Soft pneumatic grippers embedded with stretchable electroadhesion

J. Guo[1,2,4], K. Elgeneidy[2,3,4], C. Xiang[1,4], N. Lohse[2], L. Justham[2], J. Rossiter[1]

[1]Soft Robotics Group, Bristol Robotics Laboratory, University of Bristol, Bristol, UK (BS16 1QY)

[2]EPSRC Centre for Innovative Manufacturing in Intelligent Automation, The Wolfson School of Mechanical, Electrical and Manufacturing Engineering, Loughborough University, Leicestershire, UK (LE11 3TU)

[3]Lincoln Institute for Agri-Tech, University of Lincoln, Lincoln, UK (LN6 7TS)

[4]These authors contributed equally to this work.

Email: J.Guo@bristol.ac.uk

Abstract: Current soft pneumatic grippers cannot robustly grasp flat and flexible objects on curved surfaces without distorting them. Current electroadhesive grippers can efficiently grasp free-form surfaces. An easy-to-implement PneuEA gripper has been proposed by the combination of electroadhesive actuators and soft pneumatic grippers. The soft PneuEA gripper was developed by the integration of an electroadhesive actuator and a two-fingered soft pneumatic gripper. The electroadhesive actuator was fabricated by segmenting a soft conductive silicon sheet based on into a two-part electrode design and embedding it in soft dielectrics. The two-fingered soft pneumatic gripper was manufactured using a standard soft lithography approach. This novel integration has combined the benefits of both the electroadhesive and soft pneumatic grippers. As a result, the proposed PneuEA gripper was not only able to pick-and-place flat and flexible materials such as a porous cloth but also delicate objects such as a light bulb. By combining two soft proximity sensors with the electroadhesive actuator, an intelligent and shape-adaptive PneuEA material handling system has been developed. This work is expected to widen the applications of both soft gripper and electroadhesion technologies.

Keywords: electroadhesion, robotic material handling, soft electroadhesive, soft pneumatic gripper.

1 Introduction

Soft robots are bio-inspired and versatile soft machines made of intrinsically soft, extensible, and deformable materials[1-2]. Soft robots usually require smart materials, structures, and transducers to deliver desired motions and behaviours. Compared to conventional rigid counterparts, they can bring certain advantages including[3]: 1) soft robots are able to offer safer and more robust interactions with human beings and natural environments; and 2) soft robots are more resilient and capable of passively adaptint to various environments.

Soft robots are poised to revolutionize robotics in many real-life applications such as the pick-and-place of delicate objects, inspection in unknown/confined spaces, and robotic assisted living[1-4]. Soft grippers are one category of soft robots. Compared to traditionally rigid grippers, these intrinsically soft grippers or actuators are capable of achieving highly compliant and adaptable grasping performances, such as the pick-and-place of difficult-to-handle objects[1-4]. Various soft grippers have been extensively studied and implemented[1-4]. Soft pneumatic grippers (SPGs) are one of the most commonly adopted techonologies and have been configured as soft bending fingers for passively compliant soft grasping applications[1-5]. SPGs are made of highly stretchable elastomer materials with internal fluidic channels (commonly referred to as PneuNets)[5]. They can deform upon the pressurisation of the internal channels to create a predefined motion[5]. It is difficult, however, for current SPGs to robustly grasp flat objects or to pick up objects without fully enclosing them. In addition, current SPPs cannot grasp lightweight and flexible objects on curved surfaces without distorting them.

The on-going development of soft robotics has increased the need for smart and soft transducers. Smart and soft actuators are deformable components that can be energised by external stimuli (such as electric fields) to produce desired motions and forces/torques[5]. Electroadhesive actuators are promising adhesive actuators that can be employed to grasp objects in a range of real-life applications where a wide range of surfaces (from smooth glass to rough concrete surfaces) and environmental conditions (from vacuum to humidity, warm, and even dusty environments) are encountered[7]. This is because, electroadhesion[8], an electrically controllable and dynamic electrostatic attraction between an electroadhesive pad and a substrate[9], compared with other adhesion mechanisms such as magnetic, pneumatic, and bio-inspired adhesion methods[10], have certain advantages including enhanced adaptability, gentle/flexible handling, reduced complexity, and ultra-low energy consumption[7,9,11].

To date, very few electroadhesive actuators or grippers can robustly grasp free-form surfaces. In addition, they cannot grasp flexible objects from curved surfaces. Savioli et al. proposed a morphing electroadhesive gripper, combining shape memory polymer with electroadhesion, to manipulate uncooperative objects[12]. The gripper's response speed was relatively slow (over half an hour)[12]. Suresh et al. presented a curved surface gripper, combining complaint mechanical structures, gecko-inspired adhesives, and electroadhesion, to grasp various objects[13]. The gripper was developed using a delicate and complex surface and shape deposition manufacturing approach[13]. Shintake et al. combined dielectric elastomer actuators and electroadhesion together to fabricate soft grippers capable of manipulating various difficult-to-handle objects[14]. These soft grippers were created from precision designs with multiple electrode and dielectric layers under complex pre-stretches[14].

The great challenge for current SPGs is to grasp flat materials and to grasp without fully enclosing an object. It is also difficult for current electroadhesive grippers to manipulate complex-shaped objects. In this paper, we report the development of a novel and cost-effective PneuEA gripper by the integration of a stretchable electroadhesive actuator onto a two-fingered soft pneumatic bending actuator. As a result, the PneuEA gripper is not only able to pick-and-place delicate objects such as light bulbs and deformable objects such as volleyballs, but also flat objects such as porous clothes, CDs, plastic plates. This gripper demonstrates the enhancement of both technologies and may significantly promote the application of electroadhesion and soft pneumatic gripper technologies.

The contents are organized as follows: In section 2, the concept design and fabrication details of the PneuEA gripper are described; A customized experimental platform and the related experiment procedures to measure the electroadhesive forces are presented in section 3, plus several material handling case studies; The design and development of an intelligent PneuEA material handling system are illustrated in section 4, before conclusions and future work presented in section 5.

2 Design and manufacture of the PneuEA gripper

2.1 PneuEA gripper concept design

The proposed PneuEA is a synthesis of a soft and stretchable electroadhesive actuator and a two-fingered soft pneumatic actuator. A schematic diagram of the gripper in 3D is presented in figure 1. This easy-to-implement design was based on low-cost and easy-to-procure commercial conductive silicon rubber sheets and dielectric silicon elastomers.

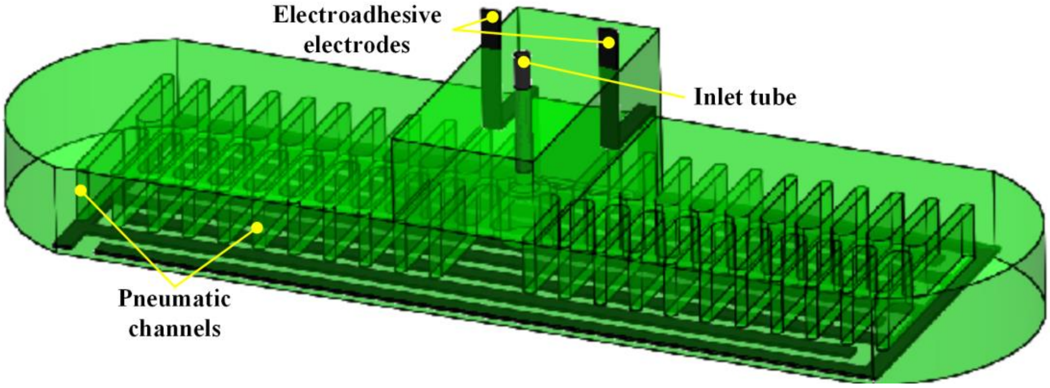

FIG. 1. Schematic diagram of the PneuEA gripper in 3D.

The fabrication procedure of the proposed gripper is straightforward and can be seen in figure 2. Specifically, the PneuEA gripper fabrication procedure contains three major steps including: 1) manufacturing the soft pneumatic actuator, as shown in figure 2 (a), 2) manufacturing the stretchable electroadhesive actuator, as shown in figure 2 (b), and 3) integrating the soft pneumatic actuator with the electroadhesive actuator, as shown in figure 2 (c).

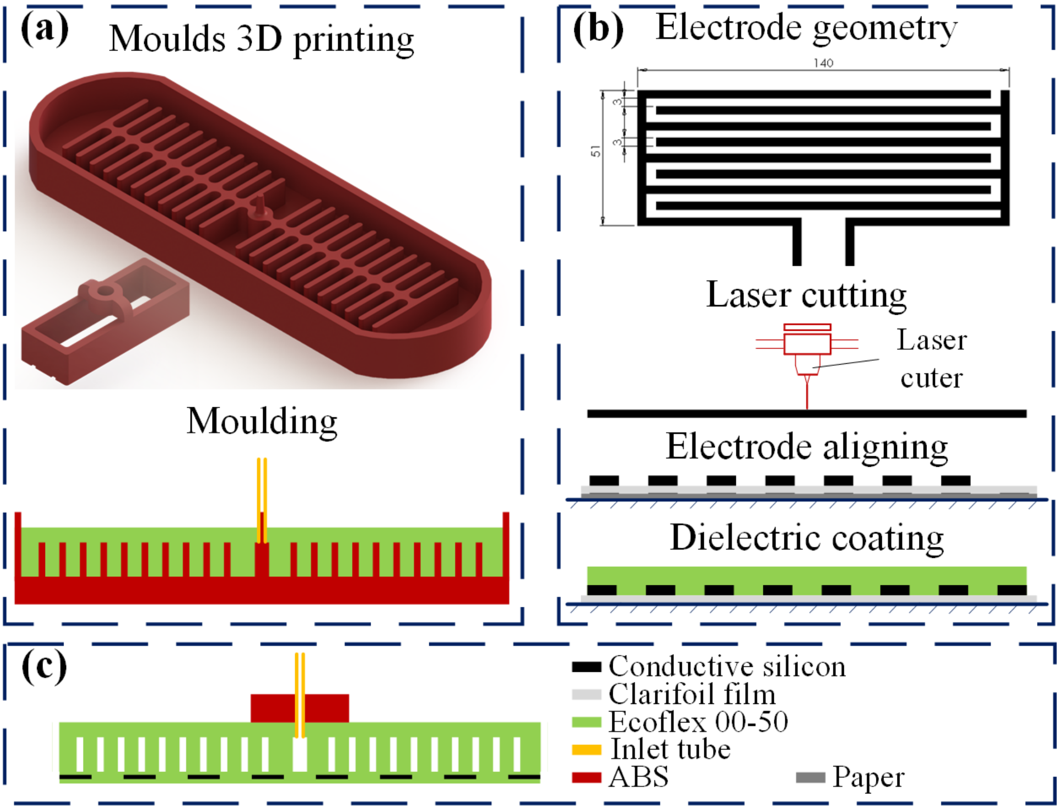

FIG. 2. The fabrication procedure of the PneuEA gripper: (a) soft pneumatic actuator fabrication, (b) stretchable electroadhesive actuator fabrication, and (c) integration of the soft pneumatic actuator and the electroadhesive actuator.

2.2 Two-fingered soft pneumatic gripper design and fabrication

A standard soft lithography approach was employed to fabricate the soft pneumatic gripper used in this paper[5]. The two-fingered design was adopted. Two moulds, as shown in the right top part of figure 2, were 3D printed using a LulzBot TAZ 6 3D printer (Aleph Object Inc, US) and a 3 mm diameter ABS filament. One was the actuator mould with negative fluidic channels. This was used to create the main body of the soft pneumatic actuator. The other was the connector mould for holding and securing the tube and electroadhesive electrode wires.

Silicon Ecoflex 00-50 (a Smooth-On Inc. product purchased from Bentley Advanced Materials, UK) was prepared by mixing equal weights of the provided parts using a wood stirrer for 2 minutes and then degassed in a vacuum oven (Fistreem International Ltd., UK) at -900 mbar for about 5 minutes to extract any trapped air bubbles. An inlet tube was plugged in the central tip of the actuator mould. The Ecoflex 00-50 was then carefully poured in the griper main body mould to create the two-fingered soft pneumatic actuator with imprinted features, and then left to cure at room temperature for 4 hours on a flat glass substrate. The curing process can be accelerated by putting the part in the oven at 50 degree celsius. When the Ecoflex 00-50 was fully cured, the main body of the soft pneumatic actuator was demoulded from the actuator mould and placed on a clean and flat glass substrate.

2.3 Electroadhesive design and fabrication

An inter-digital electrode geometry was adopted in this work and designed in Solidworks, with an effective electrode area of 51 mm x 140 mm, electrode width and space between electrodes of both 3 mm. Various stretchable electroadhesive manufacturing methods have been reported such as mixing carbon black powers with Ecoflex elastomeric dielectric materials[15]. The stretchable electrodes can also be manufactured from the aforementioned soft lithography approach such as pouring prepared cPDMS[16] into a 3D printed mould featured with a certain electrode geometry. In this paper, the electrodes for the electroadhesive actuator attached onto the soft pneumatic gripper were fabricated by laser cutting of an electrically conductive silicone sheet (J-Flex, UK), which was low-cost and easy to be fabricated. The J-Flex conductive silicon sheet has a thickness of 0.5 mm, hardness of 75˚ Shore A, volume resistivity of 4.3 Ω•cm, and elongation of 150 %.

After the laser cutting, the two electrodes were thoroughly cleaned and dried. The same electrode geometry was printed onto a white paper which was then adhered onto a flat aluminium plate. A 30 µm thick glossed cellulose acetate film (Clarifoil, Celanese Acetate Ltd., UK) was adhered on the top of the printed paper. The electrodes were then manually aligned with the printed pattern. Please note that a thin layer of adhesive (Elmer's Products Inc., UK) between the electrode and film may be useful for preventing the Ecoflex penetrating into the gaps between them. After electrode alignment, a 0.2 mm thick layer of Ecoflex 00-50 was blade coated on the top of the electrodes and left to cure at room temperature for 4 hours.

The Clarifoil film was flexible but inextensible. This limiting layer can be used to restrict the soft finger extension upon actuation. In this way, the bending response of the soft finger can be approximately predefined via the geometry of the ribbed internal channels and the properties of the material used. The Clarifoil film can also be peeled off from the gripper. The side with the film peeled off can then be coated with a layer of Ecoflex 00-50 material, making the gripper an entirely soft, flexible and stretchable electroadhesive actuator, as demonstrated in figure 3 (a).

2.4 PneuEA gripper fabrication

Stretchable electroadhesive actuators are needed for all-elastomer PneuEA grippers. In order to produce an all-elastomer PneuEA gripper, a compliant electroadhesive pad shown in figure 3 (a) should be generated. When the Ecoflex 00-50, on top of the J-flex electrodes, was fully cured, the Clarifoil film was peeled off from the electroadhesive actuator. The Ecoflex 00-50 side of the electroadhesive actuator was carefully placed on a clean and flat glass substrate. A layer of freshly mixed and vacuum degassed Ecoflex 00-50 was then poured on the top of the electroadhesive actuator. After 10 minutes, when there was no visible air bubbles, the main body of the soft pneumatic actuator produced in section 2.2 was carefully laid down on top of the uncured Ecoflex 00-50 layer. The careful bonding between the soft pneumatic actuator and the electroadhesive actuator ensured a perfect sealing between the two parts. When the adhesive layer was fully cured, the two-fingered all-elastomer PneuEA gripper was completed, as shown in figure 3 (b).

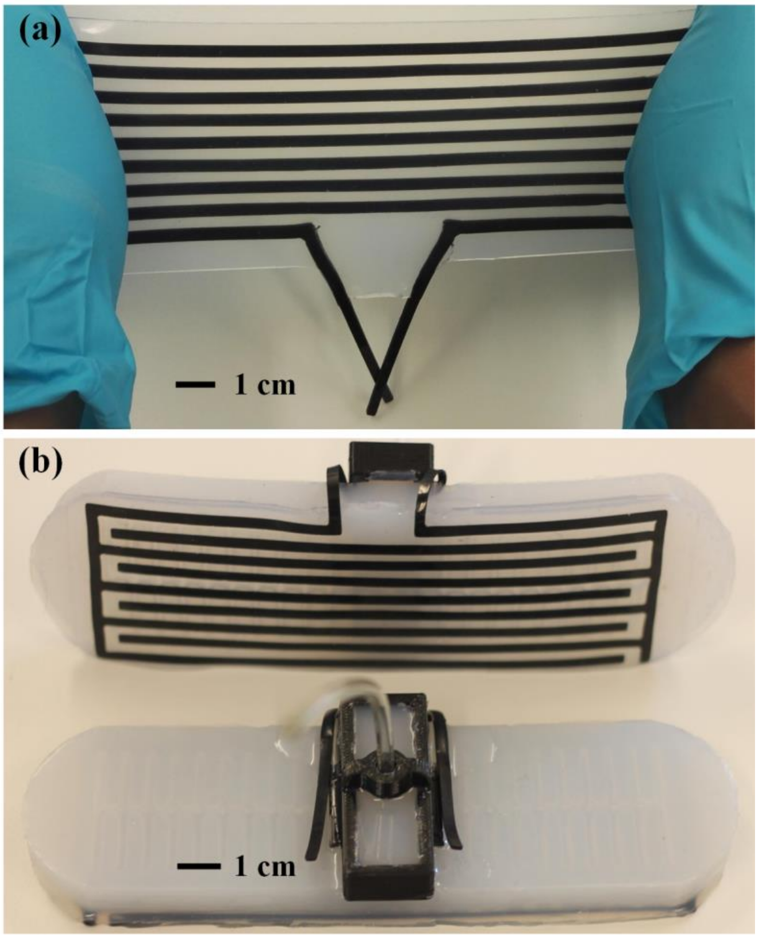

FIG. 3. PneuEA gripper: (a) the soft electroadhesive actuator shown stretched by hand and (b) the two-fingered all-elastomer PneuEA prototype.

3 Experimental results and discussions

3.1 Force measurement of the electroadhesive actuator

A shear electroadhesive force testing platform was used to quantify the electroadhesive performance, as shown in figure 4, where a 6-axis force/torque (F/T) sensor (tolerance of ± 0.05 N, ATI Industrial Automation, UK) was used to record the adhesive forces. Bolted connections were adopted between the flat acrylic plate and the F/T sensor. The Ecoflex 00-50 is adhesive and attracts dusts, debris, and particulates easily. In order to eliminate the intrinsically adhesive forces produced by Ecoflex 00-50 and highlight the electroadhesive force generated by the electroadhesive pad, the bottom of the electroadhesive actuator bonded to the Clarifoil film. The electroadhesive actuator was firstly gently laid flat down on the acrylic plate and then pulled away when no voltage was applied. As can be seen in figure 4, there was a 1.1 ± 0.09 N shear adhesive force between the electroadhesive actuator and acrylic substrate due to Van der Waals forces and some small amount of suction forces.

The electroadhesive actuator was then energized at 4.8 kV by two high voltage converters (EMCO High Voltage Corporation, US) connected to a direct current power supply unit (Instek GPD 3303, GW Instek). The pad was charged for 2, 10, 30, 60, and 90 seconds before pulling away from the acrylic substrate to investigate the relationship between the charge time and electroadhesive force obtainable and to find a proper charge time to achieve the adhesive forces close to maximum. Five tests were conducted for different charging times. Previous results showed that 90 seconds' pad charging can usually bring adhesive forces that are close to the maximum value[7,9]. The results shown in figure 4 manifest that the electroadhesive forces increased with increasing the charging time. Also, the adhesive force obtained after charging 60 seconds was close to the result when the pad was charged for 90 seconds. Only a relative difference of 7% was shown. All the following tests were performed, therefore, based on charging the electroadhesive actuators for 60 seconds.

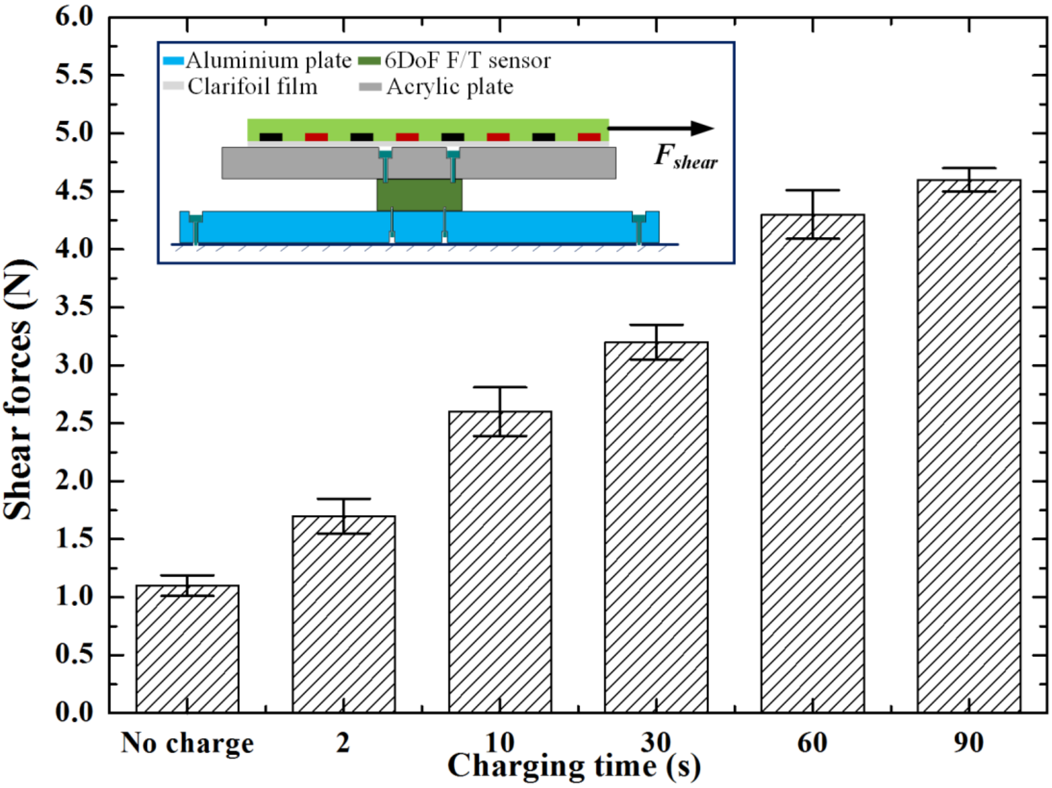

FIG. 4. Shear forces of the electroadhesive actuator under 0 V (no charge) and 4.8 kV when charging for 2 s, 10 s, 30 s, 60 s, and 90 s. The error bars show the standard deviation of the five results of each test.

In order to measure the shear adhesive forces of the all-elastomer electroadhesive actuator, the Clarifoil film was removed and a fresh layer of Ecoflex 00-50 was coated left to fully cure. After 5 hours, the all-elastomer electroadhesive actuator was then testing on the same acrylic plate in shear direction under application of 0 V and 4.8 kV for 60 seconds. The results presented in figure 5 manifest that, with electroadhesion, the shear adhesive forces of the all-elastomer electroadhesive were 26% larger than without electroadhesion. This suggests that, with electroadhesion, soft pneumatic grippers are able to grasp slightly heavier objects. Please note that all the tests were conducted in a clean and closed chamber. In addition, all the tests were conducted when the relative humidity was 53 ± 1%, temperature was 21.3 ± 0.1 ^{o}C, and ambient pressure was 1019.5 ± 0.2 hPa.

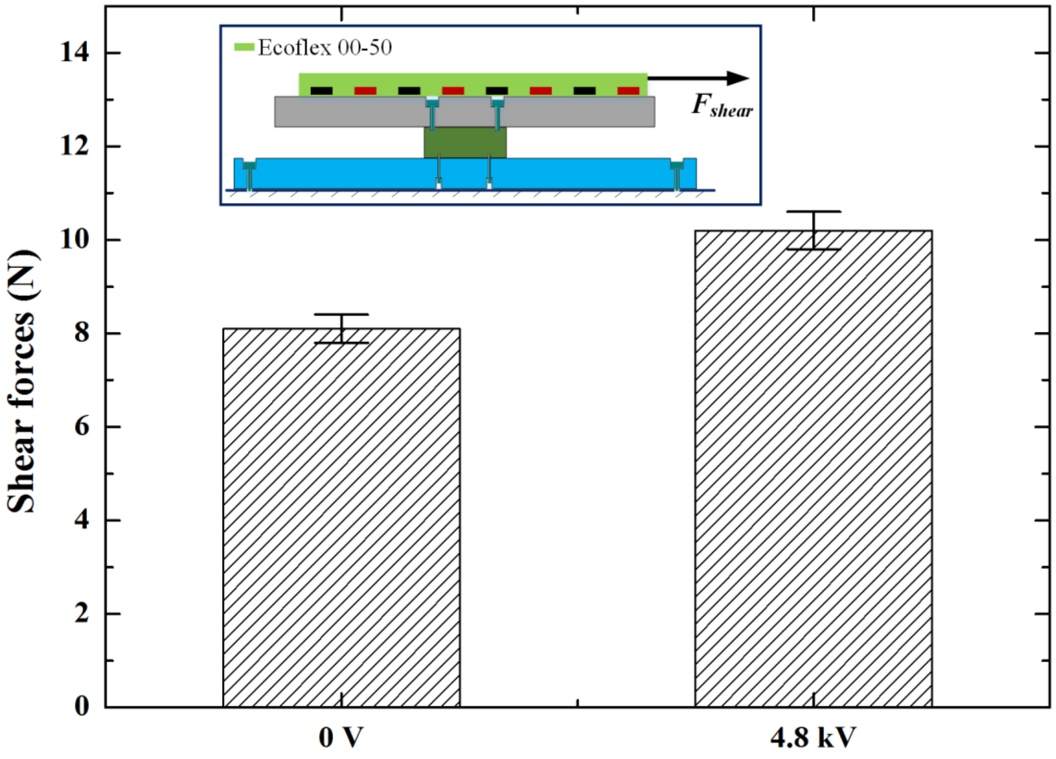

FIG. 5. Adhesive forces of the soft electroadhesive actuator under 0 V and 4.8 kV.

3.2 Case studies: grasping various objects

As is the case with other soft grippers, the two-fingered soft gripper presented here can be pneumatically actuated to grasp objects with complex geometries and delicate nature. Without exploiting its electroadhesion capabilities, examples for safely grasping a soft ball (80 g) and a light bulb (42 g) are presented in figure 6. The soft nature of this class of grippers allows conforming to the geometry of the target object without damaging the surface.

The PneuEA gripper was also tested in grasping various thin and flat materials that would be challenging for conventional soft pneumatic grippers. As demonstrated in figure 7, the PneuEA gripper successfully picked up a plastic PVC ID card (6 g, dielectric constant of 3), a porous cotton-polyester cloth (0.5 g, dielectric constant of 2), and a CD (15 g). It is shown in figure 5 that the PneuEA gripper is able to grasp a 8 N objects with its intrinsic adhesion. However, it is relatively difficult to release some lightweight and flat objects once picking them up. Without external release mechanisms, the objects would adhere to the gripper indefinitely, which is undesirable and makes the grasping process uncontrollable. Small particulates were applied on top of the gripper surface to remove its intrinsic adhesion. As shown in the **supplementary video 1**, the proposed gripper cannot pick up the ID card, the cloth, and the CD without applying electroadhesion. By exploiting electroadhesion, the proposed gripper was able to pick-up and release them successfully and controllably.

One unique benefit of the proposed PneuEA gripper was that, as showcased in figure 8 (a), it can grasp flexible and thin materials (such as the porous cloth) from curved surfaces (such as a glass ball) with different radius, as demonstrated in figure 8 (b) and (c). This is a novelty of the proposed PneuEA gripper. The grasping strategy in this case exploited both the pneumatic and electroadhesive actuation. Firstly, the PneuEA gripper conformed to the surface by adjusting its internal air pressure. 4.8 kV was then applied to enable the electroadhesion of the gripper to attract the cloth. After this, the cloth was lifted up. The cloth was finally released by turning off the voltage, which can be seen in **the supplementary video 1.** In addition, the PneuEA gripper was able to grasp a layer of flexible material from a stack due to the embedded electroadhesion. An example of grasping a layer of porous and flexible cloth from a stack can also be seen in **the supplementary video 1**.

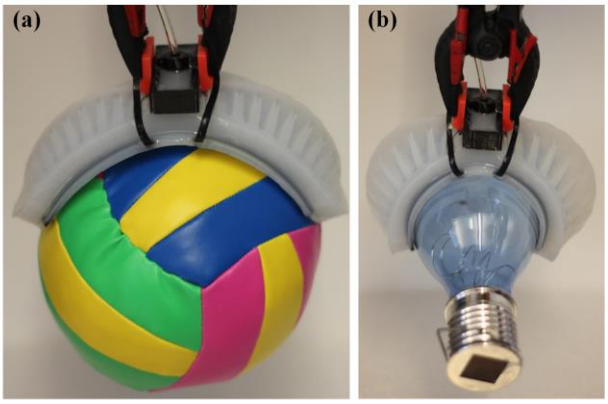

FIG. 6. Safely grasping of: (a) the soft volleyball (80 g) and (b) the light bulb (42 g), using the PneuEA gripper with electroadhesion off and pneumatic actuation on.

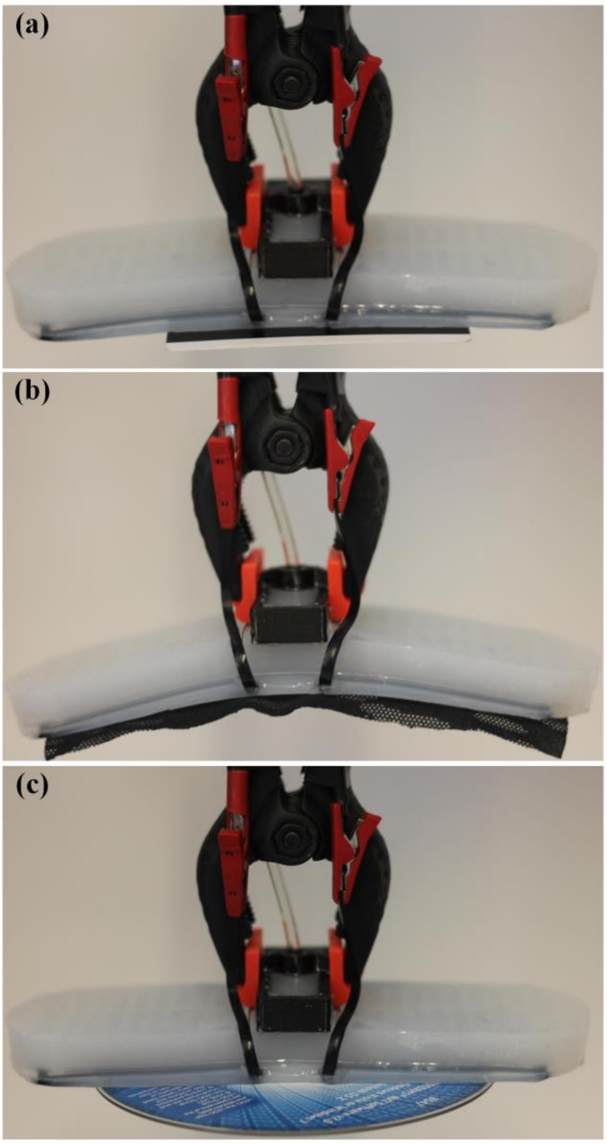

FIG. 7. Grasping of flat materials: (a) plastic ID card, (b) porous cloth, and (c) CD, using the PneuEA gripper with electroadhesion on and pneumatic actuation off.

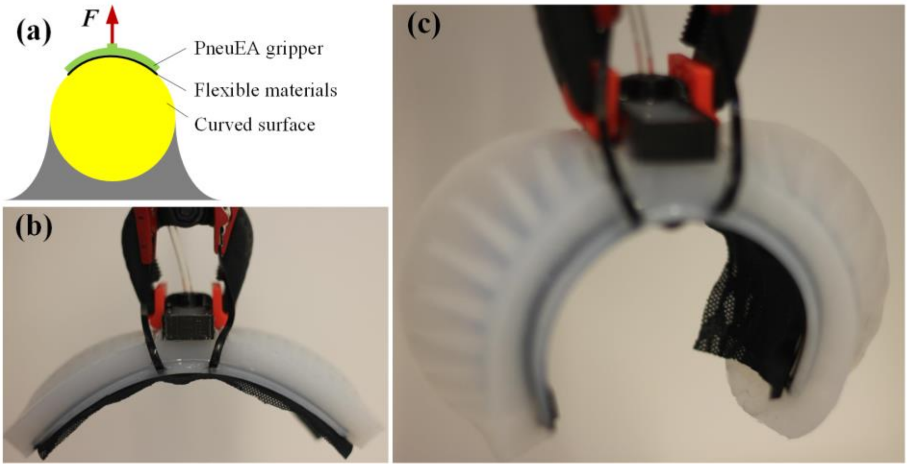

FIG. 8. Grasping of flexible materials from curved surfaces: (a) schematic diagram, (b) grasping of the cloth from a glass ball, and (c) grasping the cloth from a glass ball with different radius, using the PneuEA gripper with electroadhesion on and pneumatic actuation on.

4 Design and development of an intelligent PneuEA material handling system

4.1 Intelligent electroadhesive actuator design and fabrication

The proposed PneuEA aforementioned requires the user to determine when to activate both the pneumatic pump and the PnueEA action. In order to automate this process, extra sensors are needed to stop pressuring the gripper when the gripper is in contact with surfaces. Flexible resistive sensors can be used to enhance the intelligence level of soft grippers[17]. These commercial sensors, however, are not customizable and not stretchable. In this paper, two customized touch sensors, made of two coplanar J-flex conductive electrodes, were designed and embedded in the gripper, as shown in figure 9.

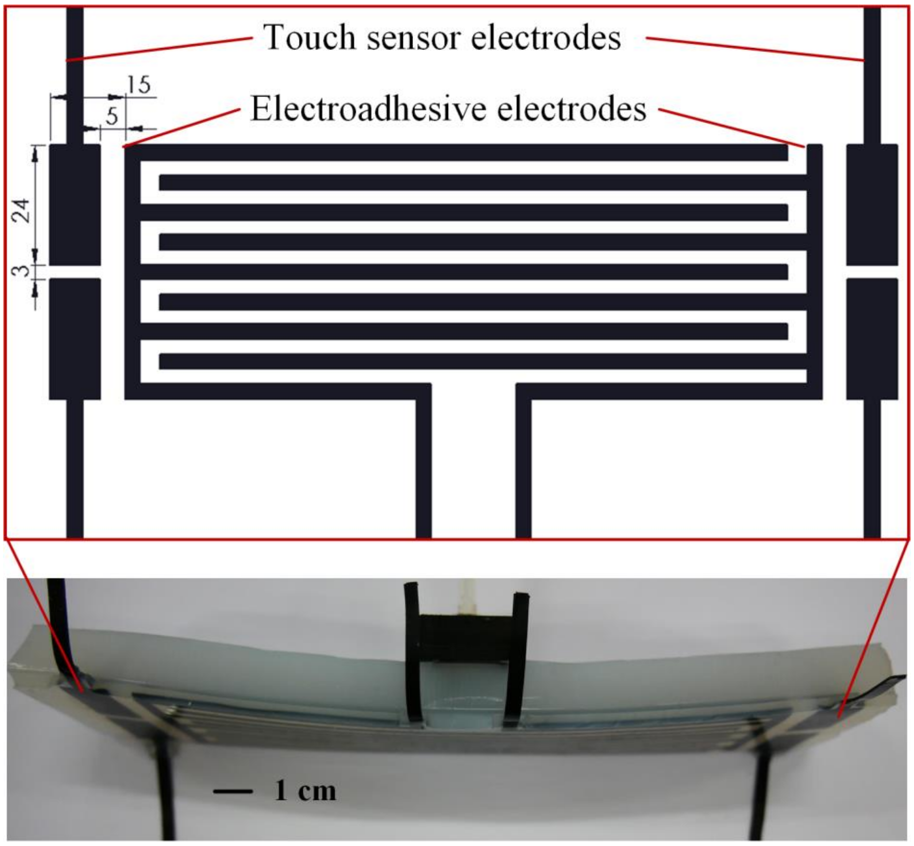

FIG. 9. The intelligent PneuEA gripper embedded with two proximity sensors.

Rather than laser cutting the J-flex sheets used in section 2.3, a Cricut 2D computer-controlled material cutter (Provo Craft & Novelty, Inc., USA) was utilized to generate both the electroadhesive electrodes and proximity sensor electrodes, providing a much easier and neater stretchable electrode cutting solution. Firstly, the 0.5 mm J-flex sheet was adhered to a 0.3 mm thick A4 size PVC sheet. Secondly, the sheet was cut by the Cricut cutter based on the electrode design shown in figure 9. Thirdly, the unwanted electrode areas were manually removed. Since there was a good adhesion between the J-flex sheet and the PVC sheet, the wanted electrode area remained on the PVC sheet. Then, Ecoflex 00-50 coating and bonding were the same with the procedures mentioned in section 2.3 and 2.4.

The schematic diagram of the sensor design is shown in figure 10 (a). Once electrode of the proximity sensor was connected to a 10 V and 1 kHz sine wave excitation from an analog output of a NI DAQ device. The other electrode of the proximity sensor was connected to an analog input. When an object was touching the touch sensor, a sudden change of the sensor reading was captured by the NI DAQ device, as seen in figure (b). A touch was then detected when V_{AI} was greater than threshold T = 10 V.

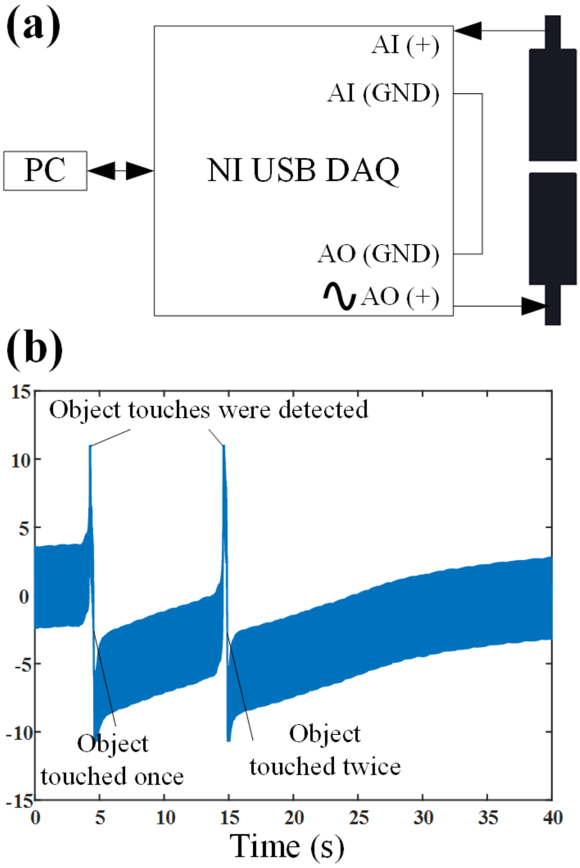

FIG. 10. The soft touch sensor: (a) schematic diagram and (b) sensor reading when there is no object and there is an object touching the sensor.

4.2 Intelligent PneuEA material handling system development

Based on the intelligent PneuEA gripper shown in figure 9, an intelligent PneuEA material handling system was developed. The schematic diagram of the system is presented in figure 11 (a). A bipolar 5kV Ultravolt high voltage power supplies (Advanced Energy Industries, Inc., USA) was used to energize the electroadhesive actuator. A Zaber linear rail (X-LSQ150B-E01, Zaber Technologies Inc., USA) was used to pull the PneuEA gripper up and down. An inline miniature S-Beam load cell (Applied Measurements Ltd., UK) was used to inform the gripper whether it touches the substrate or not. A NI USB-6343 X Series DAQ device (National Instruments, UK) was used to control the output voltage of the high voltage amplifier and the on and off of an air pump (Cool Components Ltd., China) via a solenoid valve (The Lee Company, USA). Grasping of a flexible woven conductive fabric from a curved substrate is demonstrated in figure 11 (b) and **the supplementary video 2.**

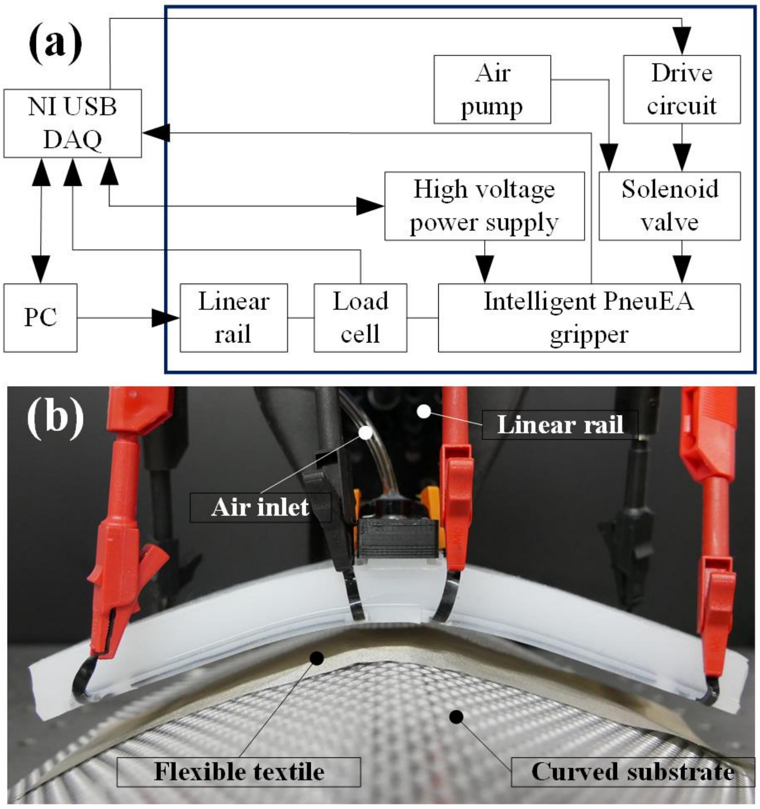

FIG. 11. The intelligent PneuEA material handling system: a) schematic diagram and (2) the physical material handling setup.

The movement and control flow chart of the intelligent PneuEA material handling system is presented in figure 12. Firstly, the linear rail moved down to approach the object to be grasped and stopped when the force sensor reading was over 1 N. Secondly, air was pressurized into the gripper so that it can conform to the flexible object on a curved substrate. The air pump stopped when the reading of both touch sensors was over a threshold T (T = 10 here in this study). Then the electroadhesion was turned on and 4.8 kV was applied for 5 seconds. After this, the linear rail moved up to pick up the object and stopped when it reached its original position. The electroadhesion was finally turned off and the object was released.

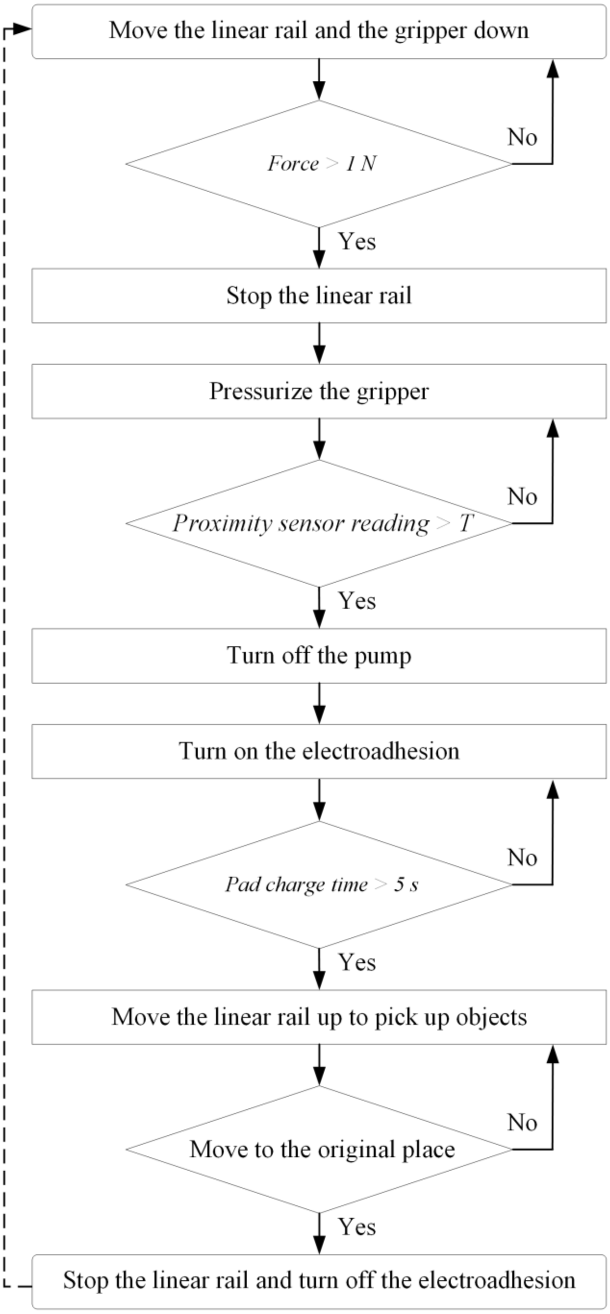

FIG. 12. The movement and control flow chart of the intelligent PneuEA material handling system.

5 Conclusions and future work

The work presented in this paper has focused upon the development of a novel, cost-effective, and easy-to-implement PneuEA gripper by the integration of an electroadhesive actuator into a two-fingered soft pneumatic actuator. The proposed gripper combines advantages of both electroadhesion and soft pneumatic actuators. This combination has not only solved the limitation of soft grippers in lifting thin and flat objects but also the limitation of electroadhesion actuators in lifting objects from non-planar surfaces. As a result, the PneuEA gripper is able to handle not only flat and flexible materials but also complex-shaped objects. This may significantly extend the capability of both current electroadhesive actuators and soft pneumatic grippers and may promote the application of both electroadhesion and soft gripper technologies. In addition, by exploiting electroadhesion, the mechanical actuation force of the pneumatic gripper can be reduced and more delicate objects can be handled.

The main contributions of this paper include: 1) the combination of electroadhesion and soft pneumatic grippers to augment the functionality of both technologies, 2) the embedding of customized soft touch sensors to make the PneuEA gripper controllable and intelligent, and 3) the development of a cost-effective stretchable electroadhesive actuator manufacturing approach. Future work will include optimizing the design of the PneuEA gripper and its performance and integrating the intelligent PneuEA gripper to a 6DOF robot for industrial material pick-and-place applications.

Acknowledgments

The authors acknowledge support from the EPSRC Centre for Innovative Manufacturing in Intelligent Automation, under grant reference number EP/IO33467/1, for undertaking the work presented in section 2 and 3. In addition, the authors acknowledge support from the EPSRC Fellowship project (Soft robotic technologies for next-generation bio-integrative medical devices), under grant reference numbers: EP/M020460/1 and EP/M026388/1, for undertaking the work presented in section 4.

References

1. Majidi C. Soft Robotics: a perspective - current trends and prospects for the future. Soft Robot. 2013 July;1(1):5-11. DOI: 10.1089/soro.2013.0001.
2. Rus D, Tolley M T. Design, fabrication and control of soft robots. Nature. 2015 May;521:467-475. DOI: 10.1038/nature14543.
3. Wehner M, Truby R L, Fitzgerald D J, Mosadegh B, Whitesides G M, Lewis J A, Wood R J. An integrated design and fabrication strategy for entirely soft, autonomous robots. Nature. 2016 August;536:451-455. DOI: 10.1038/nature19100.
4. Laschi C, Mazzolai B, Cianchetti M. Soft robotics: Technologies and systems pushing the boundaries of robot abilities. Sci. Robot. 2016 December;1(1):eaah3690. DOI: 10.1126/scirobotics.aah3690.
5. Ilievski F, Mazzeo A D, Shepherd R F, Chen X, and Whitesides G M. Soft robotics for chemists. Angew. Chem. Int. Ed. 2011 January;50:1890-1895. DOI: 10.1002/anie.201006464.
6. Hines L, Petersen K, Lum G Z, and Sitti M. Soft actuators for small-scale robotics. Adv. Mater. 2016 December;29:1603483. DOI: 10.1002/adma.201603483.
7. Guo J, Bamber T, Chamberlain M, Justham L, Jackson M. Towards adaptive and intelligent electroadhesives for robotic material handling. IEEE Robot. Autom. Lett. 2016 December;2(2):538-545. DOI: 10.1109/LRA.2016.2646258.
8. Rahbek K. Electroadhesion apparatus. Patent US2025123. 1932 November: www.google.co.uk/patents/US2025123.
9. Bamber T, Guo J, Singh J, Bigharaz M, Petzing J, Bingham PA, Justham L, Penders J, Jackson M. Visualization methods for understanding the dynamic electroadhesion phenomenon. J Phys D Appl Phys. 2017 April; 50(20):205304. DOI: https://doi.org/10.1088/1361-6463/aa6be4.
10. Guo J, Justham L, Jackson M, Parkin R. A concept selection method for designing climbing robots. Key Eng. Mater. 2015 June;649:22-29. DOI: 10.4028/www.scientific.net/KEM.649.22.
11. Graule M A, Chirarattananon P, Fuller S B, Jafferis N T, Ma K Y, Spenko M, Kornbluh R, Wood R J. Perching and takeoff of a robotic insect on overhangs using switchable electrostatic adhesion. Science. 2016 May;352:978-982. DOI: 10.1126/science.aaf1092.
12. Savioli L, Sguotti G, Francesconi A, Branz F, Krahn J, Menon C. Morphing electroadhesive interface to manipulate uncooperative objects. Proc. SPIE. 2014 March;9061:906129. DOI: 10.1117/12.2045065.

13. Suresh S A, Christensen D L, Hawkes E W, Cutkosky M. Surface and shape deposition manufacturing for the fabrication of a curved surface gripper. J. Mech. Robot. 2015 May;7(2):021005. DOI: 10.1115/1.4029492.
14. Shintake J, Rosset S, Schubert B, Floreano D, Shea H. Versatile soft grippers with intrinsic electroadhesion based on multifunctional polymer actuators. Adv. Mater. 2015 November;28(2):231-238. DOI: 10.1002/adma.201504264.
15. Germann J, Schubert B, and Floreano D. Stretchable electroadhesion for soft robots. 2014 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2014). 2014 September: 3933–3938. DOI: 10.1109/IROS.2014.6943115.
16. Chen A S, Bergbreiter S. A comparison of critical shear force in low-voltage, all-polymer electroadhesives to a basic friction model. Smart Mater. Struct. 2017 January;26(2):025028. DOI:10.1088/1361-665X/aa5484.
17. Elgeneidy K, Lohse Ni, Jackson M. Bending angle prediction and control of soft pneumatic actuators with embedded flex sensors - A data-driven approach. Mechatronics. 2017 October. DOI: https://doi.org/10.1016/j.mechatronics.2017.10.005.