarks and highlights potential areas of future work.

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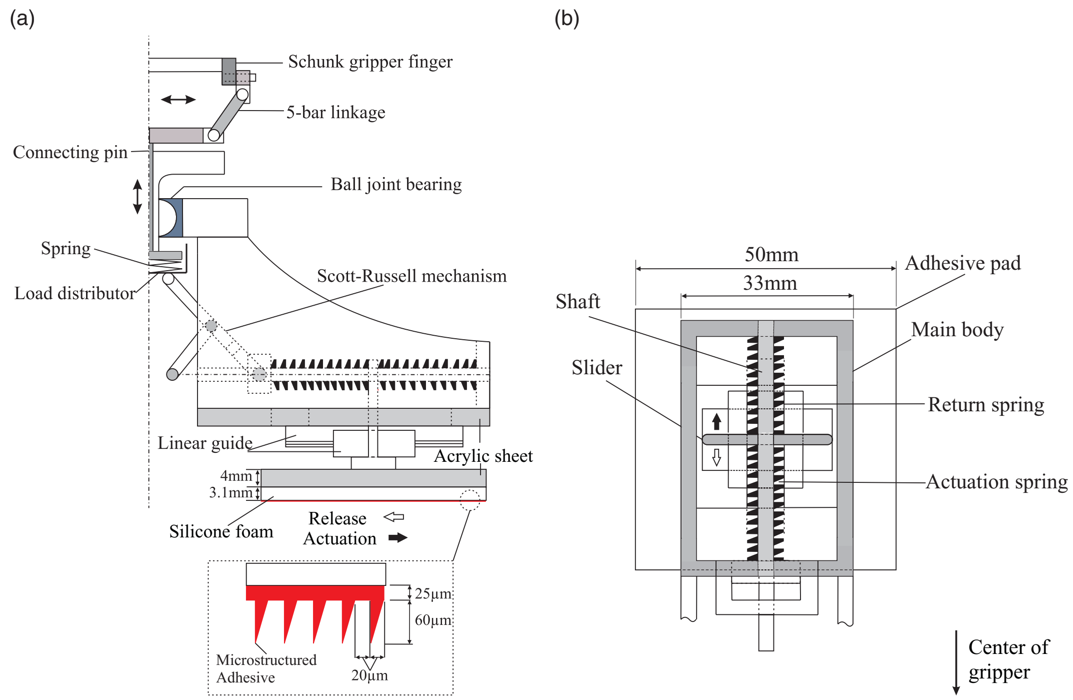

Fig. 2. (a) Transverse view of one arm of the proposed gripper and (b) cross-sectional view.

2. Gecko-like Robotic Gripper Using Scott–Russell Mechanisms

In this section, the design and fabrication of the gecko-like gripper is described.

2.1. Design

For ease of integration with an industrial manipulator arm, the gripper is actuated with a Schunk EGP 40-N-N-B two finger parallel gripper. Consequently, the Schunk's jaw displacement acts as the input parameter to the new gripper. The aim of the mechanical design of the gripper is to design a mechanism to transmit displacement of the Schunk gripper to a shear load applied to the gecko-like adhesives. This is accomplished with a five-bar linkage that converts the motion of the Schunk's two parallel fingers into a kinematically constrained vertical translation. A load transfer pin transfers the load from the Schunk to three Scott–Russell linkages through a load distributor, which converts the vertical displacement of load transfer pin to the horizontal displacement of three sliders positioned in three arms in the gripper. Figure 2 shows a transverse and cross-sectional view of one arm of the proposed gripper.

To distribute the load evenly among the linkages, Belleville disc springs are placed in series with the load distributor. The load transfer pin is placed at the center of a compliance system that allows the engagement pin to float while also transferring loads (Fig. 2a top).

The gripper mechanism uses a set of three gecko-like adhesive pads arranged in a triangular configuration. The arrangement of the adhesive pads in a triad creates a gripper that is robust to side loads. Displacement from the Scott–Russell mechanism is transferred to a slider in each arm using a shaft and spring (Fig. 2b). By adjusting the stiffness of this spring, one can tune the shear force on each pad. A mathematical model for this is presented in the following section.

For the fibular stalks of the gecko adhesive to take hold between the adhesive pads and the contact surface, a consistent and compliant engagement mechanism is necessary. To this end, a ball joint between the Schunk gripper and the body holding the linkages allows the gripper body to rotate (Fig. 2a top). This helps align the pads to the substrate within an initial misalignment of up to 30°.

A linear guide and slider transmits the displacement from the actuating spring to each adhesive pad. The linear slides prevent the transmission of any moments from the Scott–Russell mechanism to the adhesive pads (Fig. 2a bottom). Any disturbance and unwanted moments can be extremely detrimental because they initiate peeling, which can propagate through the adhesive and dislodge the pad from the substrate. A circular smooth flat acrylic plate (Fig. 2a bottom side, top acrylic sheet)

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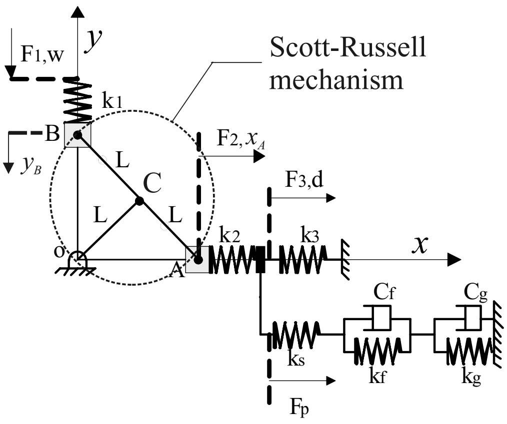

Fig. 3. Mechanical model of the proposed gripper.

between the gripper's main body and the linear guides provides a flat surface for the linear guide's connections. To improve the flexibility of the pads and compliance between the pads and substrate, silicone foam was used as a backing for the gecko-like adhesive pads.

Finally, a compression spring is placed in series with the actuating spring to return the slider to its initial position when the object is released from the gripper.

2.2. Lumped parameter model

Figure 3 shows a simplified lumped parameter model of the gripper. From a mechanics perspective, the silicone foam and gecko-like adhesive can be considered as a parallel spring and damper system with damping coefficients of C_f and C_g, and stiffness coefficients of k_f and k_g, respectively. In this model, k_{1-3} are the stiffnesses of the Belleville disc spring, actuating spring, and return spring, respectively. Finally, k_s is the stiffness of slider.

A Cartesian coordinate system is established as shown in Fig. 3. The distances from point O to points A and B are x_{AO} and y_{BO}, respectively. Since there are enough space inside the gripper body for transmitting movement using the Scott–Russell Mechanism and for decreasing stress concentration in linkages, the Scott–Russell Mechanism was designed to have same link lengths($AC = BC = CO = L$). Based on the geometric relationship of the Scott–Russel mechanism, the following holds:

$$y_{BO} = \sqrt{(2L)^2 - x_{AO}^2} \tag{1}$$

When joint B moves in the $-y$ direction with a displacement of y_B, joint A will displace x_A along the X-axis. The relationship between the displacement of joint B and A is

$$x_{AO}^2 + y_{BO}^2 = (x_{AO} + x_A)^2 + (y_{BO} + y_B)^2 \tag{2}$$

After simplifying Eq. (2), the displacement of joint B is given as

$$y_B = -y_{BO} + \sqrt{y_{BO}^2 - 2x_{AO}x_A - x_A^2} \tag{3}$$

Since the maximum normal adhesion of the gripper depends on the applied shear force, tuning the shear load applied to the gecko-like pad is necessary. In general, the normal adhesion will increase linearly with respect to the shear load up until some limit.[2] The goal is to generate a shear load just below that limit given the displacement of the Schunk gripper. This is done by choosing the appropriate spring constants as a function of displacement to yield the desired shear load. The relationship is defined as follows.

Based on Fig. 3, if we consider that the displacements of y_B and x_A are caused by the Schunk gripper, the force acting on the load distributor is given as

$$F_1 = k_1(w - y_B) \tag{4}$$

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where w is the displacement of connecting pin. The force acting on actuation spring given as

$$F_2 = k_2(x_A - d) \tag{5}$$

and the force acting on the return spring is

$$F_3 = k_3 d \tag{6}$$

where d is the displacement of the return spring. Since there are three arms and hence three Scott–Russell mechanisms in proposed gripper, the force acting between the load distributor and actuation spring is given as

$$F_1 = 3F_2 \tag{7}$$

Finally, the force acting on actuation spring is equal to the force acting on the return spring and adhesive pad/silicone foam:

$$F_2 = F_3 + F_p \tag{8}$$

where F_p is the applied shear force to gecko-like pad. Since $F_1 = 3F_2$ and $x_A = y_B$, the displacement of joint A is

$$x_A = \frac{k_1 w + 3k_2 d}{k_1 + 3k_2} \tag{9}$$

Combining Eqs. (6), (7), (8), and (9) yields

$$F_p = k_2\left(\frac{k_1 w + 3k_2 d}{k_1 + 3k_2} - d\right) - k_3 d \tag{10}$$

Using the frictional adhesion model[2] and the calculated shear force, the normal adhesion force can be estimated. In this work, w and the d are 3.5 mm and 0.5$-$1 mm, respectively. Since the displacement of the return spring, d, is much smaller than the displacement of actuation spring, the dominant factor for determining the shear force is the spring constant of the actuation spring, k_2. Calculating the theoretical normal adhesion force is challenging since the exact contact area is difficult to compute, and the adhesion force is a function of the contact area in addition to the material properties and exact dimensions of the gecko-like adhesive. Thus, only experimental results are given in this paper.

2.3. Fabrication

The 5-bar linkage, load transfer pin, and load distributor are comprised of aluminum. The main body of the gripper, slider, and Scott–Russell linkage were 3D printed from polylactic acid (PLA). To maintain a flat and smooth surface for connecting the gecko-like adhesive to the gripper, a circular, 4.5 mm-thick acrylic plate was attached to the bottom of the gripper's main body. Miniature linear guides (MISUMI-SEBSZ8-40) were then connected to the circular acrylic plate.

The adhesive/gripper interface consists of a 50 mm × 50 mm acrylic hard-backing tile, silicone foam (MARIAN-BF1000), and a gecko-like adhesive that are connected to each other using double-sided tape (3M Double Coated Adhesive Tape). The tape has a silicone adhesive on one side and non-silicone adhesive on other side.

To fabricate the gecko-like adhesive wedges, polydimethylsiloxane (PDMS, Dow Corning Sylgard 170, 184 and BJB Enterprise TC-5041) was prepared according to the manufacturer's specification and degassed in a vacuum chamber at 30 in.Hg until all air bubbles disappeared. PDMS material selection was based on previous work[8,12] and prior experience. Here, three PDMS materials were tested to illustrate and compare their effect on adhesion. A spin-coating machine created a flat thin film (approximately 150 μm) of PDMS on the surface of a negative wax mold of the microwedges, which is then cured in an oven. Further details of the manufacturing process can be found in [7].

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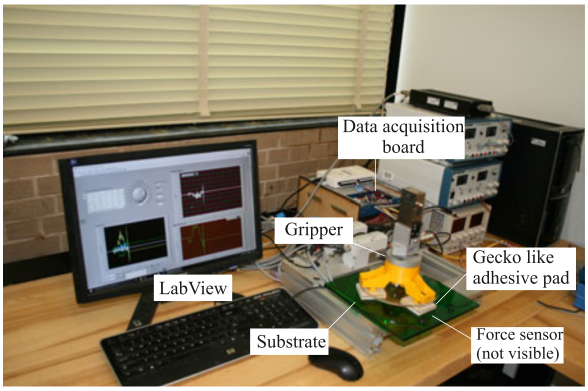

Fig. 4. Experimental set-up.

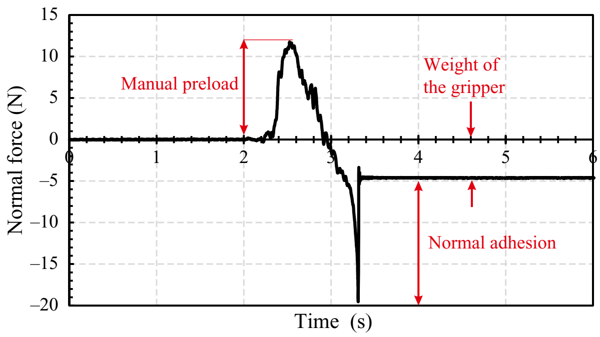

Fig. 5. Typical normal force profile.

3. Experimental Set-up

An experimental test stand was prepared to measure both shear and normal force of the gripper (see Fig. 4). A JR3 multi-axis force/torque sensor (model 67M25A3) was fixed below the selected sample substrate. For measuring both shear and normal force simultaneously, only one gripper arm is placed above the sensor. The gripper was pulled off from the substrate manually during experiments, and the experimental results were recorded using Labview.

A variety of normal preloads were applied by hand to the gripper, in addition to the gripper's weight, in an effort to increase the conformation between the adhesive pads and the substrate. Figure 5 shows a typical sensor output (normal force) during experiments. The experiments were repeated at least 10 times for each sample. Temperature and humidity were measured to be within 18–22°C and 40–45%, respectively. While not performed under ideal temperature and humidity conditions, all tests were performed under similar environmental conditions over the course of several days. Previous, unpublished work has shown that any variations in the humidity and temperature across the testing days would results in negligible differences in the adhesion.

4. Experimental Results

To demonstrate the gripper's effectiveness, the shear and normal force as a function of adhesive material, substrate material, and preload were measured. In addition, the proposed lumped parameter model was verified experimentally.

Figure 6 shows the relationship between shear adhesion and normal adhesion for the three materials on a glass substrate. Glass was selected because its smooth, flat surface engages well with the gecko-like adhesives and can serve as a control to measure prior work against.

The results show that normal adhesion in TC-5041 is generally higher than the Sylgard materials for a given shear load. However, Sylgard 170 has the most allowable normal adhesion with shear stress values around 5–6 kPa. Note that at or above 6 kPa, the normal adhesion drops for Sylgard 184 and TC-5041, indicating that applying a shear load higher than this would result in less allowable normal load.

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Table I. Comparison between calculated and measured shear force for different stiffness of actuating spring

k_2 (N/mm)	Calculated shear stress (kPa)	Measured shear stress (kPa)	Measured normal adhesion (kPa)
2.8	2.07	2.01	2.88
4.0	2.78	2.59	3.22
8.0	4.18	3.77	4.05
9.9	4.67	4.15	4.22

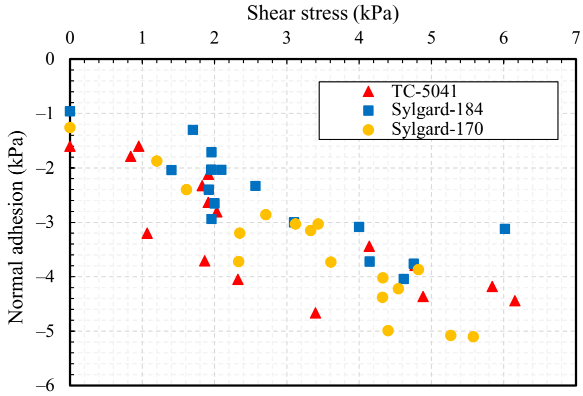

Fig. 6. Measured normal adhesion versus shear stress for Sylgard-170, Sylgard-184, and TC-5041.

Figure 7(a,b,c) shows the relationship between the preload and shear force and normal force for the three materials. The figure shows that by increasing the preload, shear force, and hence normal force, increases almost linearly. When preload increases, the contact area between the adhesive and substrate increases and consequently, the Van der waals force between the adhesive and substrate increases.

Figure 8 illustrates the normal adhesion pressure of the gripper on four rigid substrates—steel, acrylic, glass, and carbon fiber. To compare the results with prior work, Sylgard-170 was selected as adhesive material. Normal adhesion was measured under two conditions: a preload of 15 N and a preload between 15 and 30 N.

Results show that the carbon fiber substrate generates the highest normal adhesion. Comparing with prior work[8] indicates a 15%, 2%, and 42% increase in normal adhesion when preload is less than 15 N and a 42%, 40%, and 70% increase in normal adhesion when the preload is between 15 N and 30 N for acrylic, glass, and carbon fiber, respectively. Compared to the aforementioned shape memory allow gripper,[12] the experiments results show a 100%, 78% , 76%, and 90% increase in normal adhesion when preload is less than 15 N and a 103%, 138%, 162% and 128% increase in normal adhesion when the preload is between 15 N and 30 N for steel, acrylic, glass, and carbon fiber, respectively. This translates to the ability to lift 3.3 kg flat sheets comprised of a variety of materials (glass, acrylic, steel and carbon fiber) using less than a 15 N preload.

Table I demonstrates the measured shear stress and normal adhesion using springs with different stiffness for k_2, the actuation spring, and compares them with the calculated shear stress from Eq. (10). During experiments, the stiffness of k_3 was 4 N/mm and test substrate was glass. Four Belleville disc springs with stiffness of 200 N/mm were used in series to create an overall stiffness of 50 N/mm for k_1. To decrease the effect of any normal preload on the shear stress, no manual preload was applied to adhesive pads during experiment save the weight of the gripper.

The average difference between calculated shear force and measured shear force in Table I is 8%, which indicates good agreement between the model and experimental results. Deviations in the results may be attributed to unmodeled friction.

5. Conclusion

This paper describes a development of a gecko-inspired gripper that consists of three opposing gecko-like adhesive pads loaded in shear by a Schunk gripper through a Scott–Russell Mechanism. Shear and normal adhesion were measured on a variety of rigid materials, and a mechanical model was

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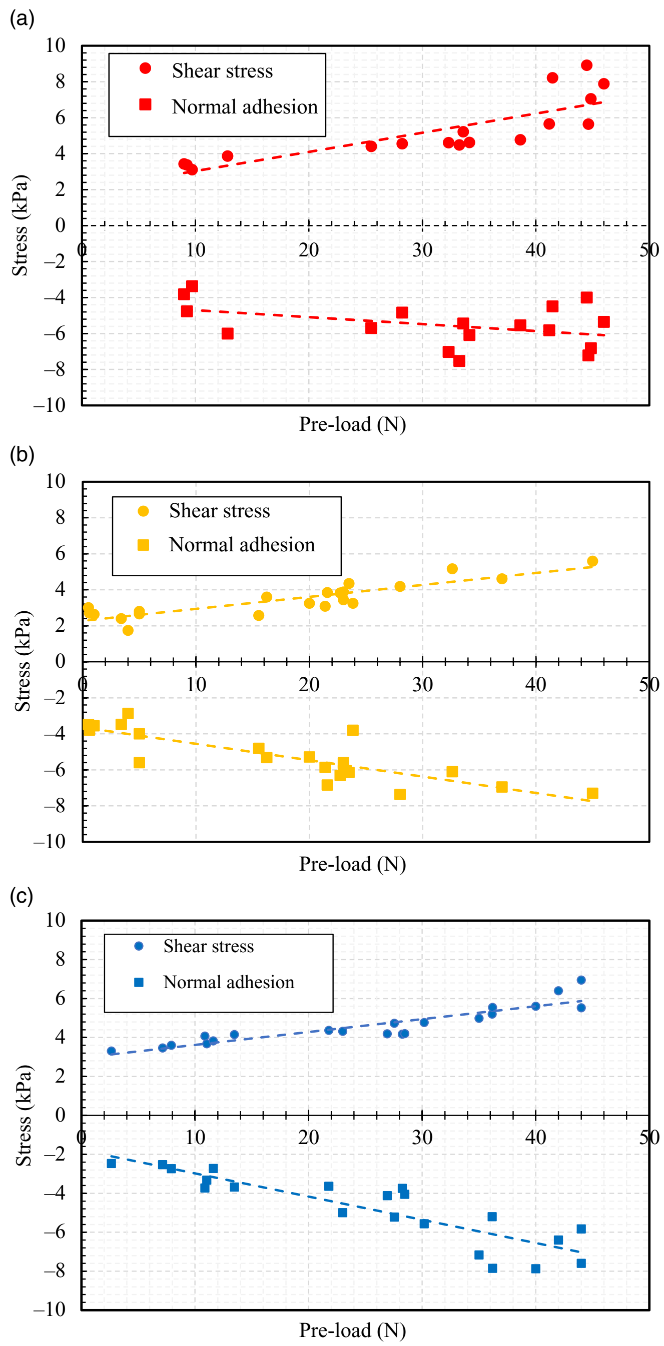

Fig. 7. Measured normal adhesion and shear stress versus preload for (a) TC-5041, (b) Sylgard-170, and (c) Sylgard-184.

presented. Experiments demonstrate that the gripper is able to successfully pick up and release glass, carbon fiber, acrylic, and steel sheets with a higher level of normal adhesion than several existing grippers.

A comparison among three materials used to fabricate the gecko-like adhesives, Sylgard-170, Sylgard-184, and TC-5041, revealed that normal adhesion in TC-5041 is the highest for low shear loads, but that Sylgard-170 provides the highest level of normal adhesion at high shear loads. In addition, the actuation performance of the prototype gripper was evaluated with a focus on the effect of varying normal preloads on performance, indicating a nearly linear response. The performance of proposed robotic gripper illustrated that this gripper is suited for automated flat panel handling systems in industrial manufacturing. For future work, we will be improving the functionality of the

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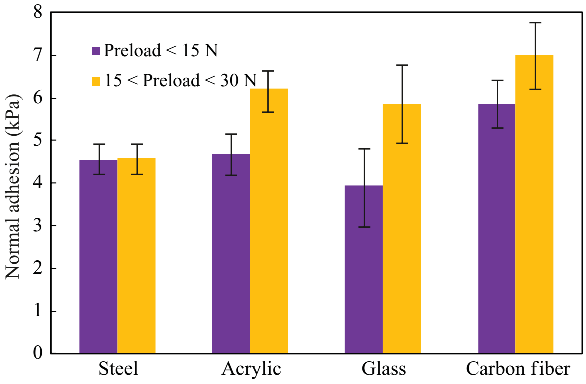

Fig. 8. Experimental evaluation of the proposed gripper on rigid substrates. Error bars represent standard deviation.

gripper by adding a force sensor to each adhesive pad to measure preload and including electrostatic adhesion to increase the adhesion force on rough surfaces.

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