



(51) International Patent Classification:

H02N 13/00 (2006.01) F16D 27/02 (2006.01)

H01H 59/00 (2006.01) F16D 37/02 (2006.01)

(21) International Application Number:

PCT/US2023/072929

(22) International Filing Date:

25 August 2023 (25.08.2023)

(25) Filing Language:

English

(26) Publication Language:

English

(30) Priority Data:

63/373,541 25 August 2022 (25.08.2022) US

(71) Applicant: **THE TRUSTEES OF THE UNIVERSITY OF PENNSYLVANIA** [US/US]; 3600 Civic Center Boulevard, 9th Floor, Philadelphia, Pennsylvania 19104 (US).

(72) Inventors: **PIKUL, James Henry**; 2213 Parrish Street, Philadelphia, Pennsylvania 19130 (US). **TURNER, Kevin**; 709 Mancill Road, Wayne, Pennsylvania 19087 (US). **LEVINE, David J.**; 2101 Chestnut Street, Unit 714, Philadelphia, Pennsylvania 19103 (US).

(74) Agent: **RABINOWITZ, Aaron B.**; 1735 Market Street, Suite 3300, Philadelphia, Pennsylvania 19103-7501 (US).

(81) Designated States (unless otherwise indicated, for every kind of national protection available): AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CV, CZ, DE, DJ, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IQ, IR, IS, IT, JM, JO, JP, KE, KG, KH, KN, KP, KR, KW, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, MG, MK, MN, MU, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, WS, ZA, ZM, ZW.

(84) Designated States (unless otherwise indicated, for every kind of regional protection available): ARIPO (BW, CV, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SC, SD, SL, ST,

SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, ME, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Declarations under Rule 4.17:

- as to applicant's entitlement to apply for and be granted a patent (Rule 4.17(ii))
- as to the applicant's entitlement to claim the priority of the earlier application (Rule 4.17(iii))

Published:

- with international search report (Art. 21(3))
- before the expiration of the time limit for amending the claims and to be republished in the event of receipt of amendments (Rule 48.2(h))

(54) Title: HIGH-FORCE CAPACITY ELECTROADHESIVES

(57) Abstract: Materials with electroprogrammable stiffness and adhesion can enhance the performance of robotic systems but achieving large changes in stiffness and adhesive forces in real time is an ongoing challenge. Electroadhesive clutches can rapidly adhere high stiffness elements, although their low force capacities and high activation voltages have limited their applications. A major challenge in realizing stronger electroadhesive clutches is that current parallel-plate models poorly predict clutch force capacity and cannot be used to design better devices. Here, we use a fracture mechanics framework to understand the relationship between clutch design and force capacity. We demonstrate and verify a mechanics-based model that predicts clutch performance across multiple geometries and applied voltages. Based on this approach, we build a clutch with 94 times the force capacity per unit electrostatic force of state-of-the-art electroadhesive clutches. Finally, we demonstrate the ability of our electroadhesives to increase the load capacity of a soft, pneumatic finger by a factor of 62 times compared to a finger without an electroadhesive.



HIGH-FORCE CAPACITY ELECTROADHESIVES

RELATED APPLICATIONS

[0001] The present application claims priority to and the benefit of United States patent application no. 63/373,541, “High-Force Capacity Electro adhesives” (filed August 25, 2022). All foregoing applications are incorporated herein by reference in their entireties for any and all purposes.

GOVERNMENT RIGHTS

[0002] This invention was made with government support under 1935294 and 1830475 awarded by the National Science Foundation. The government has certain rights in the invention.

TECHNICAL FIELD

[0003] The present disclosure relates to the field of electro adhesive clutches.

BACKGROUND

[0004] The ability to program the mechanical stiffness of robotic systems has led to many advances and increased the performance of prosthetics (1), walking robots (2), active origami structures (3–5), and human exoskeletons (6). Clutches are a common approach for programming stiffness and operate by mechanically connecting and disconnecting elements of different stiffness. Rotational clutches in robots can be activated to block force, control energy transfer between mechanical elements, and enable discrete stiffness tuning (7, 8). However, rotational clutches are restricted to rotational joints and are made from rigid materials (1, 9–11), which makes them incompatible with applications that require stretchability or in-plane mechanical programming.

[0005] For these applications, new classes of materials with programmable stiffness have been developed to modulate stiffness in soft or stretchable robotic systems. These materials enable transformations between complex, pre-programmed shapes (12), robotic fish with increased swimming efficiencies (13), and mechanically-patterned grippers for gentle object manipulation (14). The ability to program large changes in

mechanical stiffness in real time, however, has been a challenge with current soft stiffness tuning mechanisms, which consume large amounts of power, require phase changes, actuate in seconds to minutes, or have low strength (15, 16).

[0006] Accordingly, there is a long-felt need in the art for improved clutch designs and related methods.

SUMMARY

[0007] A promising technology for modulating stiffness in soft or flexible systems is an electroadhesive clutch (15). In contrast to rotational clutches, electroadhesive clutches are comprised of one or more thin, compliant, conductive, overlapping electrodes separated by a dielectric layer (Fig. 1A). When a voltage is applied between the conductive surfaces, the opposing charges on each electrode are attracted to one another, resulting in electroadhesion (17, 18). The electrostatic force produced at the contact interface can prevent sliding and increase in the in-plane stiffness (15). When the clutch is loaded in tension or by an external bending moment, each electrode is pulled parallel to its length and away from the opposing electrode so that, in the absence of an applied voltage, they slide relative to each other. Therefore, when no voltage is applied, the un-activated stiffness is determined by the materials surrounding the clutch (Fig. 1B). Electroadhesives are lightweight (<1g) due to the small thickness of the electrodes and the stiffness changes occur in milliseconds. Moreover, electroadhesive clutches are low-cost, easy to fabricate, and consume small amounts of power (<1mW) when fully charged. As a result, many electroadhesive clutches have been developed in recent years for programming stiffness changes in a variety of applications, including wearable haptic interfaces for virtual reality and robotic teleoperation (19–21), robotic exoskeletons for ankle assistance during walking tasks (22, 23), fingered gripping systems (24), modular robotic teams (25), shape-locking of pneumatic actuators (26), and electrostatic zipping actuators (3).

[0008] However, despite the proliferation of electroadhesive clutch designs in numerous applications where stiffness control is required, current electroadhesive clutches suffer from force capacities below that of other materials with an electrically-tunable stiffness, such as electrothermal and electrochemical systems (15). The force capacity

(FC) is the force above which the clutch would fail or slip. Clutches with increased force capacities can reduce the applied voltage needed to achieve a target force, shrink device dimensions, and increase the achievable stiffness range. These benefits would make electroadhesive clutches more compatible with off-the-shelf electronics and both macroscale and microscale robotic systems. To achieve this, the force capacity of electroadhesive clutches must be increased by a factor of ten compared to what is achievable today (20).

[0009] Current electroadhesive clutches rely on high operating voltages (typically >300 V) and large contact areas to achieve larger force capacities, but an incomplete understanding of clutch mechanics has prevented current designs from achieving their full potential. To date, clutches have been designed using a simple electroadhesion model based solely on electrostatic parallel plate theory and Coulombic friction to predict the force capacity (27). Although simple in nature, this model does not accurately predict real-world performance in many cases, because it does not account for non-uniform stresses and failure that occurs due to the initiation and propagation of interface crack (i.e. fracture-based failure) (Fig. 1C) (28–34). There is, therefore, a need for new models that accurately capture electroadhesive behavior, and which, in turn, will enable the design of stronger, smaller, and lower voltage clutches for programming stiffness or adhesion.

[0010] We present an experimentally validated fracture mechanics-based model that describes the relationship between clutch design and maximum force capacity, and show that using this model can enable electroadhesive clutches with dramatic improvements in force capacity. Our model correctly predicts clutch performance over a wide variety of geometries and applied voltages, unlike the widely used parallel plate equation (Fig. 1D). Using this understanding, we demonstrate that the performance of most electroadhesive clutches can be improved by simply changing their geometry, i.e. shape and thickness. Based on our design criteria, we build a Coulombic electroadhesive clutch with the highest force capacity per unit area and per applied electrostatic force, outperforming the next highest performing clutch by a factor of 94'. Finally, we demonstrate the ability of our optimized electroadhesives to increase the load capacity of a soft robotic finger by a factor of 62'. By doing so with traditional dielectrics and electrode materials, we demonstrate the power of our mechanics-based design methodology to

increase clutch performance without relying on expensive materials or intensive manufacturing processes, making our approach optimal for widespread adoption by robotics researchers. This fundamental understanding of clutch mechanics and improved force capacity will enable smaller and stronger clutches for programming the mechanical properties of robotic systems.

[0011] In one aspect, the present disclosure provides an electroadhesive clutch, comprising: a first electrode; a second electrode; and a spacer disposed between the first electrode and the second electrode and being in electrical communication with the first electrode and the second electrode, (a) the spacer comprising at least one ionoelastomer that comprises a comonomer, the comonomer giving rise to an ionoelastomer having a lower surface energy than the surface energy of the at least one ionoelastomer being free of the comonomer, (b) at least one of the first electrode and the second electrode defining a mesh structure, the mesh structure comprising strands having a thickness in the range of from about 10 to about 200 μm , or both (a) and (b).

[0012] Also provided are methods of using the disclosed electroadhesive clutches, the methods comprising applying an electric current to the electroadhesive clutch, e.g., so as to engage the clutch. Also provided are methods of using the disclosed electroadhesive clutches comprising reducing an electric current being applied to the clutch, e.g., to release the clutch.

[0013] Also provided is a method, comprising: estimating a predicted force capacity of an electroadhesive joint, the estimating being based at least in part on at least one of (1) a contact area of an electrode of the electroadhesive joint, (2) a compliance of the electroadhesive joint, and (3) a critical strain energy release rate associated with the materials comprising the contact interface and the applied voltage.

[0014] Also provided is an electroadhesive clutch, comprising: (i) a first electrode;

[0015] (ii) a second electrode; (iii) optionally a spacer disposed between the first electrode and the second electrode and being in electrical communication with the first electrode and the second electrode, and (iv) wherein (a) the spacer comprises a dielectric, or (b) at least one of the first electrode and the second electrode defines a mesh structure, the mesh structure comprising strands having a thickness in the range of from about 10 to about 200 μm , or (c) the clutch defines a direction of motion and the first electrode and the

second electrode define a superposed area, the superposed area being defined by a first axis extending in the direction of motion and a second axis extending perpendicular to the first axis, the second axis being greater than the first axis, or any two or more of (a), (b), and (c).

BRIEF DESCRIPTION OF THE DRAWINGS

[0016] The patent or application file contains at least one drawing executed in color. Copies of this patent or patent application publication with color drawing(s) will be provided by the Office upon request and payment of the necessary fee.

[0017] In the drawings, which are not necessarily drawn to scale, like numerals may describe similar components in different views. Like numerals having different letter suffixes may represent different instances of similar components. The drawings illustrate generally, by way of example, but not by way of limitation, various aspects discussed in the present document. In the drawings:

[0018] Fig. 1. Electroadhesive clutch materials, operation, and design. (A) Electroadhesive clutches that utilize Coulombic electroadhesion are comprised of two compliant, metallized electrodes separated by an insulating dielectric layer with relative permittivity k . The contact area between the dielectric and the bottom electrode is denoted in red. (B) Electroadhesive clutch operation. In the off-state, contact is made between the clutch surfaces, but they are not adhered and can slide freely past one another (left). In the on-state, the two electrodes are held together by electrostatic forces and sliding is blocked at the contact interface (right). (C) Electroadhesive force capacities are governed by interface fracture mechanics. First, a crack initiates at the edge of the contact interface (top), which grows as the load applied to the clutch increases (middle). At its force capacity, the crack propagates through the whole interface, and the surfaces of the clutch separate. (D) Previous understanding of electroadhesive force capacities was based on parallel plate theory and friction. Using this approach, static friction from electrostatic attraction holds the electrodes together (left), which increases as the load applied to the clutch increases (middle). At its force capacity, a slip event occurs, and the electrodes slide past one another (right). FIG. 1(E) illustrates the load capacity enhancement achieved by the disclosed technology and also the stiffness tuning achieved by the disclosed technology.

[0019] Fig. 2. Predictions of the analytical model of electroadhesive clutch joint stiffness and force capacity. (A) A schematic of an electroadhesive clutch, with important geometric and material parameters labeled (top), and the representative spring network used to predict total joint compliance and electroadhesive force capacity (bottom). (B) Force capacity as a function of clutch width predicted by the model. The lines of constant area were calculated using our model with a G_C value corresponding to the 200 V experiments, and the lines of constant voltage were calculated using G_C values corresponding to the 200 V & 300 V experiments, respectively. All lines of constant area (black) represent clutches operated at a set voltage of $V = 200$ V, and all lines of constant voltage (blue) represent clutches with a set area of $A = 16$ cm². (C) A design map showing electroadhesive force capacities for different electroadhesive joint lengths and joint widths. The dotted lines represent electroadhesives with constant contact areas of $A = 4$ cm² through 48 cm². (D) A design map of predicted electroadhesive force capacities for different geometric stiffness parameters and critical strain energy release rates (SERR, G_C), which correspond to different voltages. The dotted horizontal lines represent G_C values which correspond to operating voltages of 200 V and 300 V, respectively, which were determined from numerical fitting of the experimental data. All model predictions assume geometries and material properties that match our experimentally-tested clutches.

[0020] Fig. 3. Experimental validation of the analytical model and an exploration of electroadhesive clutch stiffness on force capacity. (A) Measured electroadhesive force capacity (FC , N) vs. Geometric Scaling Parameter ($(A/C)^{1/2}$, Nm^{1/2}). Each data point indicates a different electroadhesive clutch design, with $n = 3$ clutches tested per data point. The error bars indicate one SD above and below each measured FC value. The red and blue dotted lines indicate the model predicted values of electroadhesive FC with a $G_C = 68$ Jm⁻² for the 200 V data, and a $G_C = 146$ Jm⁻² for the 300V data. The red and blue shaded regions indicate a 20% deviation in G_C from the fitted parameters. The ratio of G_C values for the 300 V and 200 V datasets is 2.13, which is only 5.3% below the expected value of 2.25. (B) Measured electroadhesive FC versus electroadhesive joint widths for clutches tested with different operating voltages (V) at a set contact area of 16 cm², with all other design parameters fixed. The red dotted line indicates the model's predictions for 200 V operation, and the blue dotted line indicates the model's predictions for 300 V operation. (C) Measured electroadhesive FC versus electroadhesive joint widths for

clutches with different electrode thicknesses (t) at a set contact area of 16 cm^2 , with all other design parameters fixed. The red dotted line indicates the model's predictions for $t = 127 \text{ }\mu\text{m}$ electrodes, and the black dotted line indicates the model's predictions for $t = 254 \text{ }\mu\text{m}$ electrodes. (D) Measured electroadhesive FC versus electroadhesive joint lengths, with all other design variables. The red dotted line indicates the model's predictions for 200 V operation.

[0021] Fig. 4. Using an electroadhesive clutch to increase the load capacity of a soft robotic hand. (A) A custom-built soft robotic hand required two fingers (each inflated to 30 kPa) to successfully hold a bag containing one apple weighing 0.2 kg without dropping it. By using a clutch to mechanically anchor one of the hand's fingers to its palm, the hand now successfully held a full bag of apples weighing 4 kg with only one finger, without increasing the input pneumatic pressure. (B) A schematic of the soft finger setup. The pneumatic finger was attached to a rigid palm (black), and was connected to an air tube for inflation. One clutch electrode was attached to the palm, and the other was attached to the fingertip, and an external source and amplifier applied voltage to the clutch for activation. (C) Determining the load capacity of a finger without a clutch. As a control, a 0.1 kg mass uncurled a soft finger pressurized to 30 kPa. (D) Increasing finger load capacity with a low GSP electroadhesive clutch. Upon activation at 75 V, this clutch enabled the same finger to hold 4 kg, a 40' increase compared to the control. (E) Increasing finger load capacity with an increased GSP electroadhesive clutch. Upon activation at 75 V, this clutch enabled the same finger to hold 6.2 kg at failure, a 62' increase compared to the control.

[0022] Figs. 5A-5B provide demonstrations of an elbow wearable with an electroadhesive clutch placed on the arm of a mannequin (Fig. 5A) and a soft finger with an attached high GSP electroadhesive (Fig. 5B).

[0023] Fig. 6. A comparison of state-of-the-art Coulombic electroadhesive clutches. We compare the maximum force capacity divided by the total electrostatic force applied to the contact interface, which is plotted here versus (FIG. 6A) total shear force capacity, (FIG. 6B) shear force capacity per unit contact area and (FIG. 6C) applied voltage. The data for the clutches from the literature shown here are from references (19–22, 25).

[0024] Figure 7. An example force-displacement curve for an electroadhesive clutch. Each clutch's stiffness k (where the stiffness k is equal to the reciprocal of the compliance C) was measured in the small strain regime corresponding to average strains $<1-1.5\%$.

[0025] Figure 8. Stiffness/compliance model validation. The black dashed line indicates exact agreement between the analytical model and experimental results. The linear regression for these data is $R^2 = 0.95$, indicating good agreement between our analytical stiffness prediction and our experimentally measured stiffness values at small strains (1-1.5%). Each data point represents 3 different clutches. The green points are for clutches tested at 75 V, the red points for clutches tested at 200 V, and the blue points are for clutches tested at 300 V. Each error bar indicates one SD above and below the experimentally-measured stiffness values. We believe that the reduced stiffness of the $t = 254 \mu\text{m}$ specimens can be attributed to the fabrication approach used for these electrodes. To increase the thickness of the metallized BOPET of thickness $t = 127 \mu\text{m}$, a clear PET film also of thickness $t = 127 \mu\text{m}$ was adhered to the non-metallized side of the BOPET using a pressure-sensitive adhesive. During the axial loading of these specimens, the deformation of pressure-sensitive adhesive layer likely reduces the overall stiffness of the clutch system.

[0026] Figure 9. Experimental setup for electroadhesive clutch force capacity testing.

[0027] Figure 10. Soft finger load capacity demonstration setup.

[0028] Figure 11. Nanoindentation measurements of the Young's modulus of Parylene-C. For each data point, five indents were performed at a contact depth between 200 and 400 nm and averaged. The error bars represent one SD above and below each measured modulus and contact depth value. The average Young's modulus of 3.6 GPa from the $n = 15$ indents (assuming a Poisson's ratio of 0.4) was used as the Parylene-C modulus E_d in the analytical model.

[0029] Fig. 12. Ionoelastomer electroadhesive clutch operation and design. (A) Electroadhesive clutches that utilize electroadhesion are comprised of two compliant, metallized electrodes separated by two ionoelastomer pads. The contact area between the ionoelastomers is denoted in red. (B) Electroadhesive clutch operation. In the reverse bias state, contact is made between the clutch surfaces, the clutches are adhered by electrostatic

forced which act over an ionic double layer, and sliding is blocked at the contact interface (top). In the forward bias state, the two electrodes are held together by electrostatic forces, but can freely slide past one another. (C) Electroadhesion by ionoelastomer heterojunctions. When a small voltage is applied to the electrodes in reverse bias, mobile ions are drawn away from the polycation/polyanion interface. Fixed ions of opposite charge then build up at the interface, and the electric field generated across the nanoscale IDL causes the ionoelastomers to become adhered (top). Under forward bias, the electrodes switch polarity, and mobile ions flood the interfacial region, ceasing the electroadhesive effect, allowing the ionoelastomers to separate (bottom). (D) Electroadhesive force capacities are governed by interface fracture mechanics. First, a crack initiates at the edge of the bonded contact interface, which grows as the load applied to the clutch increases. At its force capacity, the crack propagates through the whole interface, and the surfaces of the clutch separate.

[0030] Fig. 13. Ionoelastomer materials and surface energy modification. (A) Ionoelastomer chemistry. The ionoelastomer pads which comprise the contacting interfaces of the electroadhesive clutch are polyelectrolytes, with the polycation 1-ethyl-3-methyl imidazolium poly[(3sulfopropyl) acrylate] (EA) and the polyanion poly[1-(2-acryloyloxyethyl)3-buthylimidazolium]bis(trifluoromethane) sulfonimide (AT). Both polyelectrolytes are synthesized with a low energy comonomer in order to reduce the surface energy of each pad. (B) Water contact angle measurements. The addition of comonomer decreases the surface energy of both EA and AT ionoelastomer pads, increasing the water contact angle by 30° for EA, and 10° for AT. This reduces the amount of adhesion between the ionoelastomer surfaces in the forward and reverse bias states. (C) Water contact angle (degrees) for EA, EA+comonomer, AT, and AT+comonomer.

[0031] Fig. 14. Experimental validation of the analytical model and an exploration of electroadhesive clutch stiffness on force capacity. (A) Measured electroadhesive force capacity as a function of the geometric scaling parameter. Each data point indicates a different electroadhesive clutch design, with $n = 3$ clutches tested per data point. The error bars indicate one SD above and below each measured FC value. The green, red, and blue dotted lines indicate the model predicted values of electroadhesive FC with a $G_C = 74 \text{ Jm}^{-2}$ for the 2.5 V data, 269 Jm^{-2} for the 5 V data, and a $G_C = 493 \text{ Jm}^{-2}$ for the 7.5 V data. The green, red, and blue shaded regions indicate a 20% deviation in G_C

from the fitted parameters. (B) Measured electroadhesive FC versus electroadhesive joint widths for clutches tested with different operating voltages (V) at a set contact area of 0.5 cm^2 , with all other design parameters fixed. The green dotted line indicates the model's predictions for 2.5 V operation, the red dotted line indicates the model's predictions for 5 V operation, and the blue dotted line indicates the model's predictions for 7.5 V operation. (C) Measured electroadhesive FC versus electroadhesive joint widths for clutches with different electrode thicknesses (t) at a set contact area of 0.5 cm^2 , with all other design parameters fixed. The red dotted line indicates the model's predictions for $t = 127 \text{ }\mu\text{m}$ electrodes, and the black dotted line indicates the model's predictions for $t = 254 \text{ }\mu\text{m}$ electrodes.

[0032] Fig. 15. The impact of reduced ionoelastomer pad thickness on force capacity and clutch switchability. (A) Ionoelastomer clutches with reduced pad thickness. (B) Surface roughness increases as pad thickness drops, due to the proximity of the wavy, metal mesh electrode to the pad's surface. (C) Ionoelastomer clutch force capacity vs. ionoelastomer pad thickness. At a set clutch geometry and applied voltage, both the reverse bias force capacity (shown in green) and forward bias force capacity (shown in red) decrease as the pad thickness drops from $125 \text{ }\mu\text{m}$ to $10 \text{ }\mu\text{m}$. (D) Ionoelastomer clutch switchability ratio vs. ionoelastomer pad thickness. Since the forward bias adhesion drops closer to zero as the pad thickness drops, the clutches with thinner ionoelastomer pads become increasing more releasable at a set voltage and clutch shape.

[0033] Fig. 16 provides a comparison of state-of-the-art electroadhesive clutches. We compare the maximum force capacity per unit area, which is plotted here versus (FIG. 16A) applied voltage and (FIG. 16B) contact area. The data for the clutches from the literature shown here are from references [8–10,12,13,16,19].

[0034] FIG. 17 provides an illustrative depiction of the disclosed technology.

[0035] FIG. 18: Soft dielectric electroadhesive operation, performance, and applications. (A) An electroadhesive clutch is composed of two compliant, metalized electrodes separated by an insulating dielectric layer. The dielectric layer has a low Young's modulus (E_d), which is less than 5 MPa. The clutch contact interface is noted in red (left). When a voltage is applied and the electrodes are brought close together, electrostatic forces bring the electrodes into contact, and conformal contact is made due to the high compliance of the elastomer. The combination of electrostatic and surface forces

block sliding at the contact interface. When the voltage is removed, the electrodes are free to slide but surface forces still remain, leading to latent adhesion. (B) (left) The force capacity (F_C) of a soft dielectric electroadhesive clutch is the force above which the clutch fails or slips when voltage is applied. (middle) For a low switchability design, surface forces remain high, increasing the force required to detach the electrodes when no voltage is applied (F_{OFF}), thus lowering switchability (S). (middle) For an increased switchability design, surface forces are reduced, decreasing F_{OFF} , thus increasing switchability (S). (C) Applications of soft dielectric electroadhesive clutches with increased switchability ratios. (left) Soft dielectric electroadhesives are compliant to integrate onto fabrics and lock-in or release different shapes. (right) Electroadhesive clutches for kinesthetic haptic feedback. Engaging one or two clutches in parallel enables successful rendering of compliant and stiff virtual objects. (D) A schematic comparing F_C/A , F_{OFF}/A and S for different soft dielectric electroadhesive clutches presented in this work. Each line represents a different electroadhesive clutch design investigated in this work. Soft dielectric electroadhesive clutches with control designs are denoted in blue, while enhanced switchability designs are denoted in red.

[0036] FIG. 19: Modeling and performance of constant modulus soft dielectric electroadhesive clutches. (A) A schematic of an electroadhesive clutch, with important geometric and material parameters labeled (top), and the representative spring network used to predict total joint compliance and electroadhesive force capacity (bottom). (B) Measured electroadhesive F_C and F_{OFF} as a function of GSP. Each data point indicates a different electroadhesive clutch design, with $n = 3$ clutches tested per data point. The data points with filled circles indicate clutch F_C values, and open circles indicate clutch F_{OFF} values. The error bars indicate one SD above and below each measured F_C and F_{OFF} value. The black, red, and blue dotted lines indicate the model predicted values of electroadhesive F_C with a $G_C = 5.5 \text{ Jm}^{-2}$ and a $G_{C,OFF} = 2.9 \text{ Jm}^{-2}$ for the LM data, $G_C = 24.4 \text{ Jm}^{-2}$ and a $G_{C,OFF} = 11.5 \text{ Jm}^{-2}$ for the IM data, and a $G_C = 35.5 \text{ Jm}^{-2}$ and a $G_{C,OFF} = 17.7 \text{ Jm}^{-2}$ for the HM data. The black, red, and blue shaded regions indicate a 20% deviation in G_C and $G_{C,OFF}$ from the fitted parameters. (C) Measured electroadhesive F_C versus electroadhesive joint widths for clutches tested with different operating voltages (V) at a set contact area of 4 cm^2 , with all other design parameters fixed. The blue dotted line indicates the model's predictions for IM soft dielectrics. The circular data points indicate

clutches tested at 200 V, and square data points indicate clutches tested at 300 V. The data points with filled circles indicate clutch F_C values, and open circles indicate clutch F_{OFF} values. (D) Measured switchability (S) versus F_C for different clutch designs. The horizontal and vertical error bars indicate one SD above and below each measured F_C and S value.

[0037] FIG. 20: Fabrication and performance of fixed modulus soft dielectric clutches with added surface roughness. (A) Fabrication of clutches with soft dielectric layers with added surface roughness. First, a drop of IM PDMS was placed on the surface of a metalized electrode, which was firmly attached to a silicon wafer, and spun to a thickness of 20 μm at a speed of 2500 rpm. Next, a steel foam template was added onto the dielectric surface, and cured at 150°C for 15 minutes. As the curing step began, either no mass was added to the steel foam template for low roughness clutches, or a 200 g steel weight for high roughness clutches. Finally, after curing, the template was removed, leaving the rough dielectric interface. (B) Height and roughness measurements of the added surface features using white-light interferometry. The steel foam template leaves indentations in the soft dielectric layer. The depth of the indentations remained constant between the low and high roughness clutches, but the RMS roughness increased from $4.1 \pm 1.3 \mu\text{m}$ to $6.8 \pm 0.8 \mu\text{m}$. (C) Measured electroadhesive F_C as a function of GSP for soft dielectrics with added roughness. Each data point indicates a different electroadhesive clutch design, with $n = 3$ clutches tested per data point, all tested at 200 V with $A = 4 \text{ cm}^2$ and an IM PDMS dielectric layer. The data points with filled circles indicate clutch F_C values. The error bars indicate one SD above and below each measured F_C value. The orange, green, and blue dotted lines indicate the model predicted values of electroadhesive F_C with a $G_C = 0.4 \text{ Jm}^{-2}$ and for the high roughness data, $G_C = 9.4 \text{ Jm}^{-2}$ for the low roughness data, and a $G_C = 24.4 \text{ Jm}^{-2}$ for the smooth data. The orange, green, and blue shaded regions indicate a 20% deviation in G_C and from the fitted parameters. (D) Measured switchability (S) versus F_C for different clutch designs with added roughness. The horizontal and vertical error bars indicate one SD above and below each measured F_C and S value.

[0038] FIG. 21 Utilizing multi-modulus dielectrics for increased force capacity at a fixed voltage. (A) (left) A schematic depicting an electroadhesive clutch with a constant modulus dielectric composed of stiff PDMS (modulus E_I). (right) A schematic depicting

an electroadhesive clutch with a multi-modulus dielectric composed of stiff PDMS (modulus E_1) at the clutch's center, with soft PDMS (modulus E_2) at the edges of the clutch. (B) (left) Dielectric film modulus versus distance along the dielectric layer for a constant modulus electroadhesive clutch. (right) Dielectric film modulus versus distance along the dielectric layer for a multi-modulus electroadhesive clutch. (C) (left) Normalized peel stress concentration at the edge of the clutch. We normalized the peel stress (σ_y) by a far-field stress (σ_∞) applied to the right-hand electrode. (right) By adding edge compliance, this peel stress concentration was reduced. We used a 2-D FE model to generate the stress distribution in the dielectric, assuming the interface was perfectly bonded. (D) (left) Measured electroadhesive F_C as a function of GSP for soft dielectrics with a constant modulus and multi-modulus design, with or without roughness added. Each data point indicates a different electroadhesive clutch design, with $n = 3$ clutches tested per data point, all tested at 200 V. The shape of the data point (diamond, circle, or triangle) represents the clutch's contact area ($A = 2, 4$ or 8 cm^2). The error bars indicate one SD above and below each measured F_C value. The pink and red dotted lines indicate the model predicted values of electroadhesive F_C with a $G_C = 68.6 \text{ Jm}^{-2}$ and for the multi-modulus data, and a $G_C = 35.5 \text{ Jm}^{-2}$ for the constant modulus, HM PDMS data. The cyan and orange dotted lines indicate the model predicted values of electroadhesive F_C with a $G_C = 3.3 \text{ Jm}^{-2}$ and for the multi-modulus data with roughness added, and a $G_C = 0.4 \text{ Jm}^{-2}$ for the constant modulus, IM PDMS data with roughness added. The pink, red, cyan, and orange shaded regions indicate a 20% deviation in G_C and from the fitted parameters. (right) Measured switchability (S) versus F_C for different clutches with a constant modulus or multi-modulus design, and with or without added roughness. The horizontal and vertical error bars indicate one SD above and below each measured F_C and S value.

[0039] FIG. 22: Demonstrations of electroadhesive clutches with soft dielectrics for stiffness programming of stretchable fabrics and structural elements. (A) When a clutch with a soft dielectric layer was integrated onto a stretchable fabric, it increased the fabric's tensile stiffness when a voltage was applied to the electrodes, decreasing its ability to stretch (left). When the voltage was removed, the stiffness decreased, and the fabric stretches substantially (right). Thus, an electroadhesive device according to the present disclosure can be incorporated into or otherwise engaged with a fabric. (B) When pinned at its ends, the same fabric in (A) also has a high bending stiffness when the voltage was

applied to the clutch (left), locking in a desired curvature under a 200g load. When voltage was removed, the clutch separated and the fabric reached a new curvature, displacing under the load. (C) We attached two clutches to a four-bar linkage with pinned joints, which prevented rotation of the mechanism in either direction when a voltage was applied to both clutches (left). When the voltage was removed, the clutches separated, and the linkage collapsed under its own weight (right). Thus, an electroadhesive clutch according to the present disclosure can be engaged with a linkage such that the linkage attains a first shape state when the clutch is activated, and the linkage attains a second shape state when the clutch is deactivated.

[0040] FIG. 23: Demonstration of electroadhesive clutches integrated onto a soft, pneumatic finger with a programmable stiffness for kinesthetic haptic feedback. By attaching two clutches onto the back of a soft, pneumatic finger, we modulated the finger's stiffness between a low stiffness, medium stiffness, and high stiffness state. When neither of the clutches were activated with an applied voltage, and the finger was inflated to 30 kPa, it reached a curved, concave configuration. When only one clutch was activated, the bending stiffness increased, and the finger was locked into a straight-line configuration upon inflation. When both clutches were activated, the bending stiffness increased further, and the finger bent in the opposite direction compared to the non-clutched state, reaching a convex configuration.

DETAILED DESCRIPTION OF ILLUSTRATIVE EMBODIMENTS

[0041] The present disclosure may be understood more readily by reference to the following detailed description of desired embodiments and the examples included therein.

[0042] Unless otherwise defined, all technical and scientific terms used herein have the same meaning as commonly understood by one of ordinary skill in the art. In case of conflict, the present document, including definitions, will control. Preferred methods and materials are described below, although methods and materials similar or equivalent to those described herein can be used in practice or testing. All publications, patent applications, patents and other references mentioned herein are incorporated by reference in their entirety. The materials, methods, and examples disclosed herein are illustrative only and not intended to be limiting.

[0043] The singular forms “a,” “an,” and “the” include plural referents unless the context clearly dictates otherwise.

[0044] As used in the specification and in the claims, the term "comprising" can include the embodiments "consisting of" and "consisting essentially of." The terms “comprise(s),” “include(s),” “having,” “has,” “can,” “contain(s),” and variants thereof, as used herein, are intended to be open-ended transitional phrases, terms, or words that require the presence of the named ingredients/steps and permit the presence of other ingredients/steps. However, such description should be construed as also describing compositions or processes as "consisting of" and "consisting essentially of" the enumerated ingredients/steps, which allows the presence of only the named ingredients/steps, along with any impurities that might result therefrom, and excludes other ingredients/steps.

[0045] As used herein, the terms “about” and “at or about” mean that the amount or value in question can be the value designated some other value approximately or about the same. It is generally understood, as used herein, that it is the nominal value indicated $\pm 10\%$ variation unless otherwise indicated or inferred. The term is intended to convey that similar values promote equivalent results or effects recited in the claims. That is, it is understood that amounts, sizes, formulations, parameters, and other quantities and characteristics are not and need not be exact, but can be approximate and/or larger or smaller, as desired, reflecting tolerances, conversion factors, rounding off, measurement error and the like, and other factors known to those of skill in the art. In general, an amount, size, formulation, parameter or other quantity or characteristic is “about” or “approximate” whether or not expressly stated to be such. It is understood that where “about” is used before a quantitative value, the parameter also includes the specific quantitative value itself, unless specifically stated otherwise.

[0046] Unless indicated to the contrary, the numerical values should be understood to include numerical values which are the same when reduced to the same number of significant figures and numerical values which differ from the stated value by less than the experimental error of conventional measurement technique of the type described in the present application to determine the value.

[0047] All ranges disclosed herein are inclusive of the recited endpoint and independently of the endpoints. The endpoints of the ranges and any values disclosed

herein are not limited to the precise range or value; they are sufficiently imprecise to include values approximating these ranges and/or values.

[0048] As used herein, approximating language can be applied to modify any quantitative representation that can vary without resulting in a change in the basic function to which it is related. Accordingly, a value modified by a term or terms, such as “about” and “substantially,” may not be limited to the precise value specified, in some cases. In at least some instances, the approximating language can correspond to the precision of an instrument for measuring the value. The modifier “about” should also be considered as disclosing the range defined by the absolute values of the two endpoints. For example, the expression “from about 2 to about 4” also discloses the range “from 2 to 4.” The term “about” can refer to plus or minus 10% of the indicated number. For example, “about 10%” can indicate a range of 9% to 11%, and “about 1” can mean from 0.9-1.1. Other meanings of “about” can be apparent from the context, such as rounding off, so, for example “about 1” can also mean from 0.5 to 1.4. Further, the term “comprising” should be understood as having its open-ended meaning of “including,” but the term also includes the closed meaning of the term “consisting.” For example, a composition that comprises components A and B can be a composition that includes A, B, and other components, but can also be a composition made of A and B only. Any documents cited herein are incorporated by reference in their entireties for any and all purposes.

[0049] Enhanced Design of Electroadhesive Clutches

[0050] RESULTS

[0051] Analytical Modeling

[0052] To predict force capacity, we model electroadhesive clutches as bonded lap joints. Lap joint models assume that the adhesive layer is loaded in shear (35–38), undergoes failure via fracture upon reaching its force capacity (39), and is linear elastic prior to failure (28, 29). As the same assumptions apply to electroadhesive clutches, their mechanics are akin to those of adhesively bonded lap joints. Although other fracture-based models exist for electroadhesive lap joints, they assume the electroadhesive to have no stiff electrode backing, which leads to a different failure mechanism compared to the clutches in this work (40). Using a fracture-based, analytical model of bonded lap joints (28, 29), the force capacity of an electroadhesive clutch can be expressed as

$$FC = \beta \sqrt{2G_C} \sqrt{\frac{A}{C}}, \quad (1)$$

where C is the overall compliance of the clutch system, A is the contact area between electrodes (red area in Fig. 1A), b is a constant (assumed to be 1 in this work) and G_C is the critical strain energy release rate, which describes the adhesion at the interface and is not a function of clutch geometry or compliance (31). We define compliance as the axial displacement of a clutch with no slipping divided by the applied force. Modifications to compliance through shape change (28, 29, 34) and geometric confinement (27) have been previously shown to increase force capacity for non-electrically controlled adhesive joints loaded in shear. It should be noted however, that such increases in force capacity reported in (27) could not be explained by the parallel plate friction model described in eq. (2), which was the model used to predict electroadhesive force capacity in that study. Our model assumes that force capacity is the force at which the strain energy release rate G is equal to a critical strain energy release rate, G_C . The critical strain energy release rate can be thought of as the interface toughness or interface fracture energy required to separate the clutch surfaces. In an electroadhesive clutch, G_C is directly proportional to the square of the applied voltage (V^2), which is a relationship predicted by parallel plate electrostatic theory (41). This model has notable differences from the clutch force capacity predicted by parallel plate models, which is

$$FC_{pp} = \mu F_{el} = \mu \frac{\epsilon_0 A (\kappa V)^2}{2d^2}, \quad (2)$$

where F_{el} is the electrostatic force, m is the coefficient of friction between dielectric and electrode, ϵ_0 is the permittivity of free space, A is the contact area, κ is the relative permittivity, V is the applied voltage, and d is the thickness of the dielectric. First, according to eq. (1), force capacity is directly proportional to $G_C^{1/2}$, which leads to a direct scaling with V , and not V^2 , as eq. (2) predicts. Next, our model assumes force capacity to be governed by adhesion and interface fracture (Fig. 1C), whereas the force capacity of parallel plate models depends on static friction (Fig. 1D). Finally, eq. (2) is independent of the clutch compliance (C), and only considers A and d to be relevant geometric parameters that contribute to force capacity. In contrast, our model takes C into account, which includes the contact, or overlap region, but also the free, non-contacting regions of the

clutch, along with the contact area (A). Importantly, the total compliance must be considered in a predictive model, as each clutch will undergo deformation in its overlap region and free regions, which all contribute to non-uniform shear and peel stresses that cause electrode separation at force capacity (35–38).

[0053] We denote the quantity $(A/C)^{1/2}$ as the geometric stiffness parameter (GSP), which accounts for the overall clutch compliance and electroadhesive contact area. Fig. 2A shows the spring-based model for overall clutch compliance. To satisfy the linear elastic assumption required by eq. (1), the clutch compliance is measured at small strains (1-1.5%) (Fig. 7). The electroadhesive joint is split into two distinct regions. These include: (1) the overlap region, where the electrodes are adhered and both the dielectric and electrode layers undergo deformation, and (2) the free regions away from the contact, where only the electrodes undergo deformation. In the overlap region, the dielectric and two adherends are treated as springs in parallel, and their axial compliance is

$$C_{\text{overlap, axial}} = \frac{L}{w} \left[\frac{1}{2E_e t + E_d d} \right], \quad (3)$$

where E_e is the Young's modulus of the electrodes, E_d is the Young's modulus of the dielectric, t is the thickness of the electrodes, d is the thickness of the dielectric layer, w is the width of the overlap region, and L is the length of the overlap region. For the single lap shear configuration, there is eccentricity in the loading path, which results in the joint being loaded by a moment that leads to bending as well shear deformation of the dielectric. However, since the thickness of the dielectric is smaller than the overlap length ($d \ll L$) in the clutches presented here, we neglect both the shear and bending compliance. The compliance of the two free regions, which are loaded axially, are

$$C_f = \frac{L_f}{E_e w t}, \quad (4)$$

where L_f is the length of the free region. The experimentally measured compliance of the testing machine (C_{machine}) is also included. Adding these compliances in series, the total system compliance is

$$C_{total} = \frac{L}{w(2E_e t + E_d d)} + \frac{2L_f}{E_e t w} + C_{machine} \quad (5)$$

which is similar to the system compliance used in (29). Fig. 8 shows reasonable agreement between the measured and predicted clutch stiffnesses k , which is equal to the reciprocal of the compliance ($1/C_{total}$). Finally, we combine eq. (1) and eq. (5) to find an expression for electroadhesive force capacity. This model illustrates that the electroadhesive force capacity depends on material and geometric parameters as well as contact area and applied voltage, so all of these parameters must be considered in clutch design.

[0054] Figures 2B - 2D summarize the effect of clutch shape and applied voltage on electroadhesive force capacity. Fig. 2B shows the force capacity as a function of clutch width. The lines of constant area were calculated using the model with a G_C value corresponding to our 200 V force capacity experiments ($G_C = 68 \text{ Jm}^{-2}$), and the lines of constant voltage were calculated using G_C values corresponding to our 75 V, 200 V and 300 V force capacity experiments ($G_C = 11 \text{ Jm}^{-2}$, 68 Jm^{-2} , 146 Jm^{-2}). These G_C values were determined by performing a linear regression on our GSP vs. force capacity experimental data at 75 V, 200 V and 300 V, where the slope was equal to $(2G_C)^{1/2}$. G_C was determined from the best fit lines: 75 V ($G_C = 11 \text{ Jm}^{-2}$, $R^2=0.96$), 200 V ($G_C = 68 \text{ Jm}^{-2}$, $R^2=0.95$), and 300 V ($G_C = 146 \text{ Jm}^{-2}$, $R^2=0.92$). The map in Fig. 2C assumes 200 V operation and shows force capacities for overlap lengths (L) and widths (w) ranging from 0 mm to 80 mm.

Overall, increasing the GSP of an electroadhesive clutch (decreasing total compliance and increasing contact area) increases the force capacity. Importantly, our model showed that holding contact area constant but changing clutch shape leads to changes in FC as the clutch compliance also changes ($FC \propto (A/C)^{1/2}$). This contradicts the predictions of parallel-plate electrostatic models, which do not account for joint stiffness and indicate that $FC \propto A$, which suggest that FC should be constant if A is fixed. Fig. 2B and 2D show lines of constant area to illustrate this point. In order to reduce the contact area of any electroadhesive clutch without decreasing its force capacity, its overlap width can be increased and its joint length reduced (Fig. 2C). Moreover, Fig. 2D shows how voltage influences FC , where G_C is proportional to V^2 . Lines corresponding to 75 V, 200 V and 300 V ($G_C = 11 \text{ Jm}^{-2}$, 68 Jm^{-2} & 146 Jm^{-2}) are shown, which were determined by fitting

the model to the experimental data. This relationship shows that the applied voltage can be reduced without reducing the electroadhesive FC by decreasing joint compliance and/or increasing contact area. Overall, the contour maps show the combined influence of compliance, contact area, and applied voltage on electroadhesive force capacity, which all need to be considered in the design to optimize a clutch for a set of design constraints.

[0055] Experimental Validation

[0056] To validate our analytical model for force capacity of an electroadhesive clutch, we performed mechanical tests of electroadhesives with a variety of compliances (see Materials and Methods section for details, setup is shown in Fig. 9). For each electroadhesive, we measured force capacity, stiffness (at small strains of 1-1.5%), and maximum possible contact area. First, we assessed the validity of GSP as a predictive variable for clutch force capacity. Fig. 3A shows that there is a linear relationship between the calculated GSP and measured FC , where the $(2G_C)^{1/2}$ slope matches the prediction in eq. (1). The slope of the best fit line for the 75 V, 200 V, and 300 V datasets increased by the same degree as the voltage increase: 2.54' for 75-200 V (4.8% below the expected 2.67'), and 1.46' for 200-300 V (2.7% below the expected 1.5') for clutches with the same geometric parameters, which agreed with the predicted FC a V relationship.

[0057] Next, we measured the influence of clutch stiffness on electroadhesive force capacity by changing the clutch aspect ratio as we maintained a constant contact area of 16 cm². Fig. 3B shows that the force capacity increases with increasing width, which corresponds to a decreased compliance as the length shrinks to keep the area constant (red data). The electroadhesives had a fixed free length of 24 mm, a fixed electrode thickness of 127 mm, an applied voltage of 200 V, and a set dielectric thickness of 6.8 mm, so that the electrostatic pressure (E_p) was constant. The electrostatic pressure is the total electrostatic force divided by the contact area ($E_p = F_{el}/A$). Fig. 3C shows electroadhesive force capacity as a function of width for clutches with thicker electrodes ($t = 254$ mm). These clutches (shown in black) had the same parameters used in the initial test ($A = 16$ cm², $V = 200$ V, $d = 6.8$ mm, $L_f = 24$ mm, with varying L and w), but they showed larger force capacities compared to the $t = 127$ mm specimens (shown in red) because of the decrease in total compliance, even at a fixed contact area. For both experiments, the measured data matches the predicted values from the analytical model. These results show that the electroadhesive force capacity can vary substantially under a constant area, which

contradicts prior parallel plate models and reinforces the importance of considering the clutch compliance in device design.

[0058] To investigate the effect of simultaneous changes in both electroadhesive clutch compliance and contact area on force capacity, we tested electroadhesives with the same electrode & dielectric thicknesses ($t = 127$ mm, $d = 6.8$ mm, $L_f = 40$ mm) at an applied voltage of $V = 200$ V, but held overlap width constant at $w = 80$ mm, and varied the overlap length L from 5 mm to 40 mm, which corresponded to contact areas ranging from 4 cm^2 to 32 cm^2 (Fig. 3D). We observed a non-linear increase in electroadhesive force capacity at increased overlap lengths, which corresponds with the simultaneous increase in contact area and clutch compliance predicted by the analytical model. This dependence of force capacity on overlap length arises from the clutch's load train compliance (free region compliance and machine compliance), which has been previously shown to affect force capacity for adhesive specimens that undergo electrode separation at force capacity (42), like our electroadhesive clutch designs (Fig. 7).

[0059] Finally, the clutches operated at different voltages not only followed the trend predicted by the model ($FC \propto V$), but also showed the same predicted nonlinear increase in FC for larger clutch widths and shorter clutch lengths (Fig. 3B). Overall, our experimental data for force capacity at a variety of clutch compliances and contact areas are in good agreement with the analytical model.

[0060] Soft Actuator Demonstration

[0061] Strong electroadhesives can modulate the stiffness and strength of robotic systems, but for many soft robotic applications, such as gripping, the elastomer compliance that enables robust damage-free interactions with fragile objects (43) also results in reduced load carrying capabilities. For example, we show a custom pneumatically-actuated soft hand which can carry one 0.2 kg apple with two inflated fingers (Fig. 4A). When the same fingers are loaded with a 1.8 kg bag of apples, the fingertips bend away from the palm and the hand drops the load. We show that strong electroadhesives attached to soft robotic fingertips can increase their load carrying capacity by mechanically connecting the fingertip to the palm (Fig. 4B, additional details in Fig. 10), which allows the same robotic hand to lift a 1.8 kg bag of apples with one finger without dropping it. When the electroadhesive is not activated, a finger inflated to 30 kPa can sufficiently bend to touch the palm under zero load, but is easily uncurled by a

small 0.1 kg mass, which therefore represents the load capacity of the simple finger (Fig. 4C). To utilize the electroadhesive, the finger was inflated to 30 kPa, which brought the electrodes into a parallel configuration. After turning on the voltage and lightly pressing the electroadhesive electrodes into contact, the two electrodes became adhered. Mass was then added to the finger directly underneath the electroadhesive. A secondary attachment feature (zip-tie) was used to ease the placement of mass on the finger. The zip-tie is not tightened to grip the finger, so when the finger was over-loaded, the mass and zip-tie easily slip off. An electroadhesive with $L = 80$ mm, $w = 20$ mm, $V = 75$ V, $t = 127$ mm, $d = 6.8$ mm, and $L_f = 24$ mm increased the finger's load capacity from 0.1 kg to 4 kg, at which point the electrodes separated. For this electroadhesive design operated at 75 V, our model predicts a force capacity of 4.2 kg, which is only 4.7% larger than the measured force capacity. We also tested an electroadhesive with increased GSP to further increase the finger's force capacity. The stronger electroadhesive had a larger overlap width ($w = 40$ mm) and smaller overlap length ($L = 40$ mm), with the other design variables fixed ($V = 75$ V, $d = 6.8$ mm, $t = 127$ mm and $L_f = 24$ mm). This electroadhesive increased the finger's force capacity to 6.2 kg, which is 62× the load capacity of the simple finger with no electroadhesive. Our model predicts a force capacity of 6.7 kg, which is only 7.4% larger than the measured load capacity. In this latter configuration, loads larger than 6.2 kg caused the finger to tear, even as the electroadhesive maintained adhesion, which explains why the finger's load capacity did not reach the expected value and demonstrates the strength of these electroadhesives.

[0062] Many robotic applications, such as wearables and haptic interfaces, would also benefit from strong electroadhesives to modulate bending stiffness and to resist rotation to provide kinesthetic haptic feedback. As an example, we demonstrated an elbow wearable with an electroadhesive clutch placed on the arm of a mannequin (Fig. 5A). When the electroadhesive was activated at 75 V and the electrodes were lightly pressed into contact, they became adhered. An electroadhesive with $L = 40$ mm, $w = 40$ mm, $V = 75$ V, $t = 127$ mm, $d = 6.8$ mm, and $L_f = 24$ mm reduced the bend angle of the mannequin's elbow joint by 20° when loaded under its own weight, resisting a moment of 2.67 N-m. When the clutch was not activated, the electrodes slid past one another, and the elbow freely bent downwards. Similarly, we demonstrated a soft finger with an attached high GSP electroadhesive (Fig. 5B). First, the finger was inflated to 30 kPa, which caused

it to easily bend due to its low bending stiffness. In this configuration, the clutch electrodes slid past one another until they were no longer in contact. However, when the clutch was activated at 75 V, the electrodes adhered to one another after being lightly pressed. When the finger was inflated to 30 kPa, the finger's rotation was substantially reduced, due to the increase in bending stiffness resulting from the activated electroadhesive, which increased the finger's flexural rigidity. Overall, our model can be applied to design strong electroadhesives that notably augment the force capacity and modulate the stiffness and strength of soft actuators and other robotic systems, in both bending and tensile loading scenarios. Importantly, this was all achieved at 75 V, which is considerably lower than the 300 – 1500 V used in previously reported electroadhesives (19–23, 25).

[0063] DISCUSSION

[0064] We show that a fracture mechanics-based model, and not a parallel plate model, describes the relationship between electroadhesive design and force capacity. The improved predictive accuracy originates from the model's ability to assess slip based on the electroadhesion-induced critical energy release rate required to delaminate two electrodes. From this model, a natural set of design variables emerge, which we used to tune the force capacity by changing the electroadhesive compliance. Our approach differs from previous empirical methods for electroadhesive force capacity modeling, which accurately predicted force capacity of a similar electroadhesive clutch system (23), but could not illuminate the driving physical and geometric phenomena that contribute to strength and, therefore, provided limited insight into design strategies for improving clutch strength, such as the modification of system compliance. Thus, our approach can provide insights into new clutch materials and architectures that go beyond the single system we are studying due to the derived relationship between clutch stiffness, critical strain energy release rate, and force capacity. Our approach also allowed us to design strong clutches that do not require substantial amounts of electrostatic force for operation, which was the reason for the performance gains described in this work. The clutches we developed also operated at low voltages with a dielectric of low relative permittivity ($k = 3.1$ for Parylene-C) (44), and have force capacities and force capacities per unit area that are similar or exceed that of existing clutches. The highest performing clutch we built had a force capacity per unit electrostatic force of 10 at a contact area of 16 cm^2 and 75 V operation

(Fig. 6). This is 94% higher than the highest performing clutch in the literature (23). Since electroadhesive force capacity scales with V , and electrostatic pressure scales with V^2 , force capacity per unit electrostatic force scales with $1/V$, which led to our lowest voltage designs (75 V) exhibiting the highest performance per this metric. By simply changing the clutch's aspect ratio (L/w) from 4 to $\frac{1}{4}$ at a set contact area of 16 cm^2 and operating voltage of 200 V, we increased force capacity by 2.3%. Importantly, the increases in force capacity can be achieved with simple changes to the clutch geometry or materials, which allows the application of this improvement to many robotic systems. We demonstrate this with a soft robotic hand that can pick up 62% larger loads when an electroadhesive clutch allows mechanical anchoring of the fingertip to the robot palm. These clutches are easy to manufacture, lightweight, and flexible, and their superior force capacity over prior work can enable smaller clutches that operate with lower voltages and allow larger changes in material stiffness and strength. The fundamental insight into clutch performance solves persistent engineering challenges of incorporating electroadhesive clutches into robotic systems and will enable next generation wearable and untethered robotic systems such as soft grippers (45), morphing sheets (12), prosthetics (46), orthotics (47, 48), and haptic gloves (19, 20, 49).

[0065] Although the improvements in clutch performance presented here are notable, the accuracy of the model will be limited by the model assumptions. First, as our model assumes the clutch mechanics is similar to a bonded joint, the model may not be applicable when the electrostatic pressure between surfaces is sufficiently low so that there is slip at the contact surfaces. In addition, loading conditions which are very different than the assumed tensile loading could reduce the predictive power of the model, and clutch designs with very small aspect ratios could be susceptible to alignment issues that may reduce the apparent contact area between surfaces. Overall, we found the model to be an excellent predictor of performance for clutches with geometric parameters, such as electrode thickness and aspect ratio, within the range required for most robotic applications where flexibility is desired. Although we have focused on force capacity, contact area, and operating voltage as critical metrics for electroadhesive clutches, it is important to note that response time, electrode separation, and fatigue life are also key metrics to be considered in clutch design. Future work that studies these interactions should also consider the influence of the dielectric on clutch durability.

[0066] MATERIALS AND METHODS**[0067] Electroadhesive clutch fabrication**

[0068] An automated blade cutter (Curio, Silhouette Inc.) was used to cut each electrode with a 0.2 mm thick blade. The electrodes were comprised of a 127-micrometer thick BOPET sheet coated with a thin aluminum film on one side (7538T12, McMaster-Carr, Inc.). A chemical vapor deposition system (Specialty Coating Systems, PDS2010) conformally coated the Parylene-C dielectric (poly(chloro-*p*-xylylene)) on the aluminum side of one BOPET electrode. Parylene-C dimer (1.9g) was vaporized at 175°C, which was then cleaved into monomers in a pyrolysis furnace at 690 °C. The vapor-phase monomer was then polymerized in a deposition chamber at ~25 °C, where the clutch electrodes were placed. Kapton tape masked the clutch electrodes to only coat the desired area with dielectric. An Anatech SCE 106 system cleaned all clutch electrodes with oxygen plasma at 30 W for 1 min before coating. To measure the thickness of the dielectric film, we placed 2 cm² glass slides (also pre-cleaned with oxygen plasma at 30W for 1 min) in the coating chamber with the clutch electrodes. A KLA-Tencor P7 stylus profilometer was used to measure the average dielectric thickness to be 6.8 mm ± 0.5 mm for all n = 69 electroadhesive specimens.

[0069] Tensile testing for electroadhesive force capacity experiments

[0070] To prepare each sample for a tensile test, an adhesive (Loctite 409) was used to attach each electroadhesive specimen to laser-cut acrylic grips to ensure no slipping. A signal generator (Agilent 33220A) applied a AC voltage square wave signal with a frequency of 10 Hz (for a 200mV amplitude, the voltage fluctuated between +200mV and -200mV), and a high-voltage amplifier (Trek Model 10/10B-HS) amplified the signal by 1000^x to its final value. An AC signal was used to mitigate the effect of space charge buildup in the dielectric. Electrical leads connected the amplifier to the clutch, using copper and alligator clips to obtain good electrical contact to the aluminum surface on the PET. To characterize the force capacity of each electroadhesive clutch, we performed uniaxial tensile tests using an MTS Criterion Model 43 with a 1-kN load cell with customized tensile grips. The tests were run at a speed of 1 mm min⁻¹. After the voltage was turned on, we manually applied pressure to the overlap region with a 0.8 mm thick elastomer sheet (Ecoflex 00-30, Smooth-On Inc.) to ensure good contact between the electrode and dielectric surfaces. The tensile setup is pictured in Fig. 9.

[0071] Materials testing

[0072] The modulus of the metallized PET film was determined via uniaxial tensile tests in a MTS Criterion Model 43 at a rate of 1 mm min^{-1} . An automated blade cutter (Curio, Silhouette Inc.) was used to cut the PET tensile specimens to type 5 tensile specimen (ASTM D638). The mean modulus obtained from 6 PET specimens was 2.3 GPa. A nanoindenter (Hysitron T950) was used to measure the modulus of the Parylene-C film at a variety of indentation depths (200 – 400 nanometers) with 5 indents per test. A mean measured modulus of the Parylene-C was 3.6 GPa (Fig. 11).

[0073] Soft robotic hand fabrication for load capacity tests

[0074] For the robotic hand demo, a SLA 3-D printer (Form 3, FormLabs) fabricated molds for Pneu-Net actuators (50) and a custom palm, which we designed in Fusion 360 (Autodesk). The fingers were then molded using Dragonskin 10A FAST (Smooth-On, Inc.) and cured for 20 min at 70°C . Silicone adhesive (Sil-Poxy, Smooth-On Inc) attached an inextensible paper layer to each finger, along with a flexible inlet tube and one metallized PET clutch electrode, which we cured for 20 min at 70°C .

[0075] Load capacity testing of a robotic hand with and without an attached electroadhesive

[0076] To test the load capacity of the robotic hand without electroadhesives, we inflated two fingers to 30 kPa and loaded them with a bag containing one 0.2 kg apple, which it held without dropping. An attached pressure sensor (Sparkfun Qwicc Micropressure Sensor, Sparkfun) measured the pressure value. Next, we loaded the same fingers with a full 1.8 kg bag of apples, which it could not hold. To test the load capacity of a single soft finger with an electroadhesive attached, double-sided foam tape (VHB 4910, 3M) attached one electrode to the palm. After inflating the finger, we activated the clutch at 75 V, mechanically anchoring the finger to the palm. We loaded the finger with the 1.8 kg bag, which it could successfully hold. To test the force capacity of a finger with a $w = 20 \text{ mm}$ and $L = 80 \text{ mm}$ clutch attached, we inflated it to 30 kPa, and then manually pressed the electrodes into contact. At this point, we added weight to the finger until the electrodes detached. We repeated the same procedure for a soft finger with an electroadhesive with increased GSP ($w = 40 \text{ mm}$ and $L = 40 \text{ mm}$). We attached weights to the finger using two zip-ties and an S-hook. The setup is shown in Fig. 10.

[0077] Elbow wearable demonstration with and without an activated electroadhesive

[0078] To test the ability of an electroadhesive clutch to prevent the bending of an elbow wearable, cyanoacrylate glue attached the electrodes of an increased GSP clutch ($w = 40$ mm and $L = 40$ mm) to a cotton arm sleeve. We then placed the elbow sleeve on the arm of a mannequin. When the clutch was not activated, we loaded the mannequin arm under its own weight, causing the forearm to deflect substantially, as the elbow was free to rotate. When we activated the clutch at 75 V and lightly pressed down on the contacting electrodes on the outside of the elbow joint, they adhered. When the arm was then loaded under its own weight, it deflected by a reduced amount compared to the initial, non-activated deflection.

[0079] Soft bending actuator demonstration with and without an activated electroadhesive

[0080] To test the ability of an electroadhesive clutch to prevent the bending of a soft pneumatic bending actuator, silicone adhesive (Sil-Poxy) attached the electrodes of an increased GSP clutch ($w = 40$ mm and $L = 40$ mm) to the back of a Pneu-Net finger. A custom fixture held the finger in place, oriented downwards with its air inlet tube facing up. When the clutch was not activated, we inflated the finger to 30 kPa, causing notable bending, as the finger was unobstructed. When we activated the clutch at 75 V and lightly pressed down on the contacting electrodes on the extensible side of the finger, they adhered. When the finger was once again inflated to 30 kPa, its bending angle was notably reduced amount compared to the initial, non-activated state.

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[00132] Ionoelastomer Electroadhesive Clutches

[00133] Nascent materials with electroprogrammable stiffness have made a profound impact in a wide variety of applications in recent years, improving the performance of medical devices^[1], versatile robotic grippers^[2], and morphing structures^[3]. A promising example of one such material system for programming stiffness

changes is an electroadhesive clutch. New electroadhesive clutch designs have been developed to modulate stiffness in soft or stretchable robotic systems, where traditional clutches built from rigid materials are mechanically incompatible. An electroadhesive clutch is comprised of one or more thin, compliant, conductive, overlapping electrodes separated by an insulating dielectric layer. When a voltage is applied between the conductive surfaces, the opposing charges on each electrode are attracted to one another, resulting in Coulombic electroadhesion^[4,5]. The electrostatic force produced at the contact interface can prevent sliding and increase in the in-plane stiffness^[6]. Electroadhesive clutches offer noted advantages for programming stiffness changes, including fast response times, low weights, quiet operation, and low energy consumption^[6,7]. As a result, many electroadhesive clutches for programmable stiffness have been developed in recent years for rendering virtual objects with wearable haptic gloves^[8–10], robotic exoskeletons^[11,12], fingered gripping systems^[2], modular robotic teams^[13], shape-locking of pneumatic actuators^[14], and electrostatic zipping actuators^[15].

[00134] Despite their advantages, clutches based on Coulombic electroadhesion require high operating voltages up to 1 kV^[8], cannot achieve large force capacities achieved by other materials with an electrically-programmable stiffness, such as electrothermal and electrochemical systems^[6], and suffer from low switchability. The force capacity (*FC*) is the force above which the clutch would fail or slip, and switchability is the ratio between the clutch's on-state force capacity divided by its off-state force capacity. Such high voltages present safety issues, require circuit elements (such as amplifiers) that add additional mass and cost to a given design, and lead to device failures caused by catastrophic electrical breakdown events. Clutches with increased force capacities operating at low voltages can shrink device dimensions, and increase the achievable stiffness range, while clutches with increased switchability ratios can reliably separate when desired, which is optimal for robotic systems where real-time control of stiffness is required. These benefits would make electroadhesive clutches more compatible with off-the-shelf electronics, and easily incorporated into active textiles for wearable applications where untethered operation and user safety are critical. While Coulombic electroadhesive clutches have been developed at operating voltages as low as 75 V with force capacities per unit area as high as 25 Ncm⁻²^[16], there is a need for electroadhesive clutches with four times the force capacity per unit area (100 Ncm⁻²) operating at one-

tenth of the operating voltage (7.5 V), which represent performance metrics that dielectric-based electroadhesives have never been able to reach.

[00135] To solve this challenge, non-Coulombic electroadhesives based on charged macromolecules, as opposed to those based on insulating dielectrics, have enabled reliable adhesive performance at reduced potentials. Biological systems, including mussels and sandcastle worms, commonly utilize polyelectrolyte complexation for strong, switchable adhesion.^[17,18] By utilizing a similar mechanism, Kim et. al recently demonstrated a low-voltage electroadhesive system comprised of ionoelastomers whose working mechanism is similar to the J-R effect.^[19] This electroadhesive operated at low potentials with small device sizes, as a 1 cm² ionoelastomer electroadhesive pad was able to produce 5 kPa of shear stress at 1 V, as the electric field was generated across a molecular-scale ionic double layer (IDL). An ionoelastomer is a soft, ion-conducting network formed by polymerization of an ionic liquid monomer and crosslinker into an elastomer network. In this system, one ion species is anchored by the network while the other species is mobile.^[19–21] When a small voltage is applied to the electrodes in reverse bias, as shown in Figure 12, mobile ions are drawn away from the polycation/polyanion interface. Fixed ions of opposite charge then build up at the interface, and the electric field generated across the nanoscale IDL causes the ionoelastomers to become adhered. Under forward bias, the electrodes switch polarity, and mobile ions flood the interfacial region, ceasing the electroadhesive effect, allowing the ionoelastomers to separate. Thus, ionoelastomers are a promising candidate for low-voltage electroadhesive clutches. However, their low force capacities (0.5 Ncm⁻²) and low switchability ratios must be improved for ionoelastomer clutch designs to reach their full potential.

[00136] In this work, we present a low-voltage ionoelastomer clutch that displays dramatic improvements in force capacity and switchability ratio compared to state-of-the-art electroadhesive clutches. We have previously established the ability of a fracture mechanics-based model to describe the relationship between clutch design and maximum force capacity, which enables simple changes in clutch compliance to easily improve the performance of Coulombic electroadhesive clutches. By utilizing this same approach, we improve the force capacity of our ionoelastomer clutches in reverse bias by simply changing their shape or thickness. To improve switchability ratio, we update the ionoelastomer polyelectrolytes to EA and AT, and synthesize them with a fluorinated

comonomer to decrease their surface energy (Figure 13). By doing so, we establish this decrease in ionoelastomer surface energy in conjunction with an increased pad roughness promotes clutch separation by reducing the contact area between surfaces in forward bias. Using these design approaches, we build an ionoelastomer clutch with the highest force capacity per unit area, outperforming the next highest performing Coulombic electroadhesive clutch by $3.6\times$ (at $1/27\times$ the applied voltage and $1/32\times$ the contact area) and outperforming the next highest performing ionoelastomer clutch by $178\times$. Finally, we demonstrate the ability of our ionoelastomer clutches to resist external bending moments in an ultra-small finger wearable.

[00137] RESULTS

[00138] Analytical Force Capacity Modeling

[00139] To predict force capacity, we model ionoelastomer clutches as bonded lap joints, using the same fracture mechanics-based model we used in our previous work^[16]. Lap joint models assume that the adhesive layer is loaded in shear^[22–25], undergoes failure in a single fracture event upon reaching its force capacity^[26], and is linear elastic prior to failure^[27,28]. As the same assumptions apply to ionoelastomer clutches, their mechanics are akin to those of bonded lap joints. Using a fracture-based, analytical model of bonded lap joints^[27,28], the force capacity of an ionoelastomer clutch can be expressed as

$$FC = \beta \sqrt{2G_C} \sqrt{\frac{A}{C}}, \quad (2)$$

[00140] where C is the overall compliance of the clutch system, A is the contact area between electrodes (red area in Fig. 12A), β is a constant (assumed to be 1 in this work) and G_C is the critical strain energy release rate, which describes the adhesion at the interface and is not a function of clutch geometry or compliance^[29]. We define compliance as the axial displacement of a clutch with no slipping divided by the applied force. Our model assumes that force capacity is the force at which the strain energy release rate G is equal to a critical strain energy release rate, G_C . The critical strain energy release rate can be thought of as the interface toughness or interface fracture energy required to separate the ionoelastomer surfaces. In an electroadhesive clutch, G_C is directly proportional to the square of the applied voltage (V^2), which is a relationship predicted by parallel plate electrostatic theory^[19]. Eq. (1) states that FC is proportional to V (not V^2 ,

since FC is also proportional to $G_C^{1/2}$, and importantly takes clutch compliance into account, which friction-based models overlook^[16].

[00141] We denote the quantity $(A/C)^{1/2}$ as the geometric stiffness parameter (GSP), which accounts for the overall clutch compliance and electroadhesive contact area. To satisfy the linear elastic assumption required by eq. (1), the clutch compliance is measured at small strains (1-1.5%). The electroadhesive joint is split into two distinct regions. These include: (1) the overlap region, where the electrodes are adhered and both the ionoelastomer and electrode layers undergo deformation, and (2) the free regions away from the contact, where only the electrodes undergo deformation. In the overlap region, the two ionoelastomers and two adherends are treated as springs in parallel, and their axial compliance is

$$C_{\text{overlap, axial}} = \frac{L}{w} \left[\frac{1}{2E_e t + E_{EA} d + E_{AT} d} \right], \quad (2)$$

[00142] where E_e is the Young's modulus of the electrodes, E_{EA} is the Young's modulus of the EA ionoelastomer, E_{AT} is the Young's modulus of the AT ionoelastomer, t is the thickness of the electrodes, d is the thickness of each ionoelastomer layer, w is the width of the overlap region, and L is the length of the overlap region. For the single lap shear configuration, there is eccentricity in the loading path, which results in the joint being loaded by a moment that leads to bending as well shear deformation of the ionoelastomers. However, since the thickness of the ionoelastomer is significantly smaller than the overlap length ($d \ll L$) in the clutches presented here, we neglect its bending compliance. However, the overlap still undergoes shear deformation, and its shear compliance is

$$C_{\text{overlap, shear}} = \frac{d(2(\nu + 1))}{Lw} \left(\frac{1}{E_{EA}} + \frac{1}{E_{AT}} \right), \quad (3)$$

[00143] where ν is the Poisson's ratio of the ionoelastomers. The compliance of the two free regions, which are loaded axially, are

$$C_f = \frac{L_f}{E_e w t}, \quad (4)$$

[00144] where L_f is the length of the free region. Adding these compliances in series, the total system compliance is

$$C_{\text{total}} = \frac{L}{w} \left[\frac{1}{2E_e t + E_{EA} d + E_{AT} d} \right] + \frac{d(2(\nu + 1))}{Lw} \left(\frac{1}{E_{EA}} + \frac{1}{E_{AT}} \right) + \frac{2L_f}{E_e w t}. \quad (5)$$

[00145] Finally, we combine eq. (1) and eq. (5) to find an expression for electroadhesive force capacity. This model illustrates that the electroadhesive force capacity of an ionoelastomer clutch depends on material and geometric parameters as well as contact area and applied voltage, so all of these parameters must be considered in device design.

[00146] Experimental Validation of the Force Capacity Model

[00147] To validate our analytical model for force capacity of an ionoelastomer electroadhesive clutch, we performed tensile tests of ionoelastomer electroadhesives with a variety of compliances. For each ionoelastomer electroadhesive, we measured force capacity, stiffness (at small strains of 1-1.5%), and maximum possible contact area. First, we assessed the validity of GSP as a predictive variable for ionoelastomer clutch force capacity. Fig. 14A shows that there is a linear relationship between the calculated GSP and measured FC , where the $(2G_C)^{1/2}$ slope matches the prediction in eq. (1). The slope of the best fit line for the 2.5 V, 5 V, and 7.5 V datasets increased by the same degree as the voltage increase: $1.9\times$ for 2.5-5 V (4.5% below the expected $2\times$), and $1.35\times$ for 5-7.5 V (9.7% below the expected $1.5\times$) for clutches with the same geometric parameters, which agreed with the predicted $FC \propto V$ relationship.

[00148] Next, we measured the impact of clutch stiffness on electroadhesive force capacity by changing the clutch aspect ratio while maintaining a constant contact area of 0.5 cm^2 . Fig. 14B shows that the force capacity increases with increasing width, which corresponds to a decreased compliance as the length shrinks to keep the area constant (red data). The electroadhesives had a fixed free length of 24 mm, a fixed electrode thickness of $127 \text{ }\mu\text{m}$, an applied voltage of 5 V, and a set ionoelastomer thickness of $125 \text{ }\mu\text{m}$, so that the electrostatic pressure (E_p) was constant. The electrostatic pressure is the total electrostatic force divided by the contact area ($E_p = F_{el}/A$). Fig. 14C shows electroadhesive force capacity as a function of width for clutches with thicker electrodes ($t = 254 \text{ }\mu\text{m}$). These clutches (shown in black) had the same parameters used in the initial test ($A = 0.5 \text{ cm}^2$, $V = 5 \text{ V}$, $d = 125 \text{ }\mu\text{m}$, $L_f = 24 \text{ mm}$, with varying L and w), but they showed larger force capacities compared to the $t = 127 \text{ }\mu\text{m}$ specimens (shown in red) because of the decrease in total compliance, even at a fixed contact area. For both experiments, the measured data matches the predicted values from the analytical model. These results show that the electroadhesive force capacity can vary significantly under a

constant area, which contradicts prior parallel plate models and reinforces the importance of considering the clutch compliance in device design.

[00149] Exploration of Ionoelastomer Thickness and Switchability

[00150] To further improve ionoelastomer clutch switchability, we investigated the effect of reducing the thickness of the ionoelastomer pads (Fig. 15A). By doing so, we increased their surface roughness, as the wavy surface of the metal mesh electrodes was now closer to the ionoelastomer surface (Fig. 15B). For these clutches, the reduction in ionoelastomer thickness only marginally changes the overall compliance, but significantly reduces the contact area between the surfaces, which lowers the electroadhesion in both the reverse and forward bias states. For example, the reverse bias force capacity of an ionoelastomer clutch with parameters $A = 0.5 \text{ cm}^2$, $V = 5 \text{ V}$, $L_f = 24 \text{ mm}$, $L = 10 \text{ mm}$, and $w = 5 \text{ mm}$ drops by a factor of $3.6\times$ when the ionoelastomer pad thickness dropped from $125 \text{ }\mu\text{m}$ to $10 \text{ }\mu\text{m}$, shown in green in Fig. 15C. However, since this also corresponded to a $1.8\times$ increase in surface roughness (and a predicted contact area reduction of $13\times$, using the model from eq. 1), the forward bias force capacity drops by over $110\times$, from 11.9 N to 0.1 N , shown in red in Figure 15C. This indicates that ionoelastomer clutches with reduced pad thicknesses have significantly increased switchability, as the switchability ratio increased by $16\times$ when the ionoelastomer pad thickness dropped from $125 \text{ }\mu\text{m}$ to $10 \text{ }\mu\text{m}$. These results show that electroadhesive force capacity of ionoelastomer clutches can vary greatly upon the introduction of a roughness or waviness by simply reducing the ionoelastomer thickness, due to the relative degree of contact area formation between soft surfaces. Ionoelastomer clutches with increased waviness are then weaker in the reverse bias state, but more releasable in the forward bias state, a desirable characteristic for applications which require the programmed removal of electroadhesion to reliably remove stiffness changes.

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- [00181] Additional Disclosure
- [00182] Here, we use soft, elastomeric dielectrics to build small, strong, Coulombic electroadhesive clutches with high force capacity per unit contact area at a fixed voltage. Analytical models from fracture mechanics explain how clutch compliance, shape, and surface roughness affect force capacity and switchability. We use these models to design electroadhesives with soft dielectric films that achieve force capacities similar to those of state-of-the-art clutches with stiff dielectrics in terms of force capacity per unit area, but with common dielectrics with one-fifteenth of the relative permittivity. In addition, we use controlled surface roughness to increase the switchability of any given electroadhesive clutch design. Finally, we demonstrate the ability of our soft dielectric clutches in example applications, including programmable stiffness in reconfigurable robotic fabrics, structural elements, and robotic fingers.
- [00183] Electroadhesion has emerged as an attractive strategy for programming stiffness in high performance applications, including haptic interfaces, wearables, morphing structures, robotic exoskeletons, modular robotic teams and versatile grippers. In particular, electroadhesive clutches are promising candidates for such applications due to their low weight, fast response times, high flexibility, and low power consumption. To date, electroadhesive clutches utilize two overlapping electrodes with an insulating dielectric film between them. Therefore, when a voltage is applied to a clutch's electrodes,

the opposing charges on either electrode are attracted to one another, and the electrostatic forces produced at the contact interface prevent sliding when loaded in tension, increasing the in-plane stiffness. When the voltage is removed, the clutch electrodes separate. The current reliance on electrostatic pressure alone to increase electroadhesive clutch force capacity (FC) per unit contact area (A), leveraging dielectric films with high relative permittivity (>10) and small dielectric thicknesses ($< 50 \mu\text{m}$), has prevented the current generation of clutches from reaching their full potential, as this design approach is inherently limited by electrostatic breakdown and cost.

[00184] The next generation of electroadhesive clutches should achieve increased force capacities at a fixed operating voltage to improve their performance in wearable haptics and morphing applications, where they would not preclude user flexibility or shape change without sacrificing strength. While Coulombic electroadhesive clutches have been developed with force capacities per unit area as high as 21 N/cm^2 , the next generation of electroadhesive clutches should achieve the same or increased performance and be composed of commonly available materials to provide the desired stiffness range at a small device size necessary for wearables and morphing robot applications, without requiring high permittivity dielectric layers or rigid fillers.

[00185] Here, we describe the ability of compliant dielectric films to enhance electroadhesive clutch force capacity per unit area at a fixed operating voltage. We display that electroadhesive clutches with soft dielectric films composed of polydimethylsiloxane (PDMS) can increase force capacity per unit contact area in the voltage-on state because the surface compliance allows for conformal electrode contact and engagement of surface forces, despite limiting switchability in the voltage-off state. Next, we demonstrate that the addition of surface roughness to a compliant dielectric interface increases the switchability ratio. In addition, spatial compliance patterning forms a multi-modulus dielectric film that increases force capacity beyond what was achieved using a smooth, soft interface alone. We use analytical models from fracture mechanics to explain how clutch compliance, modulus of the dielectric film, electrode shape, and surface roughness affect force capacity and switchability. In all, our strongest electroadhesive clutch with a soft dielectric interface performs similarly to state-of-the-art clutches with a stiff dielectric interface in force capacity per unit area at the same operating voltage but at one-fifteenth the relative permittivity. We also design rough, multi-modulus clutches with a soft dielectric film to

increase switchability by approximately three-fold compared to our control design. Finally, we demonstrate our soft dielectric clutches in a reconfigurable robotic fabric which can resisting bending moments and tensile loads, a mechanical linkage with programmable stiffness for tunable structural mechanisms, and a soft robotic finger with a programmable bending stiffness for multi-stiffness rendering in kinesthetic haptic feedback interfaces for augmented reality (AR) or virtual reality (VR).

[00186] Design and Performance of Electroadhesive Clutches with Fixed Modulus Soft Dielectrics

[00187] In order to design clutches with a soft dielectric interface to maximize force capacity per unit area and minimize switchability, we used a fracture-based modeling approach introduced in our previous work to guide the design process, where we model electroadhesive clutches as bonded lap joints, as opposed to frictional systems. We can predict the force capacity F_C from the overall clutch compliance C , the contact area between electrodes A (red/shaded area in Figure 18A at contact interface), and applied voltage using

$$\mathbf{[00188]}\quad F_C = \beta \sqrt{2G_C} \sqrt{\frac{A}{C}} \quad (1)$$

where β is a constant (assumed to be 1 in this work) and G_C is the critical strain energy release rate of the interface. The critical strain energy release rate is the toughness or fracture energy of the elastomeric dielectric interface required to separate the clutch surfaces. G_C is a function of the applied voltage and the modulus of the dielectric. When a voltage is applied to the electrodes, our model assumes that F_C is the force at which the strain energy release rate G is greater than or equal to the critical strain energy release rate, G_C . Using the same approach, we can predict F_{OFF} using clutch compliance and contact area using

$$F_{OFF} = \beta \sqrt{2G_{C,OFF}} \sqrt{\frac{A}{C}}. \quad (2)$$

[00189] When no voltage is applied, our model assumes that F_{OFF} is the force at which the strain energy release rate G is greater than or equal to an off-state critical strain energy release rate, $G_{C,OFF}$. In this work, we assume that the clutch's overall compliance is not affected by the application or removal of voltage.

[00190] We denote the quantity $(A/C)^{1/2}$ as the geometric stiffness parameter (GSP), which accounts for the overall clutch compliance and electroadhesive contact area.

Figure 19A shows the spring-based model for overall clutch compliance. While we can use equation (1) to predict F_C and F_{OFF} for different clutch designs, we can also utilize this relationship to predict switchability (S) of any given design. We calculate S using

$$(3) \quad S = \frac{F_C - F_{OFF}}{F_C},$$

so each clutch's switchability falls between 0 (where F_C equals F_{OFF}) and 1 (where F_{OFF} is equal to zero). To achieve a soft dielectric interface, we spin coat PDMS on a thin, metalized electrode. By coupling the GSP-driven design approach with this fabrication technique, we produced soft dielectric electroadhesive clutches of set thickness with smooth surfaces, which are both critical to increasing F_C/A and S (if F_{OFF} remains fixed).

[00191] Figures 19B – 19D display the force capacity and switchability performance of smooth electroadhesive clutches with constant modulus dielectric layers. First, we assessed the validity of GSP as a predictive variable for soft dielectric clutch F_C and F_{OFF} . Figure 19B shows that there is a linear relationship between the calculated GSP and both the measured F_C and F_{OFF} , where the slope of each line is $(2G_C)^{1/2}$ or $(2G_{C,OFF})^{1/2}$, matching the predictions of equations (1) and (2). For each clutch design, we found that G_C is greater than $G_{C,OFF}$, which indicated the greater contribution of electrostatic forces to force capacity, compared to the contribution of surface forces. We found that electroadhesives with soft dielectrics display G_C values which are directly proportional to V^2 (as predicted by electrostatic parallel plate models), and F_C values which are directly proportional to V . In both cases, we found that $F_C \propto V$, not V^2 , as force capacity models based on Coulombic friction suggest, despite the use of different dielectric interfaces. Lines corresponding to 200 V and 300 V operation are shown for clutches with an IM elastomer dielectric layer, which were determined by fitting the model to the experimental data. The slope of the best fit line for the 200 V and 300 V datasets increased by the same degree as the voltage increase for clutches with the same GSP, which agreed with the predicted $F_C \propto V$ relationship.

[00192] Next, we measured the effect of dielectric film modulus on electroadhesive force capacity. We adjusted the elastomer dielectric modulus by changing the ratio of crosslinker and monomer. We explored soft dielectric clutches with $A = 4 \text{ cm}^2$ and $d = 20 \text{ }\mu\text{m}$ tested at $V = 200 \text{ V}$, with three types of PDMS with different crosslinker to monomer ratios to produce elastomeric dielectrics ranging from soft to stiff (low modulus

(LM), intermediate modulus (IM), and high modulus (HM) PDMS, with moduli of 1.9 MPa, 4.4 MPa, and 5.5 MPa). Figure 19B shows that G_C and $G_{C,OFF}$ both increase as the modulus of the soft dielectric also increases (while GSP stays relatively fixed for a given clutch aspect ratio L/w despite different dielectric moduli), which can then be leveraged for increased F_C . We then measured the impact of clutch compliance on electroadhesive force capacity by changing the clutch aspect ratio at a constant A (4 cm²). Figure 19C shows that the force capacity increases with increasing width, which corresponds to a decreased compliance as the length becomes smaller to keep the area constant. This demonstrates the importance of considering clutch compliance in design. We also found that F_{OFF} follows this same trend, but did not depend on the voltage applied to bring the electroadhesive surfaces into contact (see Methods and Materials).

[00193] Finally, we investigated the impact of GSP, dielectric film modulus, and operating voltage on switchability. First, since $F_C \propto V$ and F_{OFF} is independent of V , the switchability S also increases with V . Figure 19D shows this relationship, where the blue dotted lines correspond to the model's prediction for 200 V and 300 V switchability with an IM PDMS dielectric layer, and red and black dotted lines correspond to the model's predictions for clutches with HM and LM PDMS dielectric layers, respectively, all tested at 200 V. All predictions which were determined by fitting the model to the F_C and F_{OFF} data, and subsequent application of equations (1), (2) and (3). The square data points indicate clutches tested at 300 V, and circular data points indicate clutches tested at 200 V. Switchability does not increase with GSP at a set voltage or dielectric film modulus, as F_C and $F_{C,OFF}$ increase by fixed slopes of $(2G_C)^{1/2}$ and $(2G_{C,OFF})^{1/2}$. S also remains mostly unchanged as different types of PDMS are implemented as the dielectric layer, as F_C and F_{OFF} are both affected equally for each PDMS dielectric introduced. Despite the increase in S with the increase to 300 V seen in Figure 19D, equation (3) also indicates that as larger voltages are applied, S increases by smaller amounts, as it asymptotically approaches the maximum value of 1. This demonstrates that an increased voltage can be applied directly to increase the force capacity and switchability of any given clutch design, although this approach is inherently limited by the breakdown strength of the dielectric, and the voltage requirements of the electroadhesive application.

[00194] Design and Performance of Electroadhesive Clutches with Increased Roughness

[00195] To increase electroadhesive clutch switchability, we added roughness to the soft dielectric surface. We achieved high roughness electroadhesives by spinning a thin PDMS layer on one metallized electrode, and then applying a steel foam template, which was removed after curing at 150°C (Figure 20A). The features which remained on the soft dielectric surface inversely matched the rough surface of the steel foam, taking the shape of concave indentations of 15 μm depth. Adding weight to the steel foam template increased the number of features on the surface, while only marginally changing their size. As the curing step began, either no mass was added to the steel foam template to produce low roughness clutches, or a 200 g steel weight was added to achieve high roughness clutches. The root-mean-squared (RMS) roughness increased from $4.1 \pm 1.3 \mu\text{m}$ to $6.8 \pm 0.8 \mu\text{m}$ for the low roughness and high roughness designs, respectively, which was higher than the RMS roughness of the PDMS surface with no features added ($2.1 \pm 0.3 \mu\text{m}$). For traditional electroadhesive clutches with stiff dielectric layers, the addition of surface features would greatly reduce the total attractive force at the contact interface, as the surface features would keep the electrodes from coming into conformal contact. Because the applied electrostatic force becomes smaller as the contacting surfaces become further apart, the total attraction at the interface drops. For a soft dielectric electroadhesive clutch, which relies on a combination of electrostatics and surface forces for increased adhesion, we can utilize electrostatic forces to bring the surfaces together even in the presence of roughness, as the dielectric's high surface compliance is easily deformed. Once conformal contact is made, we then can leverage surface forces to increase force capacity.

[00196] We then measured the impact of surface roughness on clutch force capacity and switchability. To do so, we fabricated clutch designs with no roughness, low roughness, or high roughness, all with a 20 μm soft dielectric layer composed of IM PDMS, at a variety of GSP values while holding contact area constant at $A = 4 \text{ cm}^2$ and operating voltage constant at $V = 200 \text{ V}$. Figures 20C and 20D display the force capacity and switchability performance of the soft dielectric electroadhesive clutches with added surface roughness. First, it was notable that the fracture-based modeling approach used for the smooth soft dielectric electroadhesives in Figure 19 was also applicable for the designs with added roughness. Figure 20C displays a linear relationship between GSP and F_C for both the low roughness (data shown in green) and high roughness (data shown in orange) designs, which were related by a slope of $(2G_C)^{1/2}$. The orange, green, and blue dotted

lines indicate the model predicted values of electroadhesive F_C with a $G_C = 0.4 \text{ Jm}^{-2}$ and for the high roughness data, $G_C = 9.4 \text{ Jm}^{-2}$ for the low roughness data, and a $G_C = 24.4 \text{ Jm}^{-2}$ for the smooth data. As roughness increases, G_C decreases due to the addition of surface features, which create voids in the contact interface. As the number of voids increase, there are more sites where cracks can form, and the energy required to detach the surfaces drops. We attribute this effect to the increase in S which follows the added roughness. Since there is a lack of electrostatic force contributing to adhesion in addition to the increased roughness in the voltage-off state, there is a larger drop in F_{OFF} relative to the drop in F_C . Switchability does not increase with GSP at a set roughness, as F_C and $F_{C,OFF}$ increase by fixed slopes of $(2G_C)^{1/2}$, as we found to be the case for the smooth clutch designs. We were able to use roughness to increase switchability while minimizing loss of force capacity due to the presence of surface forces which contribute to total adhesion in both the voltage-on and voltage-off states, and due to the storage of strain energy at the surface features which push the surfaces apart. We were also able to achieve this with minimal electrical breakdown at the surface features, which has been previously shown to reduce force capacity in clutch designs at defect locations. This approach is useful in building high switchability clutches without solely relying on increasing operating voltages to add force capacity.

[00197] Design and Performance of Electroadhesive Clutches with Multi-Modulus Dielectrics

[00198] In this work, we model our soft dielectric electroadhesives as bonded interfaces, whose mechanics are akin to those of single-lap joints. Thus, in any electroadhesive clutch, just as is the case for a single-lap joint, peel and shear stress concentrations will occur in the dielectric layer, due to eccentricity in the load path and unequal axial strains in the electrodes, respectively. These stress concentrations occur at the ends of the dielectric, and, as a result, will lead to crack initiation at these locations when a clutch is loaded in tension. Most electroadhesive clutch designs are composed of a dielectric with a fixed elastic modulus, and have not leveraged such a spatially-tailored design due to limitations in fabrication for stiff dielectric materials. Here, we designed electroadhesives with a spatially-varying elastic modulus (Figure 21A), adding compliance to the ends of the dielectric layer (Figure 21B). Through nanoindentation experiments, we confirmed the spatial tailoring of edge compliance. By doing so, we

reduced the peel stress concentrations which drive failure at the ends of the clutch (Figure 21C), which we modeled using finite element analysis (see Methods and Materials for details).

[00199] We then explored the ability of a multi-modulus dielectric to increase force capacity compared to our strongest clutch design with a constant modulus dielectric (HM PDMS). For the constant modulus and multi-modulus designs, we tested clutches at a fixed voltage ($V = 200$ V) with a fixed electrode length ($L = 20$ mm) and three different electrode widths ($w = 10$ mm, 20 mm, 40 mm) which yielded three different contact areas ($A = 2$ cm², 4 cm², 8 cm²). For our multi-modulus designs, we used our stiffest PDMS (HM) as the dielectric in the center of the dielectric and our softest PDMS (LM) at each end of the dielectric to add edge compliance. We then fabricated and tested multi-modulus clutches with the same design parameters, but added high roughness using the process shown in Figure 20A. Figure 21D displays force capacity and switchability results of the fixed modulus and multi-modulus designs with and without added surface roughness. First, we found that G_C increased for the multi-modulus designs, compared to that of the constant modulus designs, both without roughness ($G_C = 68.6$ Jm⁻², pink data) and with roughness added ($G_C = 3.3$ Jm⁻², cyan data). Thus, by reducing stress concentrations at the edges of the clutch, we were able to increase force capacity without increasing operating voltage or contact area. By combining this approach with the addition of high roughness, we built clutches with increased force capacity and switchability compared to our high roughness design with a fixed modulus, all without increasing the applied voltage. In all, these results show that clutch design approaches that redistribute stresses within the dielectric layer can increase electroadhesive clutch force capacity without increasing electrostatic pressure, which should be optimized with GSP for any clutch design to reach its full potential.

[00200] Soft Clutch Demonstrations

[00201] To demonstrate some of the applications of our high performance electroadhesives for programmable stiffness, we integrated a clutch with a soft dielectric layer into (1) a morphing fabric with a programmable tensile and bending stiffness (Figure 22A-22B), (2) a programmable four-bar linkage structural element (Figure 22C), and (3) a pneumatic finger which could switch between three stiffness states (Figure 23). Our electroadhesives are small ($A = 4$ cm²), can carry a heavy load, detach reliably over

multiple loading cycles, and easily integrate onto flexible substrates to enable discretely controllable stiffness changes with an electrical input. For example, our clutchable fabric supported a 500 g weight in tension, locking in a minimal stretch configuration when 200 V was applied to the clutch. When the voltage was removed, the clutch detached, and the fabric stretched by 20 mm. When the same clutchable fabric was supported at its ends, it could support a 200 g weight in bending, locking-in a minimal bend configuration upon the application of 200 V, while it displaced by 10 mm when the voltage was removed, which caused the clutch electrodes to separate. In our programmable linkage demonstration, we showed our clutches' ability to modulate the stiffness of a stiff structural element, which stood and resisted light perturbation when the attached clutches were engaged with 200 V. When the voltage was removed, the structure easily rotated about its pinned joints when perturbed in the same manner, collapsing under its own weight. Finally, in our pneumatic finger demonstration, we attached two clutches with a soft dielectric in parallel with an elastomeric Pneu-Net actuator. By doing so, we modulated the finger's stiffness between a low stiffness, medium stiffness, and high stiffness state. When neither of the clutches were activated with an applied voltage, and the finger was inflated to 30 kPa, it reached a curved, concave configuration. When only one clutch was activated, the bending stiffness increased, and the finger was locked into a straight-line configuration upon inflation. When both clutches were activated, the bending stiffness increased further, and the finger bent in the opposite direction compared to the non-clutched state, reaching a convex configuration. These discrete stiffness states are notable, as they could be implemented in a electroadhesive-based haptic interface capable of rendering virtual objects ranging from stiff to squishy, improving the immersive experience for the use. In all, our electroadhesives demonstrated here enhances the performance of morphing wearable skins, programmable structures, and shape-changing robots, where two-dimensional, flexible materials must lock-in discrete tensile and bending stiffnesses to match the mechanical impedance or curvature of a human subject or robot for rehabilitation or haptic feedback, or to provide enhanced load carrying capacity which can be switched on or off in real time.

[00202] Conclusion

[00203] We have demonstrated that soft, compliant dielectric layers can enable electroadhesive clutches with increased force capacities per unit area at a fixed operating

voltage while also maintaining practical switchability through surface roughness and stiffness patterning. We achieved the high force capacity by leveraging the inherent compliance of the soft dielectric material, which enabled conformal contact between the clutch electrodes, engaging surface forces which operate on nanometer length scales. The contribution of electrostatic and surface forces to the total adhesion led to the performance enhancement we report in this work. Our fracture mechanics model explained how clutch compliance and surface roughness affected force capacity and switchability, which we validated over different geometries and voltages. Our strongest clutch designs utilized a minimized system compliance and an increased surface compliance. Therefore, we have demonstrated that different compliance-based design approaches should be applied to a clutch's dielectric interface and electrodes separately for clutch designs to reach their full potential. We were able to achieve an increase in force capacity at a fixed voltage while using a dielectric material with a low relative permittivity and electrostatic pressures which are significantly lower than those leveraged by existing clutch designs.

[00204] We also have demonstrated that an increased surface roughness leads to increased switchability, as surface features reduce the critical energy required to debond the clutch's contacting surfaces in the absence of electrostatic forces. It is notable that the addition of roughness reduced G_C at a fixed voltage, which, in turn, reduced F_C , although this result was most notable for our high roughness clutches. To mitigate this loss in force capacity, we introduced a soft dielectric with spatially-tailored modulus, which increased G_C by reducing stress concentrations at the edges of the clutch, which led to an increase in F_C without increasing the voltage applied. This method, applied in concert with the addition of roughness, enabled increased switchability and force capacity without increasing voltage, which is critical for integration into untethered, robotic applications. This design approach enabled us to integrate our soft dielectric electroadhesive clutches into morphing fabrics and structures with programmable bending and tensile stiffness and a pneumatic finger capable of locking-in discretely tunable stiffnesses and shapes. These clutches are easily manufacturable, lightweight, and flexible, and their enhanced force capacity per unit area can enable larger changes in material stiffness and strength. The reversible electroadhesion and high switchability of the presented clutches, despite the presence of surface forces, is also critical in robotic, prosthetic, and haptic applications that must undergo repeatable stiffness changes in real time.

[00205] To improve on the soft dielectric electroadhesive designs we presented in this work, future work should focus on other clutch design metrics not explored here, such as response time and fatigue life. Furthermore, force capacity and switchability could be enhanced beyond the performance achieved in this work by patterning soft dielectric into pre-determined features, such as pillars, onto the electrode surface, as has been demonstrated previously for structural adhesives.^[17] In addition, additive manufacturing techniques such as soft material 3-D printing could enable novel dielectric designs with spatially tailored properties further optimized to reduce stress concentrations at the clutch's edges.

[00206] Methods and Materials

[00207] Soft dielectric electroadhesive clutch fabrication

[00208] An automated blade cutter (Curio, Silhouette Inc.) was used to cut each electrode with a 0.2 mm thick blade. The electrodes were comprised of a 127-micrometer thick BOPET sheet coated with a thin aluminum film on one side (7538T12, McMaster-Carr, Inc.). Polydimethylsiloxane (Sylgard 184) was mixed in the desired ratio of monomer to crosslinker (HM, IM or LM) to set the modulus of the dielectric layer. The PDMS was then thoroughly mixed for 2 minutes and desiccated for 10 minutes to remove air bubbles. Next, each electrode was cleaned using isopropanol and acetone, and then attached to a 4 cm silicon wafer with Kapton tape and cleaned for 5 min with air plasma. Next, .08 g of PDMS was applied to the clutch electrode and spread evenly over the pre-determined contact region. To make the final dielectric film, we spun the electrode and wafer for 5 minutes at 2500 rpm, and then cured at 150 °C. We used a micrometer to measure the thickness of the resulting dielectric film after removing the electrode from the silicon wafer. Three measurements were made for each of the $n = 40$ electroadhesive specimens, and the average thickness was found to be $20 \mu\text{m} \pm 2.5 \mu\text{m}$.

[00209] Soft dielectric electroadhesive clutch fabrication with added roughness

[00210] To add roughness, a steel wool pad (3M, Extra-Fine Grit #000) was added before the curing step. To achieve high roughness, a steel shim of 200g was added on top of the steel wool pad, which was placed on top of the PDMS dielectric layer during the curing process. To achieve low roughness, the steel wool pad was added to the PDMS dielectric without any added weight. Height and roughness measurements of the added surface features were measured using white-light interferometry (Zygo NewView

7300 Optical Profilometer). A 50 nm gold layer was applied to the dielectric surfaces using an electron-beam evaporation tool (Lesker PVD75, Lesker, Inc.) before measurements were taken. The RMS roughness was measured to be $4.1 \pm 1.3 \mu\text{m}$ for the low roughness clutches and $6.8 \pm 0.8 \mu\text{m}$ for the high roughness clutches.

[00211] Multi-modulus soft dielectric electroadhesive clutch fabrication

[00212] To fabricate a multi-modulus dielectric, .04 g of LM PDMS was applied to a $w = 40 \text{ mm}$ and $L = 5 \text{ mm}$ section of a BOPET electrode, at one edge of the contact region. After spinning for 5 min at 2500 rpm (with the BOPET electrode attached to a silicon wafer during the spin process), a 20 micron thick layer of LM PDMS was formed in that region. This was then repeated for the other $w = 40 \text{ mm}$ and $L = 5 \text{ mm}$ section of the BOPET electrode, after rotating the electrode by 180 degrees on the silicon wafer. Next, .08 g of HM PDMS was applied to the $w = 40 \text{ mm}$ by $L = 10 \text{ mm}$ region at the clutch's center, spun at the same parameters, and then the entire electrode was cured at 150°C . This resulted in a dielectric film of $20 \mu\text{m}$ thickness, which was the same as the fixed modulus specimens.

[00213] Tensile testing for soft dielectric electroadhesive force capacity experiments

[00214] To prepare each sample for a tensile test, an adhesive (Loctite 409) was used to attach each electroadhesive specimen to laser-cut acrylic grips to ensure no slipping. A signal generator (Agilent 33220A) applied a AC voltage square wave signal with a frequency of 10 Hz (for a 200mV amplitude, the voltage fluctuated between +200mV and -200mV), and a high-voltage amplifier (Trek Model 10/10B-HS) amplified the signal by $1000\times$ to its final value. An AC signal was used to mitigate the effect of space charge buildup in the dielectric. Electrical leads connected the amplifier to the clutch, using copper and alligator clips to obtain good electrical contact to the aluminum surface on the PET. To characterize the force capacity of each electroadhesive clutch, we performed uniaxial tensile tests using an MTS Criterion Model 43 with a 1-kN load cell with customized tensile grips. The tests were run at a speed of 1 mm min^{-1} . The tensile setup can be found in the SI.

[00215] Materials testing

[00216] The modulus of the metallized PET film was determined via uniaxial tensile tests in a MTS Criterion Model 43 at a rate of 1 mm min^{-1} as described in our

previous work.^[4] A nanoindenter (Hysitron T950) was used to measure the modulus of the PDMS film using an indentation load of 25 μN with 30 indents per test. A mean measured modulus of the LM, IM, and HM PDMS was 1.9 MPa, 4.4 MPa, and 5.5 MPa, respectively.

[00217] Finite element analysis

[00218] To visualize the peel and shear stress distribution at the edges of the clutch, we modeled the clutch as a two-dimensional, plane-strain, perfectly bonded shear lap joint using a commercially available finite element analysis software (ABAQUS Standard 2018). The geometry for the fixed modulus and multi-modulus models used in our finite element matched the ones we used in our experiments, and we applied the same linear elastic material properties to the BOPET electrodes and PDMS dielectric which we found experimentally. We meshed the models using two-dimensional, bilinear, hybrid, plane strain quadrilateral elements (CPE4H). We constrained the edge of the left-hand electrode in the horizontal and vertical directions, and applied a far-field tensile stress (σ_∞) to the right-hand electrode, while constraining it in the vertical direction to simulate our experimental boundary conditions. To identify the minimum mesh size for the edges of the dielectric, we performed a mesh convergence study which yielded a minimum element size of 0.5 μm . When the mesh size was decreased below this value, the maximum peel and shear stress values at the edges of the dielectric did not change more than 2%. To reduce computational effort, we used a course element size (20 μm) at the center of the dielectric. While there is a singularity in the stress field near the edge of the dielectric/electrode interface, our goal was not to evaluate the singular stress field, but to compare the stress fields in a fixed modulus clutch and multi-modulus clutch design.

[00219] Morphing fabric fabrication and demonstration

[00220] To test the ability of a soft dielectric electroadhesive clutch to change the bending and tensile stiffness of a stretchable polyester fabric (Nike, Inc.), we attached the electrodes of a clutch with an IM PDMS dielectric layer and low roughness ($w = 40$ mm, $A = 4 \text{ cm}^2$, $d = 20 \mu\text{m}$) using cyanoacrylate glue and attached electrical leads to a high-voltage supply. The fabric was secured using VHB tape (3M) and laser-cut acrylic shims.

[00221] Programmable linkage demonstration

[00222] To test the ability of a soft dielectric electroadhesive clutch to change the stiffness of a four-bar linkage, we cut eight linkage elements using a laser-cutter and attached them via pin connection using ¼” hex screws into a cube configuration. We then attached the electrodes of a clutch with a IM PDMS dielectric layer and low roughness ($w = 40 \text{ mm}$, $A = 4 \text{ cm}^2$, $d = 20 \text{ }\mu\text{m}$) using VHB tape diagonally across each side of the linkage.

[00223] Discrete stiffness programming of a soft bending actuator

[00224] To test the ability of an electroadhesive clutch to modulate the stiffness of a soft pneumatic bending actuator, we used silicone adhesive (Sil-Poxy) to attach the electrodes to the back of a Pneu-Net finger. A custom fixture held the finger in place, oriented downwards with its air inlet tube facing up.

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[00275] Aspects

[00276] The following Aspects are illustrative only and do not limit the scope of the present disclosure or the appended claims. It should be understood that the present technology can include any combination of any part or parts of any one or more of the following Aspects.

[00277] Aspect 1. An electroadhesive clutch, comprising: a first electrode; a second electrode; and a spacer disposed between the first electrode and the second electrode and being in electrical communication with the first electrode and the second electrode, (a) the spacer comprising at least one ionoelastomer that comprises a comonomer, the comonomer giving rise to an ionoelastomer having a lower surface energy than the surface energy of the at least one ionoelastomer being free of the comonomer, (b) at least one of the first electrode and the second electrode defining a mesh structure, the mesh structure comprising strands having a thickness in the range of from about 10 to about 200 μm , or both (a) and (b).

[00278] Aspect 2. The electroadhesive clutch of claim 1, wherein the at least one elastomer comprises two oppositely charged ionoelastomers, the two oppositely charged ionoelastomers defining an interface therebetween.

[00279] Aspect 3. The electroadhesive clutch of any one of claims 1-2, wherein the mesh structure comprises metallic strands.

[00280] Aspect 4. The electroadhesive clutch of any one of claims 1-3, wherein the at least one ionoelastomer comprises at least one of $[\text{EMIM}]^+[\text{APST}]^-$, $[\text{AEBI}]^+[\text{TSFI}]^-$, 1-ethyl-3-methyl imidazolium poly[(3sulfopropyl) acrylate] (ES), or poly[1-(2-acryloyloxyethyl)3-buthylimidazolium]bis(trifluoromethane) sulfonimide (AT).

[00281] Aspect 5. The electroadhesive clutch of any one of claims 1-4, wherein the comonomer comprises a fluorinated comonomer, the fluorinated comonomer optionally having the following structure:



[00282] Other examples of comonomers used to increase the hydrophobicity of a surface include, e.g., allyl methacrylate (ALMA) and diacetone-acrylamide (DAAM).

[00283] Aspect 6. The electroadhesive clutch of any one of claims 1-5, wherein the first electrode and the second electrode define a superposed area, the superposed area being in the range of from about 0.1 to about 10 cm², preferably in the range of from about 0.1 to about 5 cm².

[00284] Aspect 7. The electroadhesive clutch of any one of claims 1-6, wherein the first electrode and the second electrode define a superposed area and wherein the electroadhesive clutch exhibits a force capacity per unit area in the range of from about 20 to about 100 N/cm² at an applied voltage of less than about 10 V.

[00285] Aspect 8. The electroadhesive clutch of any one of claims 1-7, wherein the first electrode and the second electrode define a superposed area and wherein the electroadhesive clutch exhibits a force capacity per unit area in the range of from about 20 to about 100 N/cm² at a superposed area of less than about 10 cm².

[00286] Aspect 9. The electroadhesive clutch according to any one of claims 1-8, the electroadhesive clutch being incorporated into a gripper device, a lifter device, a strain sensor, a haptic device, a wearable device, a prosthetic device, an implant, a vibration control device, an orthotic device, an exoskeletal device, a shape-morphing device, or any combination thereof.

[00287] Aspect 10. A method, comprising: estimating a predicted force capacity of an electroadhesive joint, the estimating being based at least in part on at least one of (1) a contact area of an electrode of the electroadhesive joint, (2) a compliance of the electroadhesive joint, and (3) a critical strain energy release rate associated with the materials comprising the contact interface and the applied voltage.

[00288] Aspect 11. The method of claim 10, wherein the predicted force capacity (FC) is estimated according to the following relationship:

$$FC = \beta \sqrt{2G_c} \sqrt{\frac{A}{C}}$$

wherein C is the overall compliance of the electroadhesive joint, A is the contact area between electrodes, β is a constant, and G_c is the critical strain energy release rate.

[00289] Aspect 12. The method of any one of claims 10-11, wherein (1) a dimension and/or composition of a component of the electroadhesive joint is configured based on the predicted force capacity, (2) a voltage applied to the electroadhesive joint is configured based on the predicted force capacity, or both (1) and (2).

[00290] Aspect 13. The method of any one of claims 10-11, wherein (1) a dimension of a first electrode of the electroadhesive joint is selected based on the predicted force capacity; (2) a dimension and/or a composition of a separator disposed between the first electrode of the electroadhesive joint and a second electrode of the electroadhesive joint is selected based on the predicted force capacity, or both (1) and (2).

[00291] Aspect 14. The method of any one of claims 10-11, wherein the electroadhesive joint defines a direction of motion, wherein a first electrode of the electroadhesive joint defines a length measured along the direction of motion, wherein the first electrode defines a width perpendicular to the direction of motion, wherein the first electrode defines a contact area superposed on a separator disposed between the first electrode and a second electrode, wherein the first electrode defines a free area that is free of superposition on the separator disposed between the first electrode and a second electrode, and wherein (1) the length of the first electrode is selected based on the predicted force capacity, (2) the width of the first electrode is selected based on the predicted force capacity, (3) the contact area of the first electrode is selected based on the predicted force capacity, (4) the free area of the first electrode is selected based on the predicted force capacity, (5) a dimension of the separator and/or a composition of the separator is selected based on the predicted force capacity, or any two or more of (1) – (5).

[00292] Aspect 15. The method of any one of claims 10-14, wherein the electroadhesive joint defines a direction of motion, wherein a first electrode of the electroadhesive joint defines a length measured along the direction of motion, wherein the first electrode defines a width perpendicular to the direction of motion, and wherein (1) based on the predicted force capacity, the length is configured to be greater than the width,

(2) based on the predicted force capacity, the length is configured to be equal to the width, or (3) based on the predicted force capacity, the length is configured to be less than the width.

[00293] Aspect 16. The method of any one of claims 10-15, further comprising incorporating the electroadhesive joint into a gripper device, a lifter device, a strain sensor, a haptic device, a wearable device, a prosthetic device, an implant, a vibration control device, an orthotic device, an exoskeletal device, a shape-morphing device, or any combination thereof.

[00294] Aspect 17. An electroadhesive joint, at least one component of the electroadhesive joint comprising a component having at least one dimension based on a predicted force capacity estimated according to any one of claims 10-11.

[00295] Aspect 18. The electroadhesive joint of claim 17, wherein the electroadhesive joint (a) comprises a first electrode, a second electrode, and an ionoelastomer separator between the first electrode and the second electrode or (b) comprises a first electrode, a second electrode, and a separator between the first electrode and the second electrode, at least one of the first electrode and the second electrode defining a mesh structure, the mesh structure optionally comprising metallic strands.

[00296] Aspect 19. The electroadhesive joint of claim 18, wherein the ionoelastomer comprises a comonomer, the comonomer giving rise to an ionoelastomer having a lower surface energy than the surface energy of the at least one ionoelastomer being free of the comonomer.

[00297] Aspect 20. The electroadhesive joint of any one of claims 18-19, at least one of the first electrode and the second electrode defining a mesh structure, the mesh structure comprising strands having a thickness in the range of from about 10 to about 200 μm .

[00298] Aspect 21. An electroadhesive clutch, comprising: (i) a first electrode; (ii) a second electrode; (iii) optionally a spacer disposed between the first electrode and the second electrode and being in electrical communication with the first electrode and the second electrode, and (iv) wherein (a) the spacer comprises a dielectric, or (b) at least one of the first electrode and the second electrode defines a mesh structure, the mesh structure comprising strands having a thickness in the range of from about 10 to about 200 μm , or (c) the clutch defines a direction of motion and the first electrode and the second electrode

define a superposed area, the superposed area being defined by a first axis extending in the direction of motion and a second axis extending perpendicular to the first axis, the second axis being greater than the first axis, or any two or more of (a), (b), and (c). Thus, as an example, the superposed area can be greater in width than in length, wherein the length is measured in the direction of motion of the clutch.

[00299] As described above, a spacer is optional. When the spacer is present, the spacer can be a dielectric material. Example such materials include polymers and the like.

[00300] By reference to FIG. 2A and FIG. 17, in some embodiments, the width (w) of the superposed area can be greater than the length (l) of the superposed area. In some embodiments, the width (w) can be less than the length (l) of the superposed area. In some embodiments, the width can be equal to the length of the superposed area. Without being bound to any particular theory or embodiment, to reduce the contact area of an electroadhesive clutch without decreasing its force capacity, its overlap width can be increased and its joint length reduced.

[00301] Aspect 22. The electroadhesive clutch of Aspect 21, wherein the second axis is up to about 10 times the first axis. The second axis can be, for example, about 1.1, 1.5, 2, 2.5, 3, 3.5, 4, 4.5, 5, 5.5, 6, 6.5, 7, 7.5, 8, 8.5, 9, 9.5, or even about 10 times the first axis. In this way, the superposed area can be greater in width than in length, wherein the length is measured in the direction of motion of the clutch. It should be understood, however, that in some embodiments the superposed area can be greater in length than in width, wherein the length is measured in the direction of motion of the clutch.

[00302] Aspect 23. The electroadhesive clutch of any one of Aspects 21-22, wherein the mesh structure comprises metallic strands.

[00303] Aspect 24. The electroadhesive clutch of any one of Aspects 21-23, wherein the first electrode and the second electrode define a superposed area, the superposed area being in the range of from about 0.1 to about 10 cm², preferably in the range of from about 0.1 to about 5 cm².

[00304] Aspect 25. The electroadhesive clutch of any one of Aspects 21-24, wherein the first electrode and the second electrode define a superposed area and wherein the electroadhesive clutch exhibits a force capacity per unit area in the range of from about 20 to about 100 N/cm² at an applied voltage of less than about 10 V.

[00305] Aspect 26. The electroadhesive clutch of any one of Aspects 21-25, wherein the first electrode and the second electrode define a superposed area and wherein the electroadhesive clutch exhibits a force capacity per unit area in the range of from about 20 to about 100 N/cm² at a superposed area of less than about 10 cm².

[00306] Aspect 27. The electroadhesive clutch according to any one of Aspects 21-26, the electroadhesive clutch being incorporated into a gripper device, a lifter device, a strain sensor, a haptic device, a wearable device, a prosthetic device, an implant, a vibration control device, an orthotic device, an exoskeletal device, a shape-morphing device, or any combination thereof.

[00307] Aspect 28. A method, comprising: estimating a predicted force capacity of an electroadhesive joint, the estimating being based at least in part on at least one of (1) a contact area of an electrode of the electroadhesive joint, (2) a compliance of the electroadhesive joint, and (3) a critical strain energy release rate associated with the materials comprising the contact interface and the applied voltage.

[00308] Aspect 29. The method of Aspect 28, wherein the predicted force capacity (FC) is estimated according to the following relationship:

$$FC = \beta \sqrt{2G_c} \sqrt{\frac{A}{C}}$$

[00309] wherein C is the overall compliance of the electroadhesive joint, A is the contact area between electrodes of the electroadhesive joint, β is a constant, and G_c is the critical strain energy release rate.

[00310] Aspect 30. The method of any one of Aspects 28-29, wherein (1) a dimension and/or composition of a component of the electroadhesive joint is configured based on the predicted force capacity, (2) a voltage applied to the electroadhesive joint is configured based on the predicted force capacity, or both (1) and (2).

[00311] Aspect 31. The method of any one of Aspects 28-30, wherein (1) a dimension of a first electrode of the electroadhesive joint is selected based on the predicted force capacity; (2) a dimension and/or a composition of a separator disposed between the first electrode of the electroadhesive joint and a second electrode of the electroadhesive joint is selected based on the predicted force capacity, or both (1) and (2).

[00312] Aspect 32. The method of any one of Aspects 28-31, wherein the electroadhesive joint defines a direction of motion, wherein a first electrode of the

electroadhesive joint defines a length measured along the direction of motion, wherein the first electrode defines a width perpendicular to the direction of motion, wherein the first electrode defines a contact area superposed on a separator disposed between the first electrode and a second electrode, wherein the first electrode defines a free area that is free of superposition on the separator disposed between the first electrode and a second electrode, and wherein (1) the length of the first electrode is selected based on the predicted force capacity, (2) the width of the first electrode is selected based on the predicted force capacity, (3) the contact area of the first electrode is selected based on the predicted force capacity, (4) the free area of the first electrode is selected based on the predicted force capacity, (5) a dimension of the separator and/or a composition of the separator is selected based on the predicted force capacity, or any two or more of (1) – (5).

[00313] Aspect 33. The method of any one of Aspects 28-32, wherein the electroadhesive joint defines a direction of motion, wherein a first electrode of the electroadhesive joint defines a length measured along the direction of motion, wherein the first electrode defines a width perpendicular to the direction of motion, and wherein (1) based on the predicted force capacity, the length is configured to be greater than the width, (2) based on the predicted force capacity, the length is configured to be equal to the width, or (3) based on the predicted force capacity, the length is configured to be less than the width.

[00314] Aspect 34. The method of any one of Aspects 28-33, further comprising incorporating the electroadhesive joint into a gripper device, a lifter device, a strain sensor, a haptic device, a wearable device, a prosthetic device, an implant, a vibration control device, an orthotic device, an exoskeletal device, a shape-morphing device, or any combination thereof.

[00315] Aspect 35. An electroadhesive joint, at least one component of the electroadhesive joint comprising a component having at least one dimension based on a predicted force capacity estimated according to any one of Aspects 28-33.

[00316] Aspect 36. The electroadhesive joint of Aspect 35, wherein the electroadhesive joint comprises any one or more of (a) a first electrode, a second electrode, and a separator between the first electrode and the second electrode, (b) comprises a first electrode, a second electrode, and a separator between the first electrode and the second electrode, at least one of the first electrode and the second electrode

defining a mesh structure, the mesh structure optionally comprising metallic strands, and (c) the electroadhesive joint defining a direction of motion and the first electrode and the second electrode defining a superposed area, the superposed area being defined by a first axis extending in the direction of motion and a second axis extending perpendicular to the first axis, the second axis being greater than the first axis

[00317] Aspect 37. The electroadhesive joint of Aspect 36, wherein the second axis is up to 10 times the first axis .

[00318] Aspect 38. The electroadhesive joint of any one of Aspects 35-38, at least one of the first electrode and the second electrode defining a mesh structure, the mesh structure comprising strands having a thickness in the range of from about 10 to about 200 μm .

[00319] Aspect 39. An electroadhesive joint, comprising: a first electrode; a second electrode, the first and second electrode superposed so as to define a superposed area therebetween; and a spacer disposed between the first electrode and the second electrode, the spacer comprising a dielectric material. Without being bound to any particular theory or embodiment, the spacer material can be a polymer, such as PDMS. Again without being bound to any particular theory or embodiment, surface compliance allows for conformal electrode contact and engagement of surface forces.

[00320] Aspect 40. The electroadhesive joint of Aspect 39, wherein the spacer includes a region of a first dielectric modulus and a region of a second dielectric modulus. The first dielectric modulus and the second dielectric modulus differing from one another. This, the spacer can have a spatially-varying electric modulus. In some embodiments, the dielectric modulus of the spacer can be greater toward or at an end of the spacer, and lower toward the middle of the spacer or away from the end of the spacer. As shown in FIG. 21, in some embodiments stress within the spacer can be concentrated at the ends of the dielectric.

[00321] Aspect 41. The electroadhesive joint of any of Aspects 39-40, wherein (1) the the spacer can have one or more smooth surfaces that contact an electrode; or (2) the spacer can include a roughened surface, which surface can be patterned. One such example is provided in FIG. 20A and 20B, which illustrate forming a dielectric spacer with a roughened surface. A root-mean-squared (RMS) roughness can be in the range of from about 3 to about 20 μm , as well as all intermediate values and subranges.. Without

being bound to any particular theory or embodiment, one can introduce roughness to increase switchability while minimizing loss of force capacity due to the presence of surface forces which contribute to total adhesion in both the voltage-on and voltage-off states, and due to the storage of strain energy at the surface features which push the surfaces apart.

[00322] A device according to the present disclosure can include a single electroadhesive clutch. A device according to the present disclosure can also include a plurality of electroadhesive clutches. In such an embodiment, the device can include two electroadhesive clutches that exhibit equal or near-equal stiffness. This is not a requirement, however, as a device can include two electroadhesive clutches that exhibit different stiffnesses. An example is provided in FIG. 23, which depicts a device according to the present disclosure, with the device including two clutches.

[00323]

[00324] a

What is Claimed:

1. An electroadhesive clutch, comprising:
 - (i) a first electrode;
 - (ii) a second electrode;
 - (iii) optionally a spacer disposed between the first electrode and the second electrode and being in electrical communication with the first electrode and the second electrode; and
 - (iv) wherein
 - (a) the spacer comprises a dielectric, or
 - (b) at least one of the first electrode and the second electrode defines a mesh structure, the mesh structure comprising strands having a thickness in the range of from about 10 to about 200 μm , or
 - (c) the clutch defines a direction of motion and the first electrode and the second electrode define a superposed area, the superposed area being defined by a first axis extending in the direction of motion and a second axis extending perpendicular to the first axis, the second axis being greater than the first axis, or
2. The electroadhesive clutch of claim 1, wherein the second axis is up to 10 times the first axis.
3. The electroadhesive clutch of any one of claims 1-2, wherein the mesh structure comprises metallic strands.
4. The electroadhesive clutch of any one of claims 1-3, wherein the first electrode and the second electrode define a superposed area, the superposed area being in the

- range of from about 0.1 to about 10 cm², preferably in the range of from about 0.1 to about 5 cm².
5. The electroadhesive clutch of any one of claims 1-4, wherein the first electrode and the second electrode define a superposed area and wherein the electroadhesive clutch exhibits a force capacity per unit area in the range of from about 20 to about 100 N/cm² at an applied voltage of less than about 10 V.
 6. The electroadhesive clutch of any one of claims 1-5, wherein the first electrode and the second electrode define a superposed area and wherein the electroadhesive clutch exhibits a force capacity per unit area in the range of from about 20 to about 100 N/cm² at a superposed area of less than about 10 cm².
 7. The electroadhesive clutch according to any one of claims 1-6, the electroadhesive clutch being incorporated into a gripper device, a lifter device, a strain sensor, a haptic device, a wearable device, a prosthetic device, an implant, a vibration control device, an orthotic device, an exoskeletal device, a shape-morphing device, or any combination thereof.
 8. A method, comprising:

estimating a predicted force capacity of an electroadhesive joint, the estimating being based at least in part on at least one of (1) a contact area of an electrode of the electroadhesive joint, (2) a compliance of the electroadhesive joint, and (3) a critical strain energy release rate associated with the materials comprising the contact interface and the applied voltage.
 9. The method of claim 8, wherein the predicted force capacity (FC) is estimated according to the following relationship:

$$FC = \beta \sqrt{2G_c} \sqrt{\frac{A}{C}}$$

wherein C is the overall compliance of the electroadhesive joint, A is the contact area between electrodes of the electroadhesive joint, β is a constant, and G_c is the critical strain energy release rate.

10. The method of any one of claims 8-9, wherein (1) a dimension and/or composition of a component of the electroadhesive joint is configured based on the predicted force capacity, (2) a voltage applied to the electroadhesive joint is configured based on the predicted force capacity, or both (1) and (2).
11. The method of any one of claims 8-10, wherein (1) a dimension of a first electrode of the electroadhesive joint is selected based on the predicted force capacity; (2) a dimension and/or a composition of a separator disposed between the first electrode of the electroadhesive joint and a second electrode of the electroadhesive joint is selected based on the predicted force capacity, or both (1) and (2).
12. The method of any one of claims 8-11,

wherein the electroadhesive joint defines a direction of motion,

wherein a first electrode of the electroadhesive joint defines a length measured along the direction of motion,

wherein the first electrode defines a width perpendicular to the direction of motion,

wherein the first electrode defines a contact area superposed on a separator disposed between the first electrode and a second electrode,

wherein the first electrode defines a free area that is free of superposition on the separator disposed between the first electrode and a second electrode, and

wherein (1) the length of the first electrode is selected based on the predicted force capacity, (2) the width of the first electrode is selected based on the predicted force capacity, (3) the contact area of the first electrode is selected based on the predicted force capacity, (4) the free area of the first electrode is selected based on the predicted force capacity, (5) a dimension of the separator and/or a composition of the separator is selected based on the predicted force capacity, or any two or more of (1) – (5).
13. The method of any one of claims 8-12, wherein the electroadhesive joint defines a direction of motion, wherein a first electrode of the electroadhesive joint

defines a length measured along the direction of motion, wherein the first electrode defines a width perpendicular to the direction of motion, and wherein (1) based on the predicted force capacity, the length is configured to be greater than the width, (2) based on the predicted force capacity, the length is configured to be equal to the width, or (3) based on the predicted force capacity, the length is configured to be less than the width.

14. The method of any one of claims 8-13, further comprising incorporating the electroadhesive joint into a gripper device, a lifter device, a strain sensor, a haptic device, a wearable device, a prosthetic device, an implant, a vibration control device, an orthotic device, an exoskeletal device, a shape-morphing device, or any combination thereof.

15. An electroadhesive joint, at least one component of the electroadhesive joint comprising a component having at least one dimension based on a predicted force capacity estimated according to any one of claims 8-14.

16. The electroadhesive joint of claim 15, wherein the electroadhesive joint comprises any one or more of (a) a first electrode, a second electrode, and a separator between the first electrode and the second electrode, (b) comprises a first electrode, a second electrode, and a separator between the first electrode and the second electrode, at least one of the first electrode and the second electrode defining a mesh structure, the mesh structure optionally comprising metallic strands, and (c) the electroadhesive joint defining a direction of motion and the first electrode and the second electrode defining a superposed area, the superposed area being defined by a first axis extending in the direction of motion and a second axis extending perpendicular to the first axis, the second axis being greater than the first axis

17. The electroadhesive joint of claim 16, wherein the second axis is up to 10 times the first axis .

18. The electroadhesive joint of any one of claims 15-18, at least one of the first electrode and the second electrode defining a mesh structure, the mesh

structure comprising strands having a thickness in the range of from about 10 to about 200 μm .

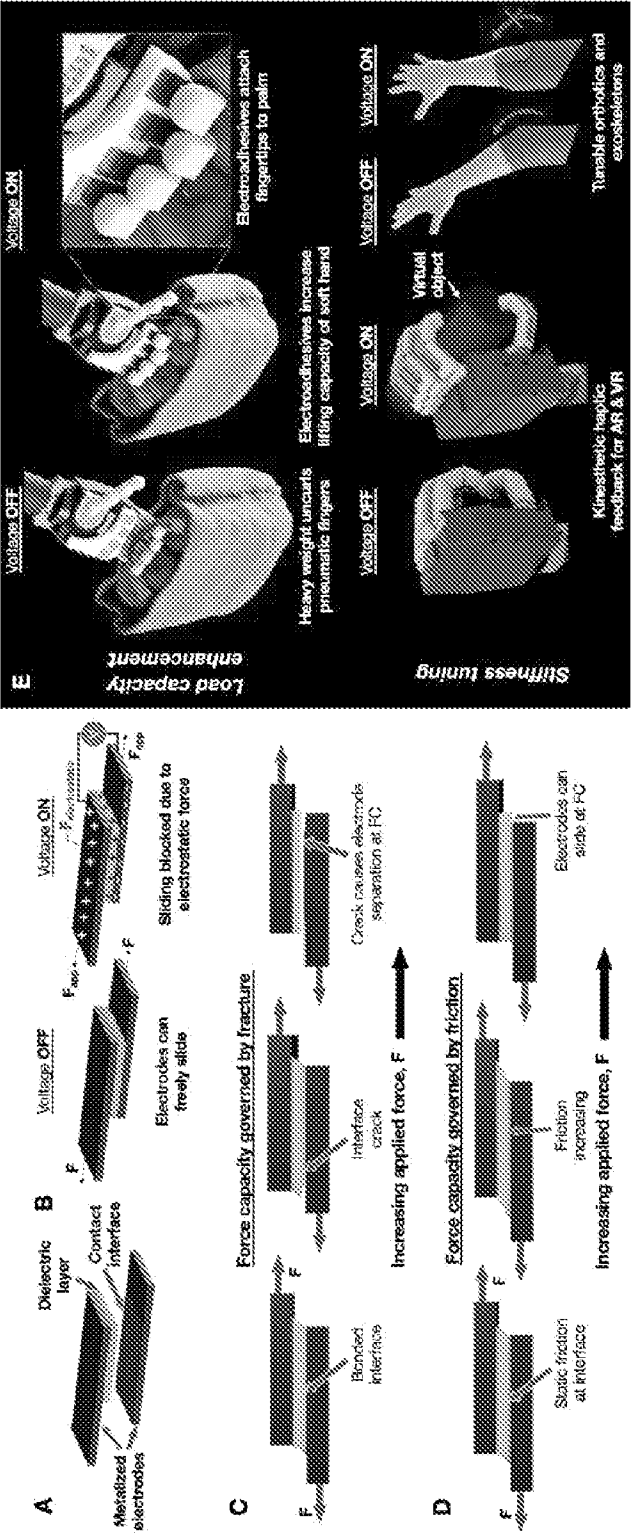
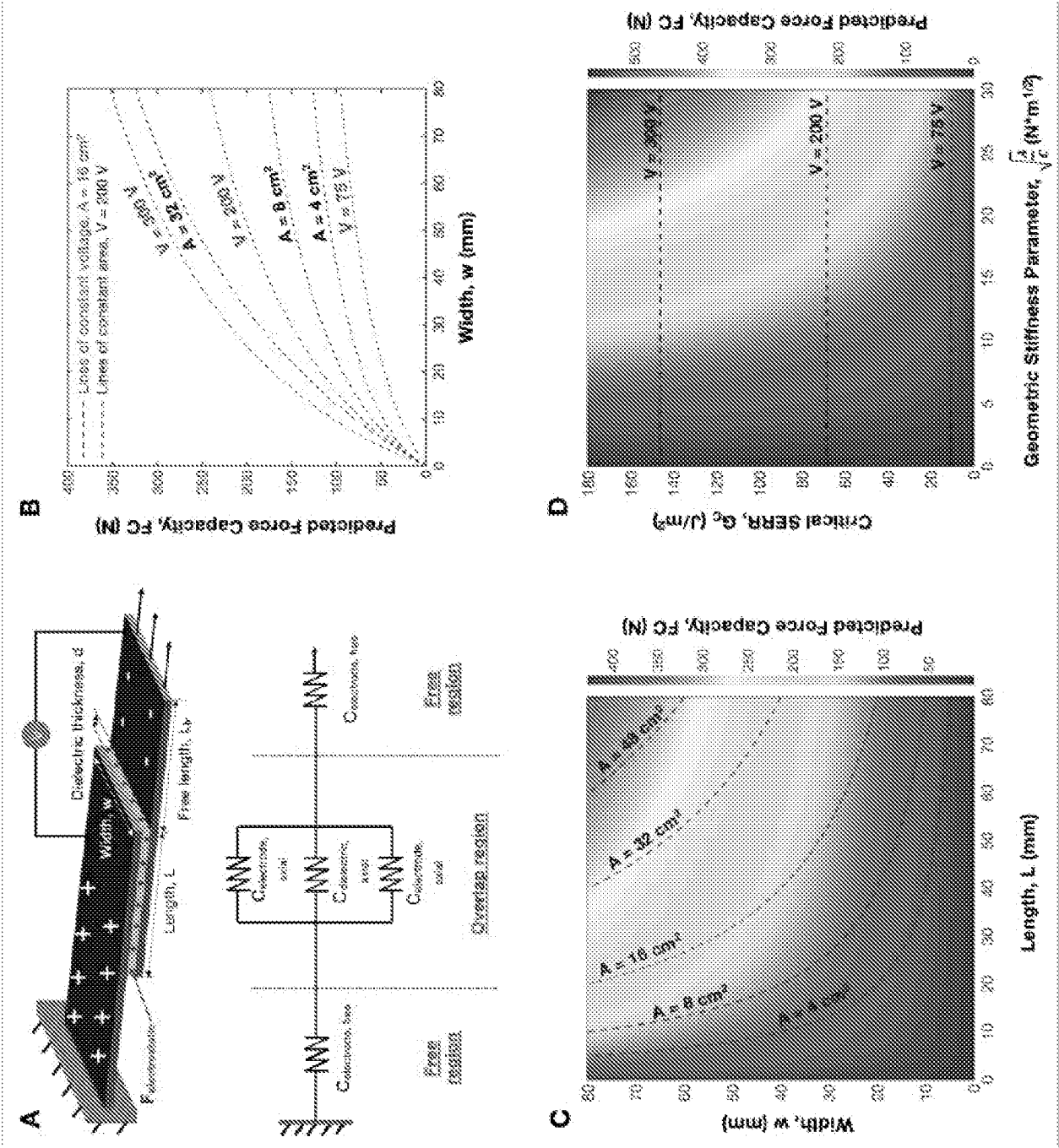


FIG. 1



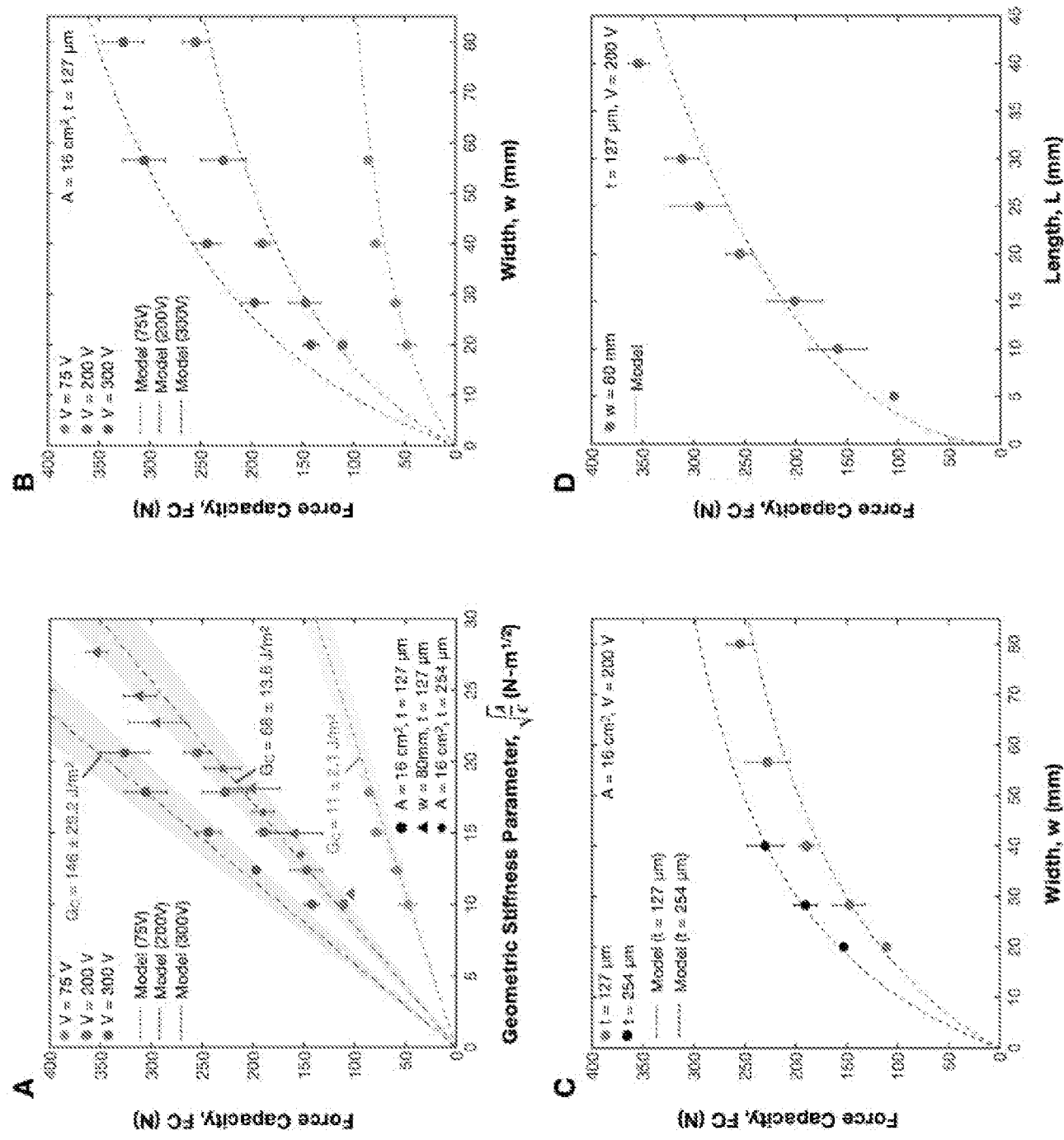


FIG. 3

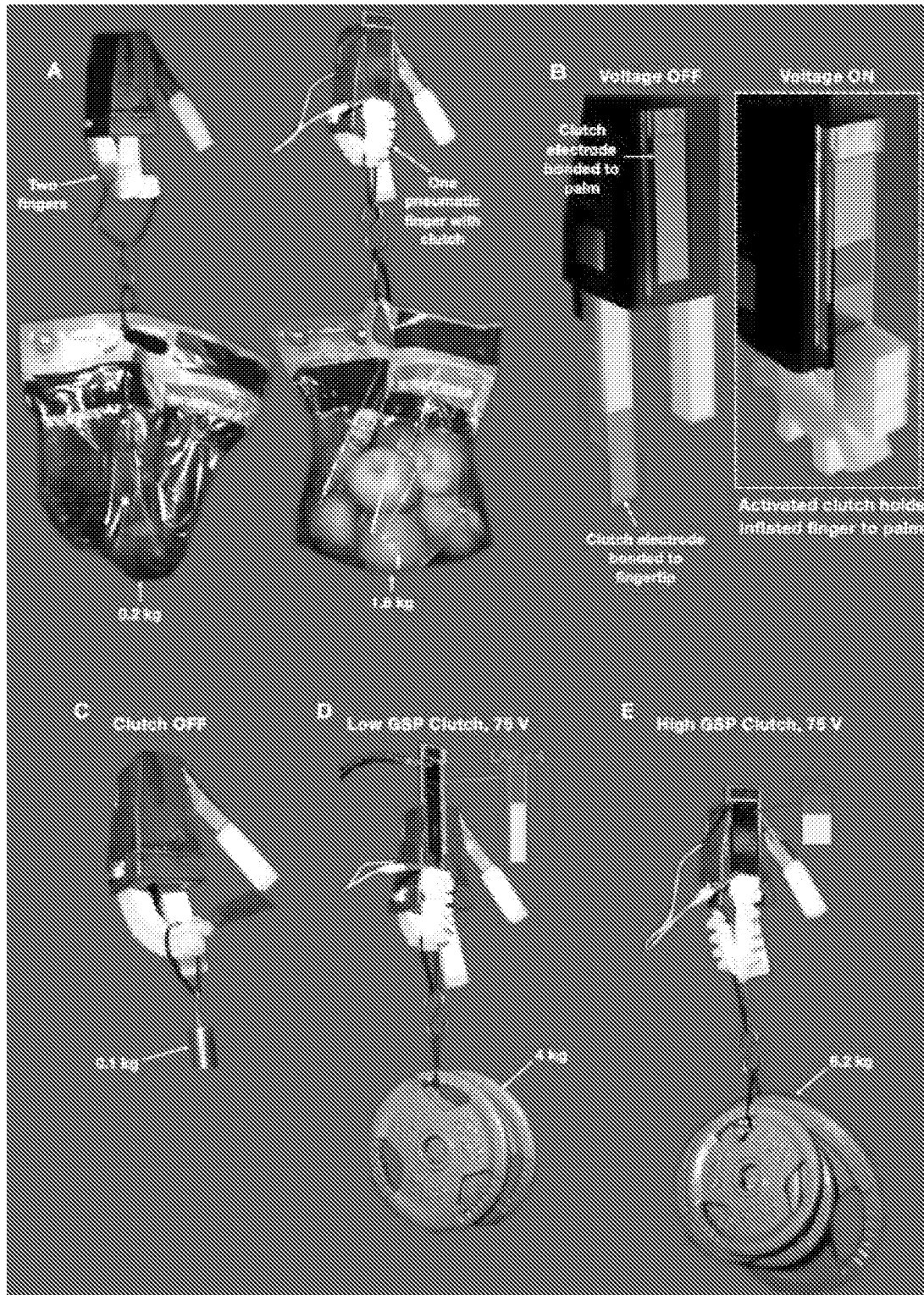


FIG. 4

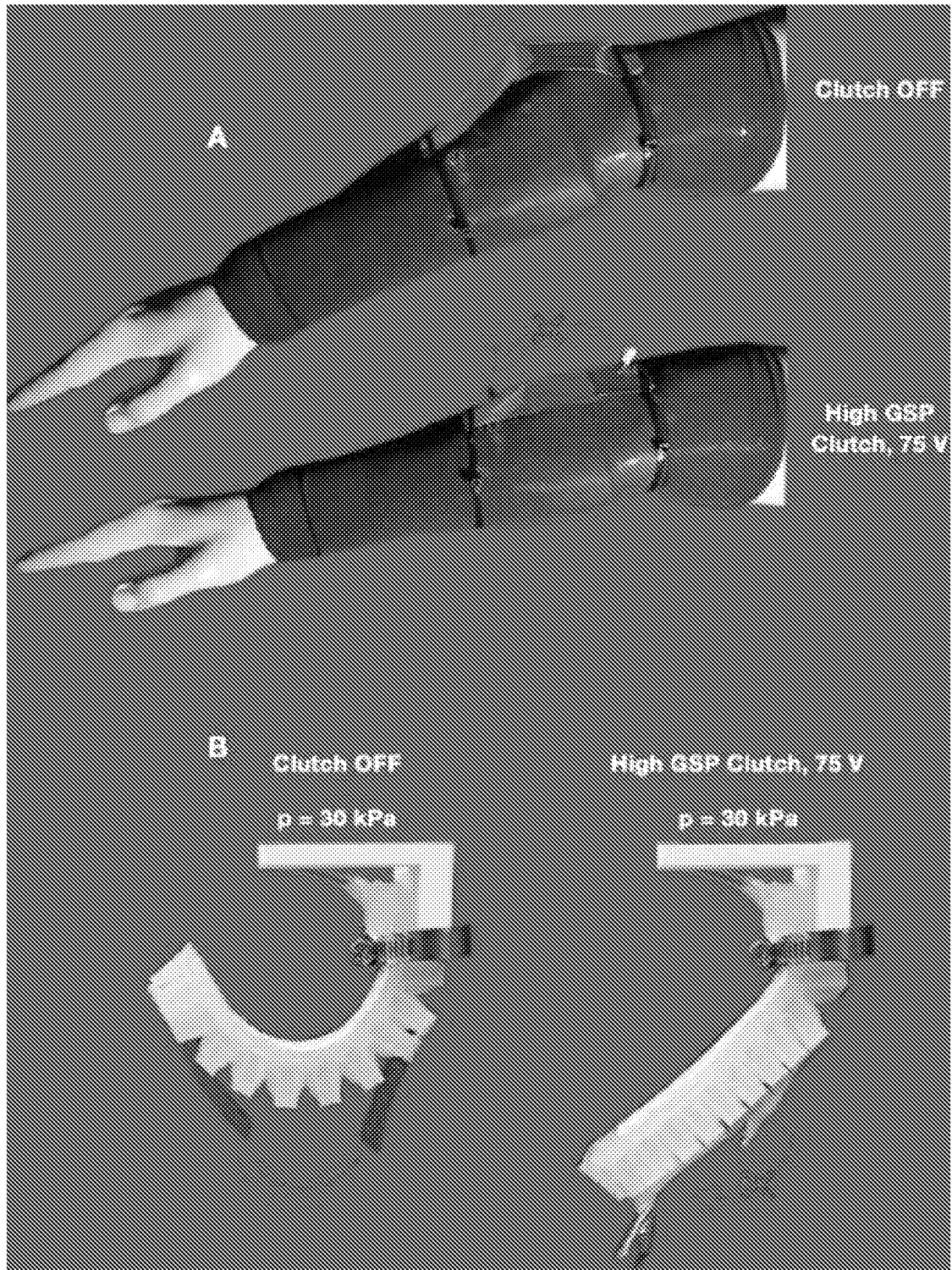


FIG. 5

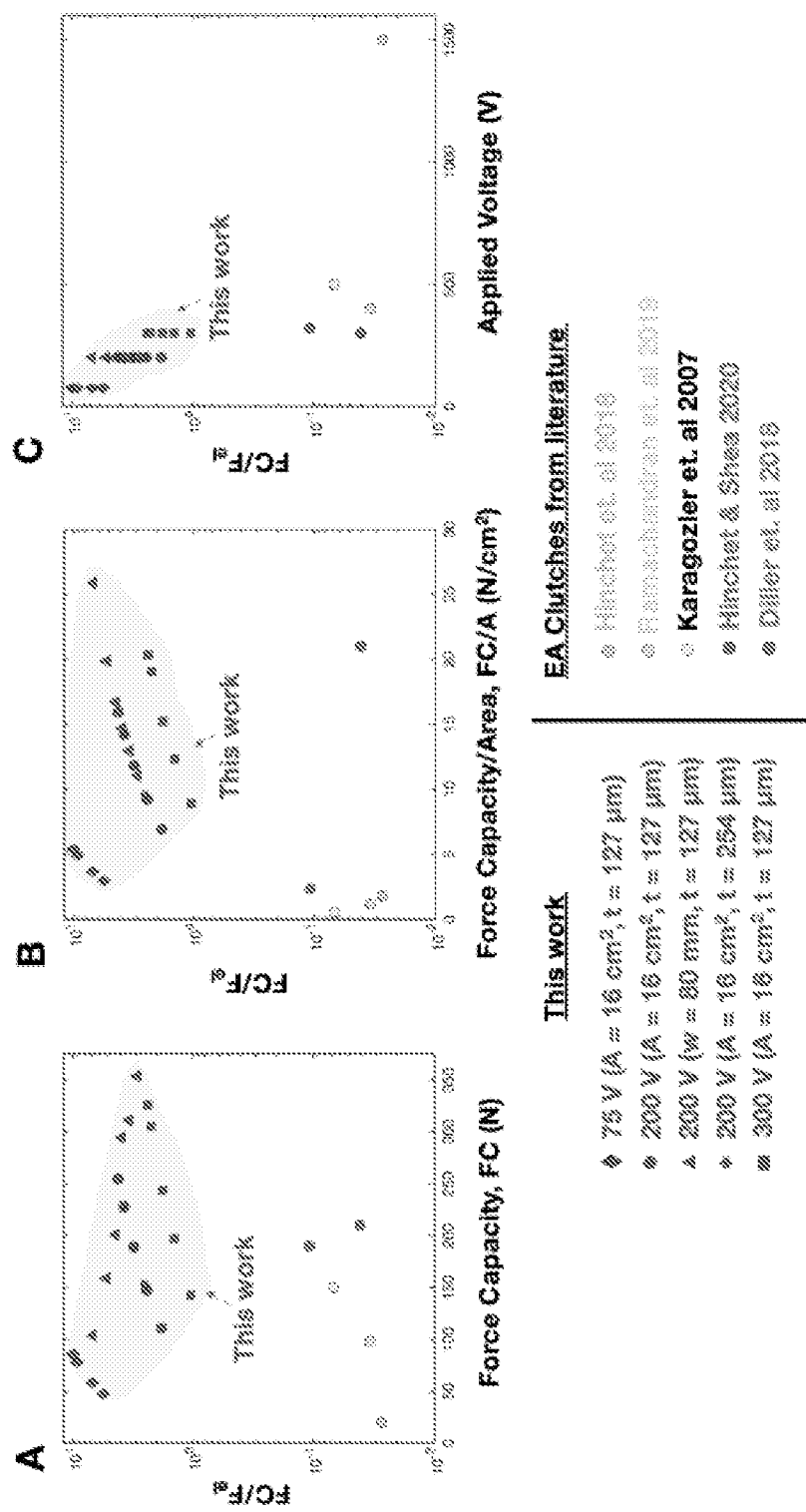


FIG. 6

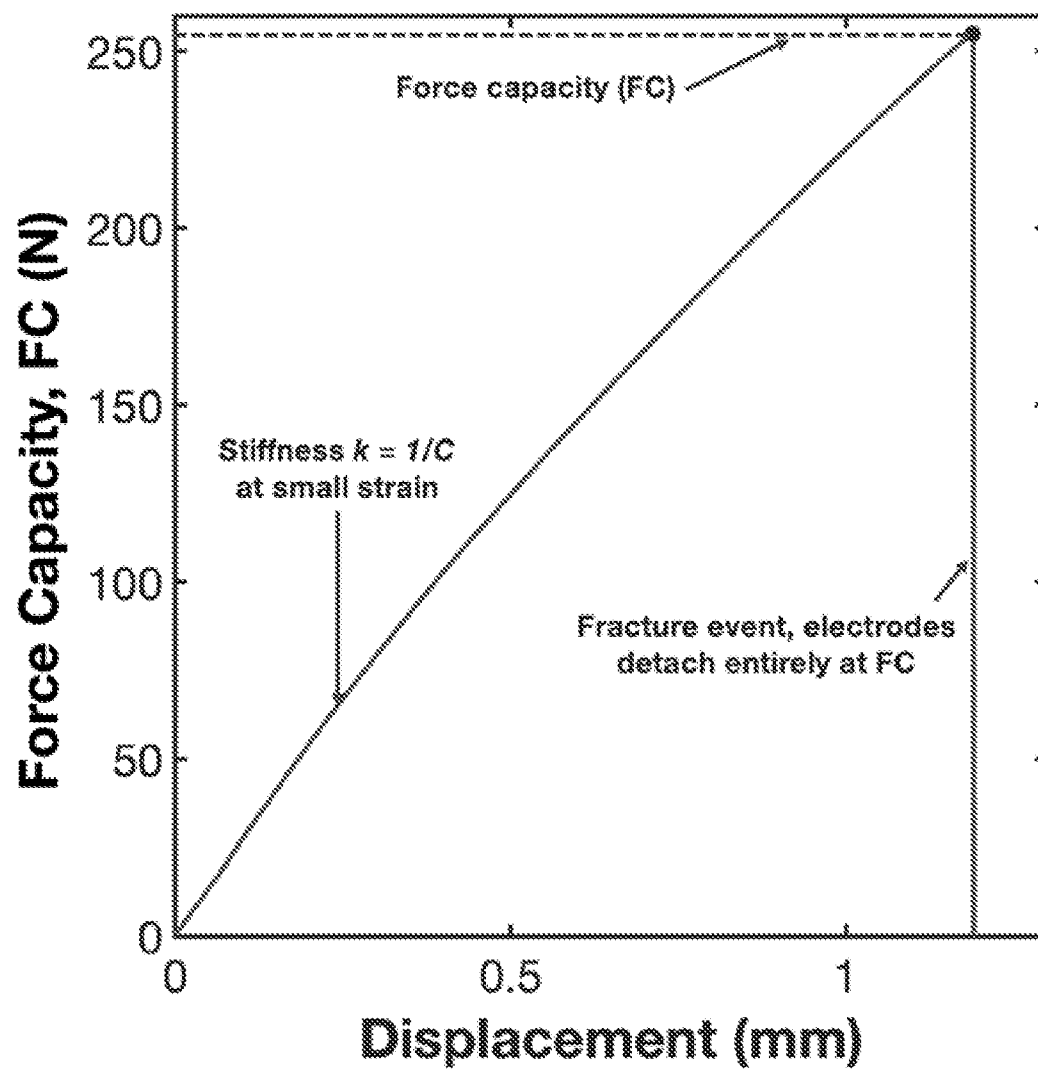


FIG. 7

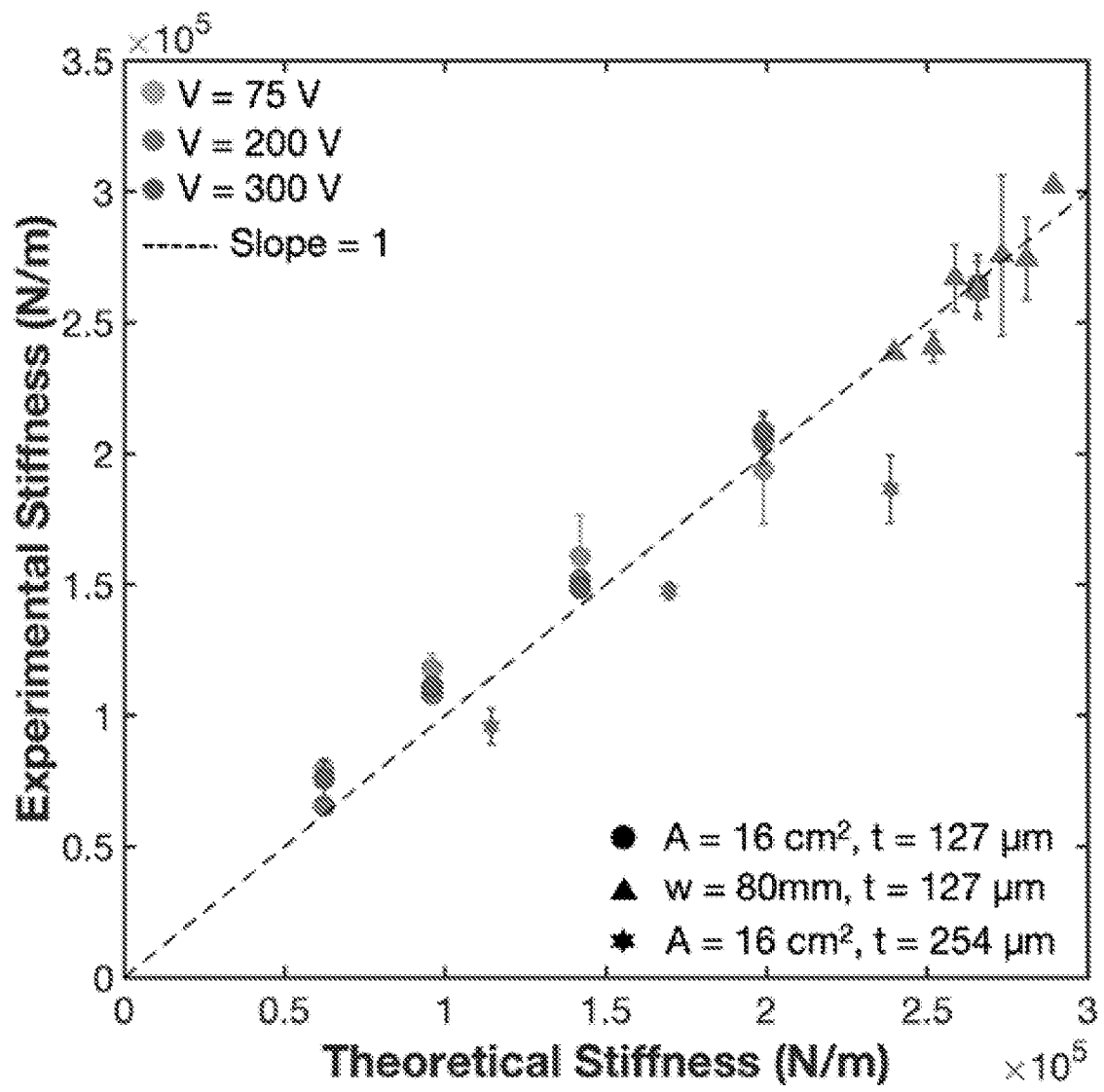


FIG. 8

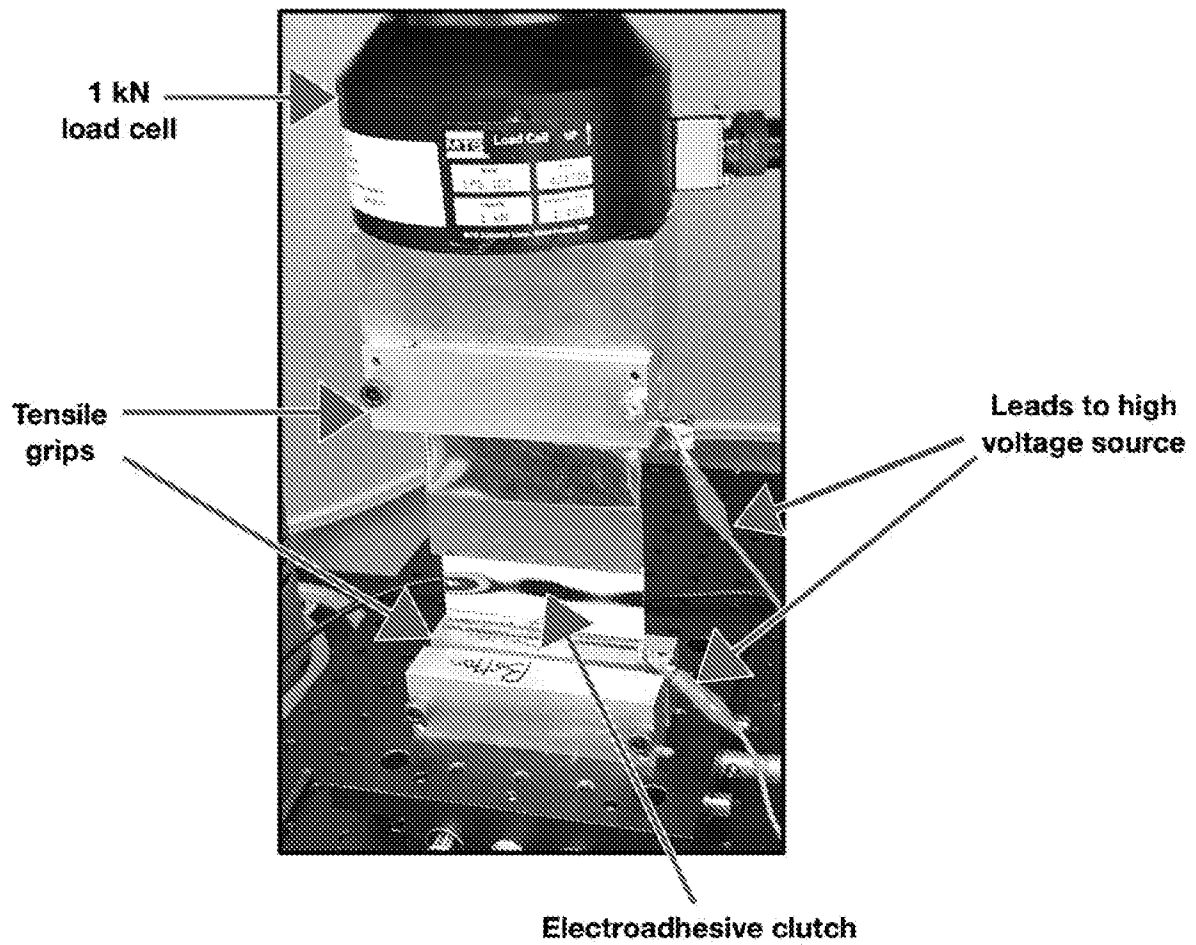


FIG. 9

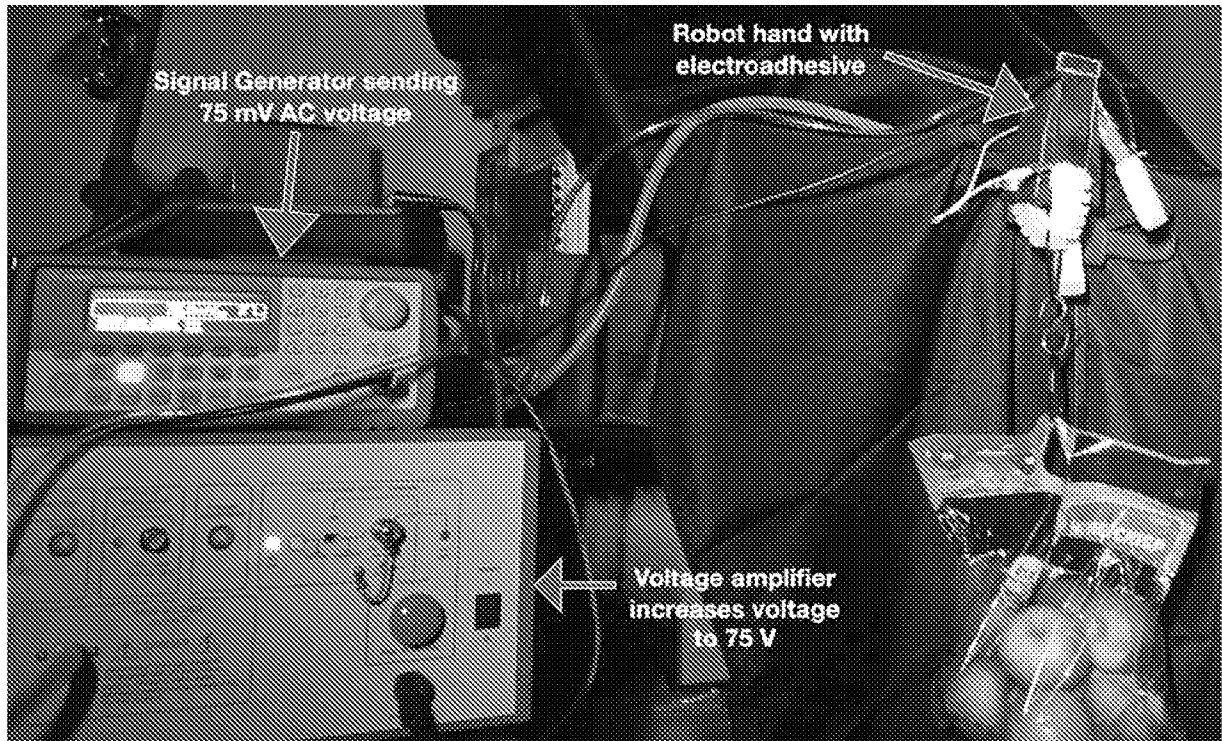


FIG. 10

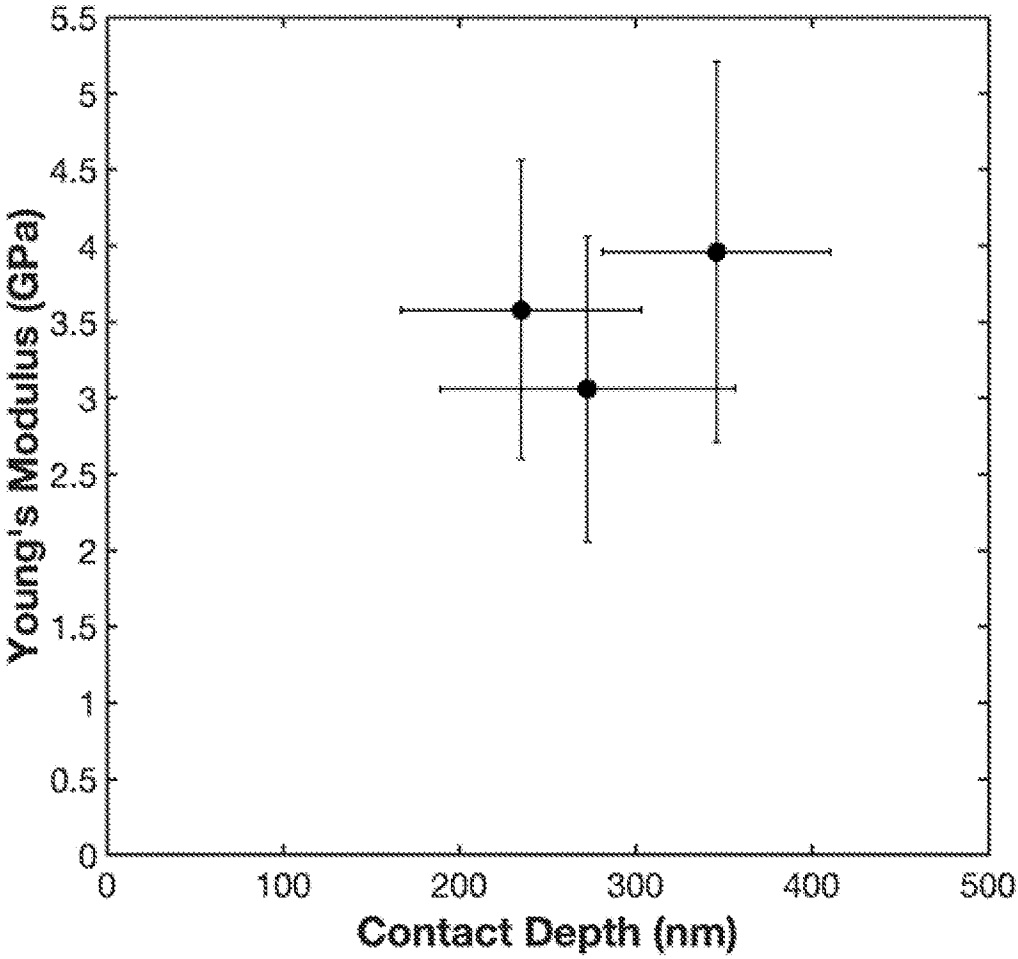


FIG. 11

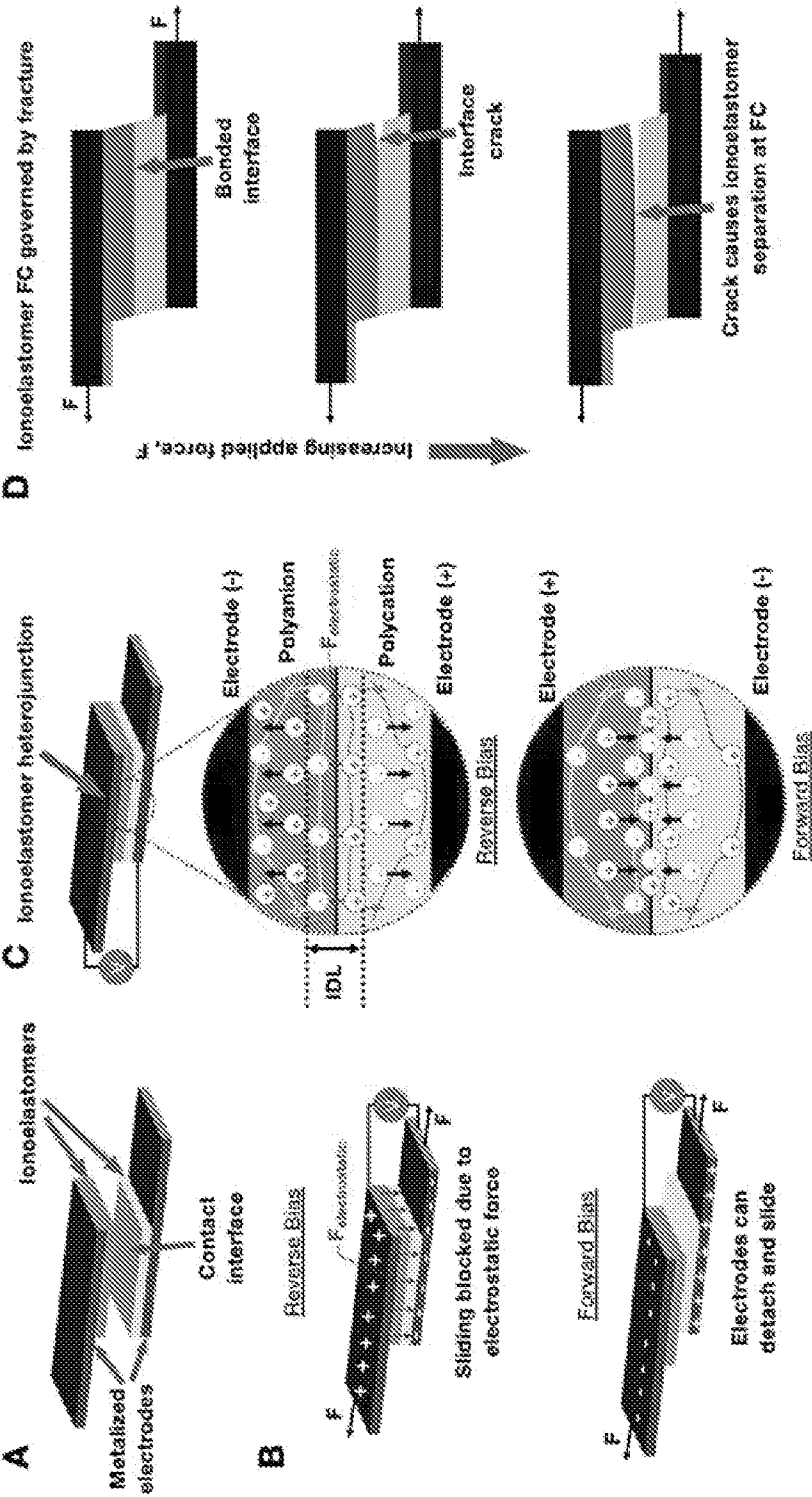


FIG. 12

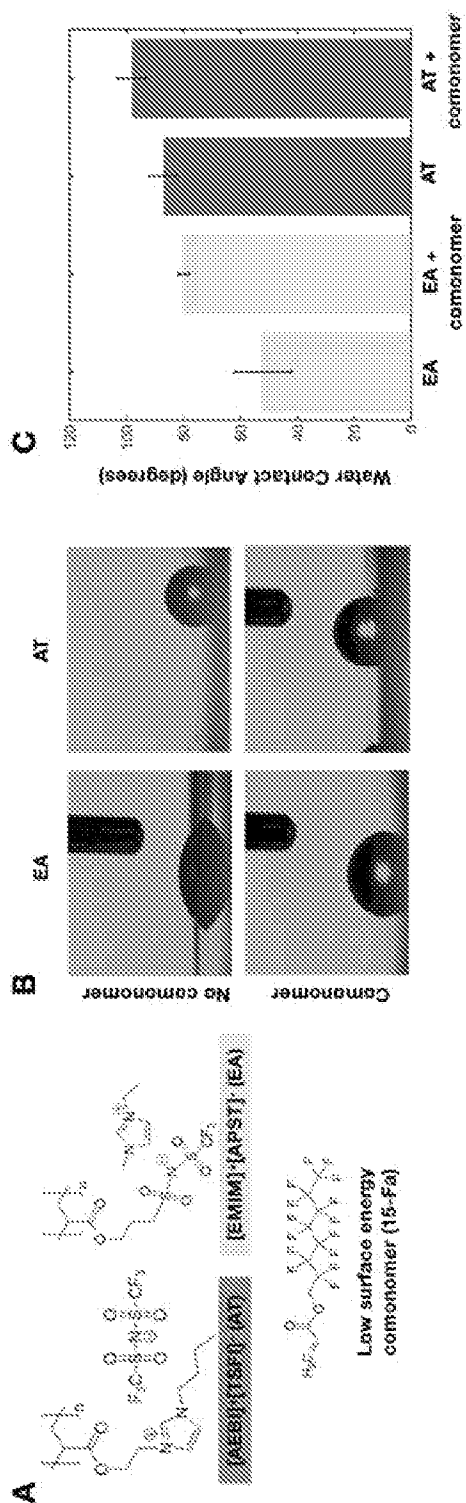


FIG. 13

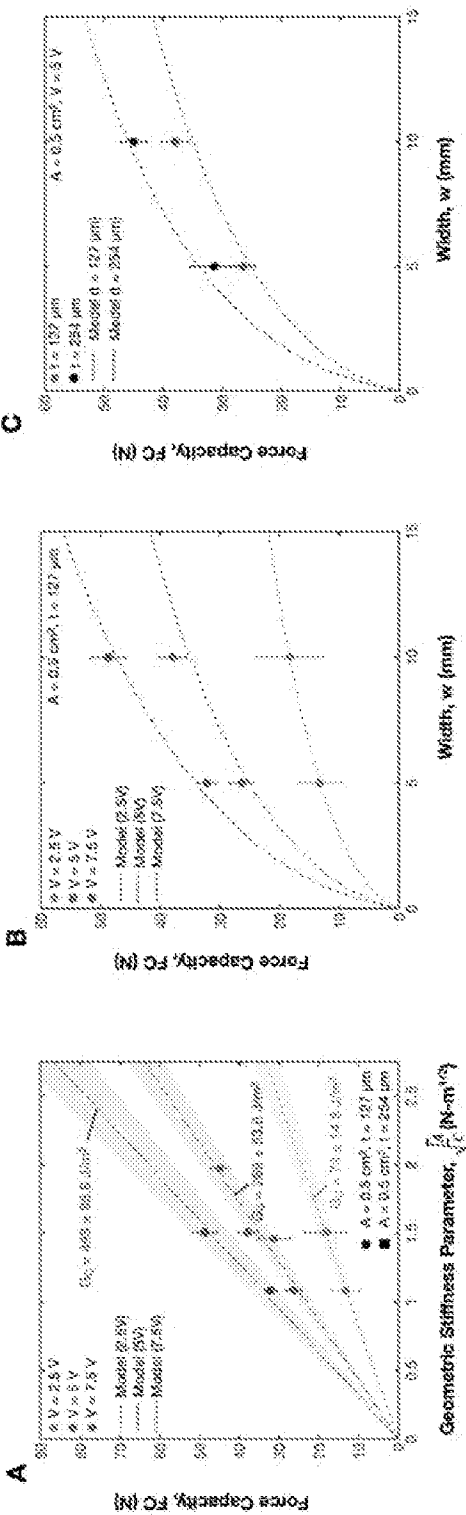


FIG. 14

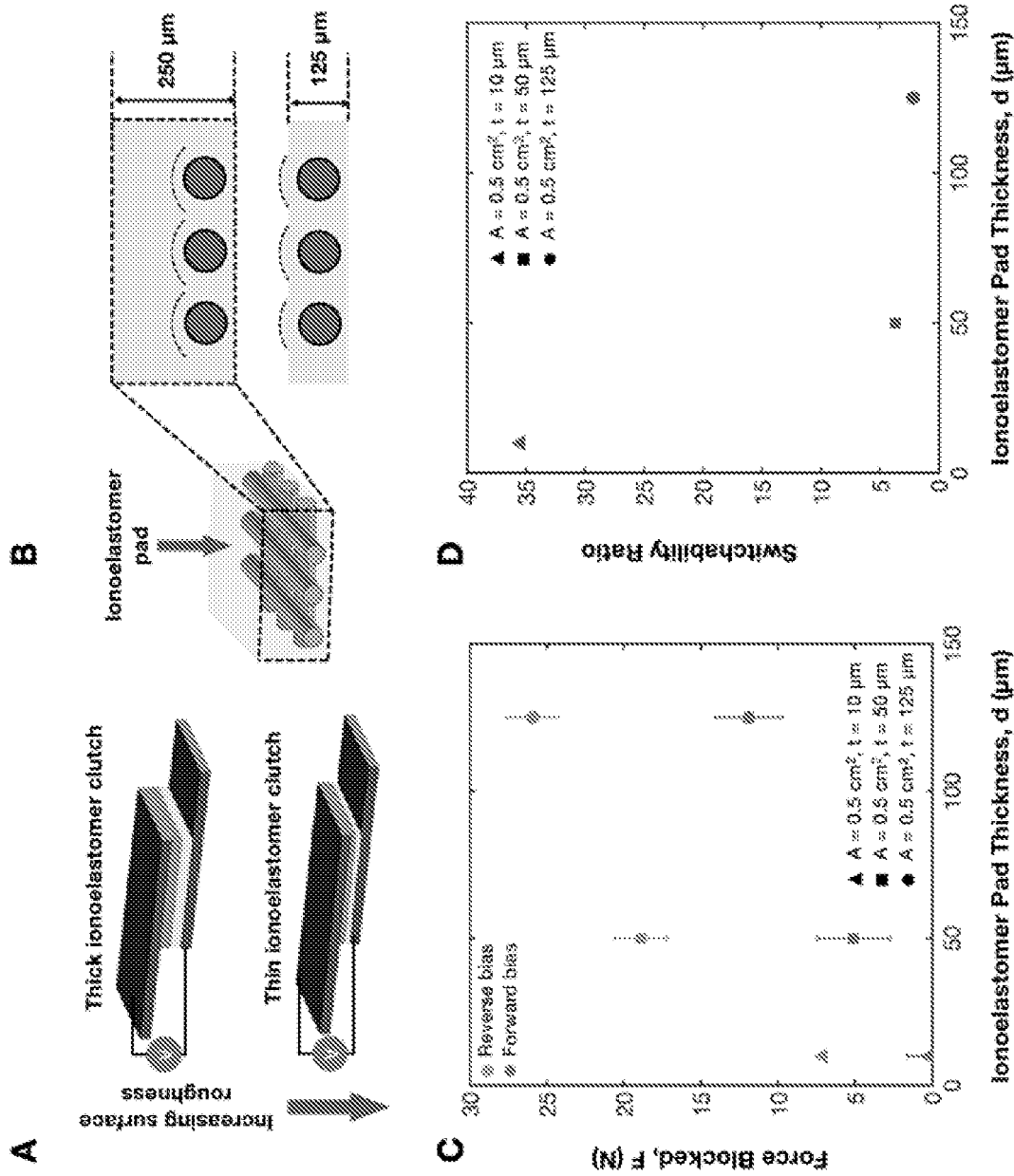


FIG. 15

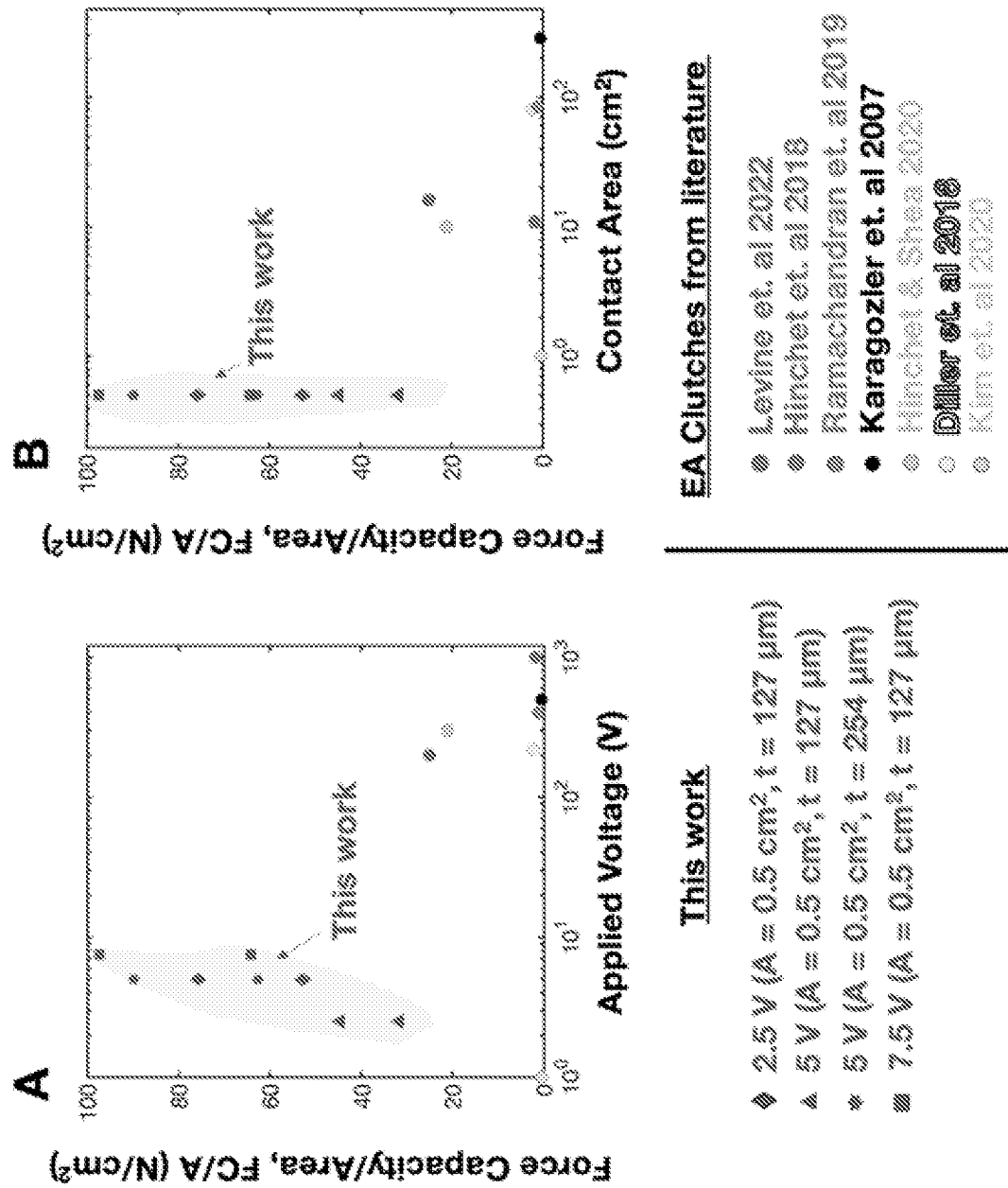


FIG. 16

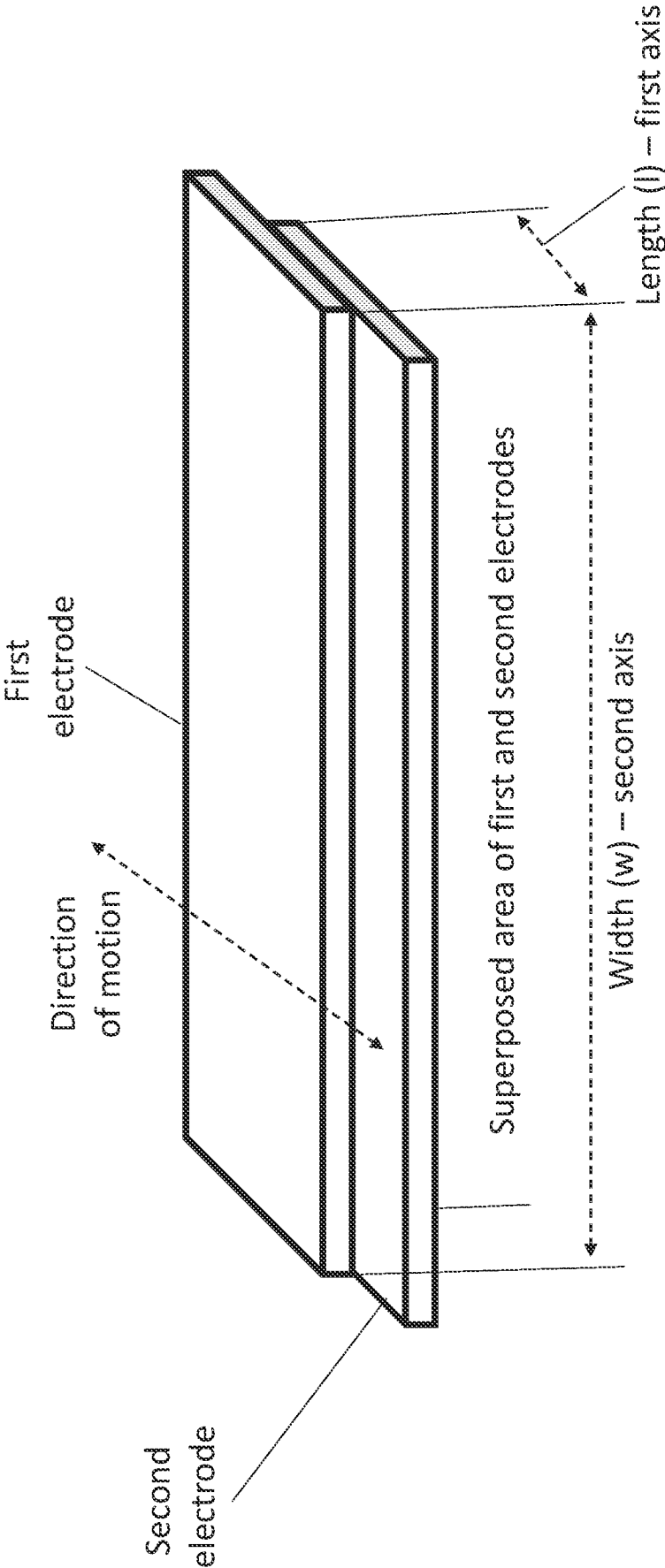


FIG. 17

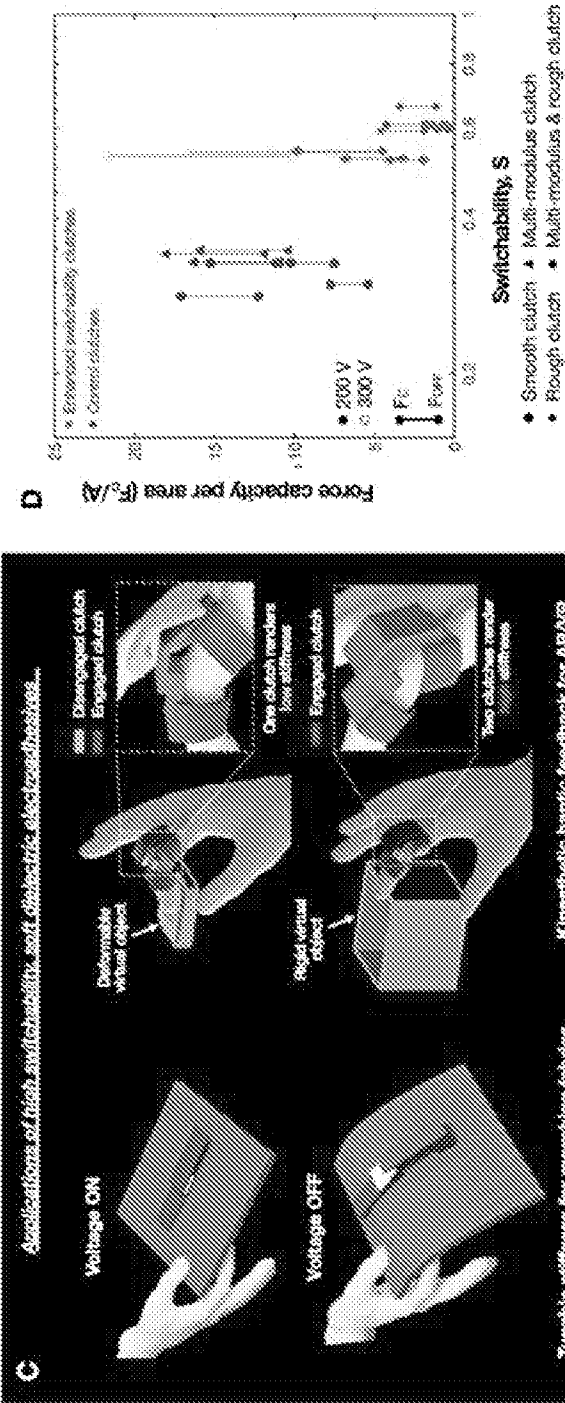
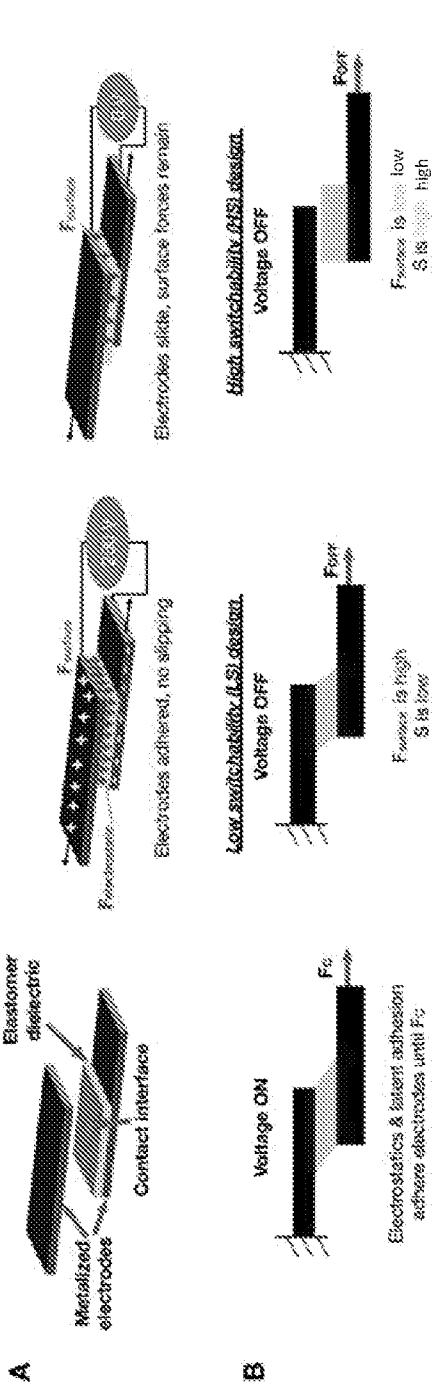
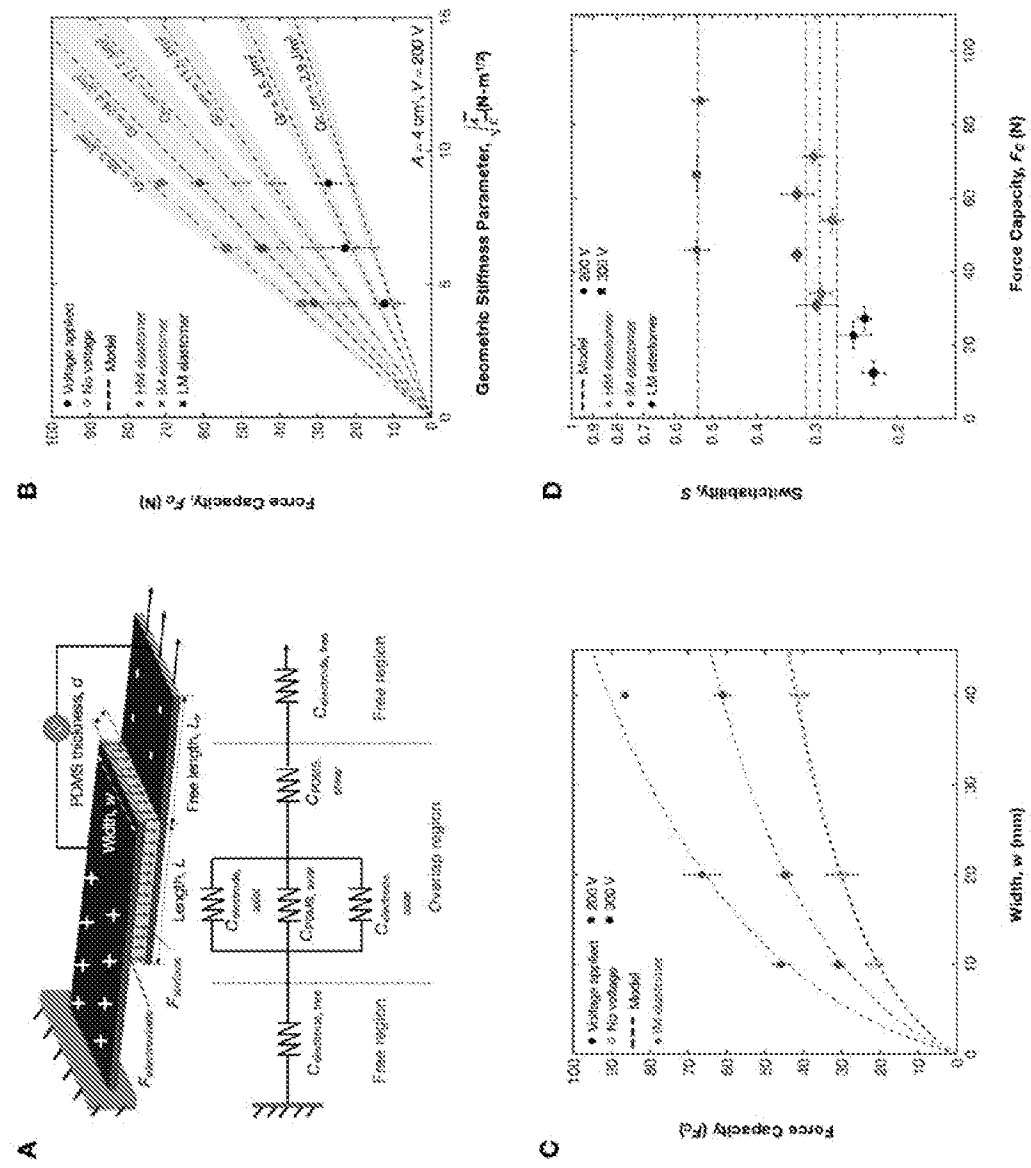


FIG. 18



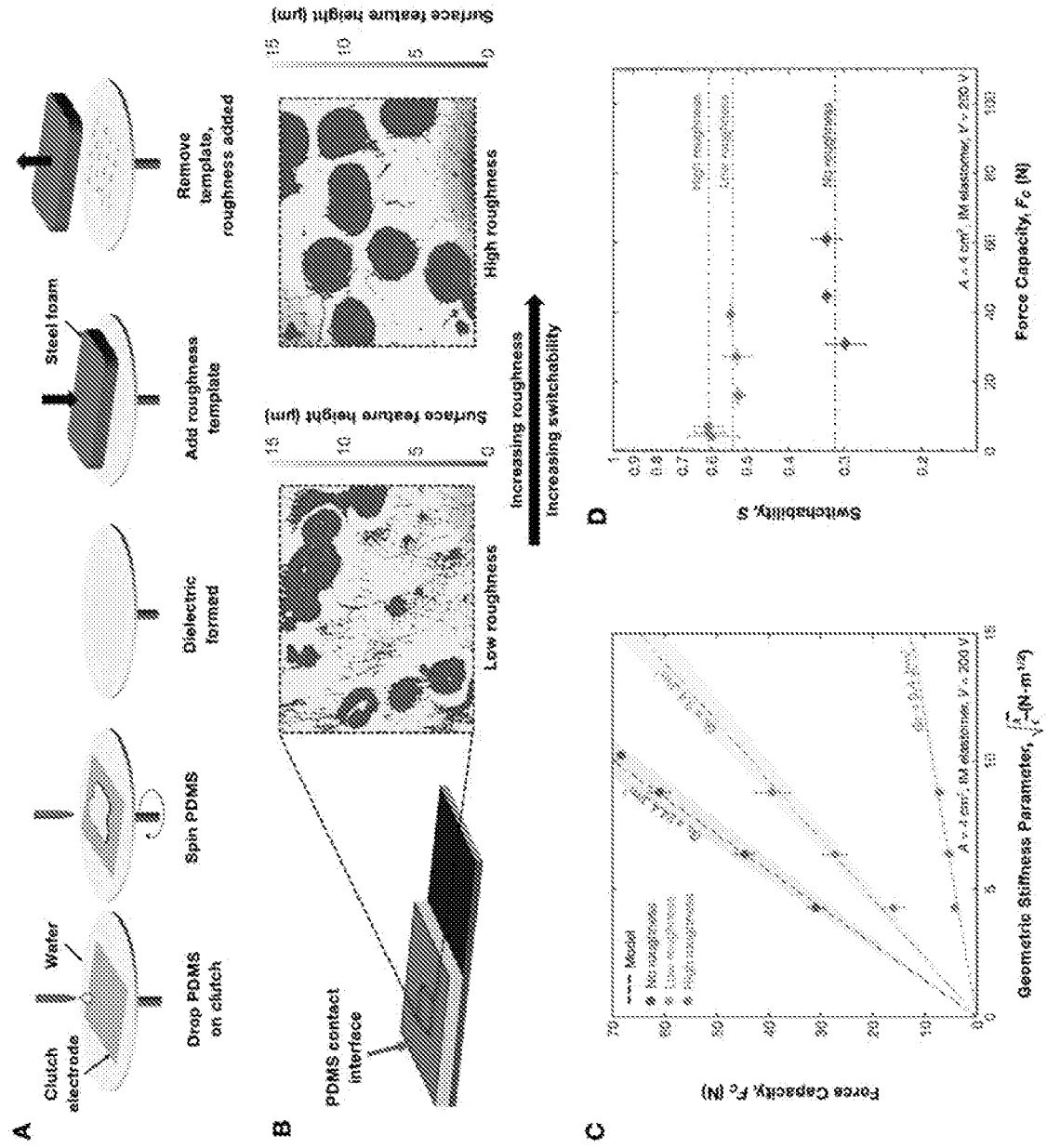


FIG. 20

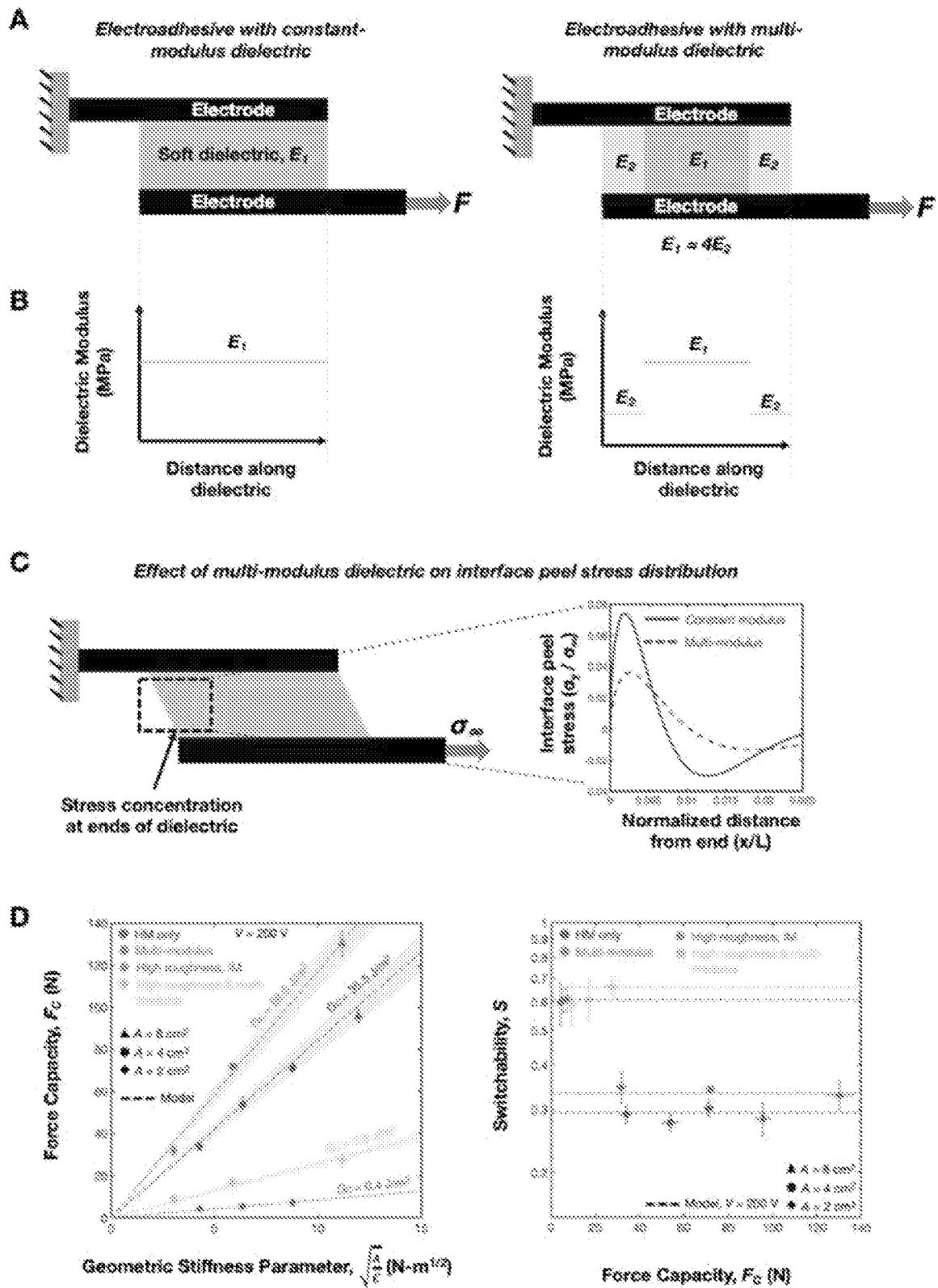


FIG. 21

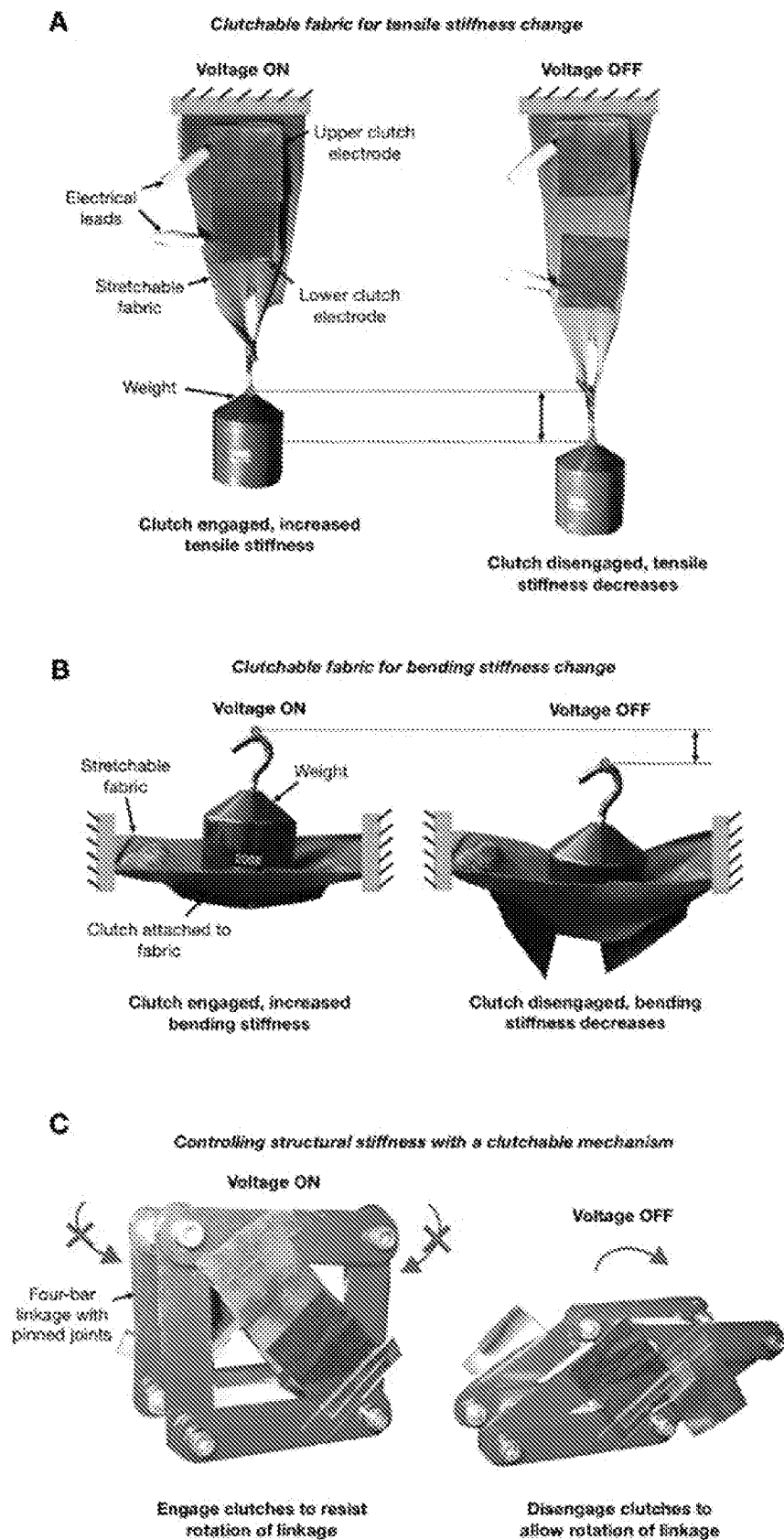


FIG. 22

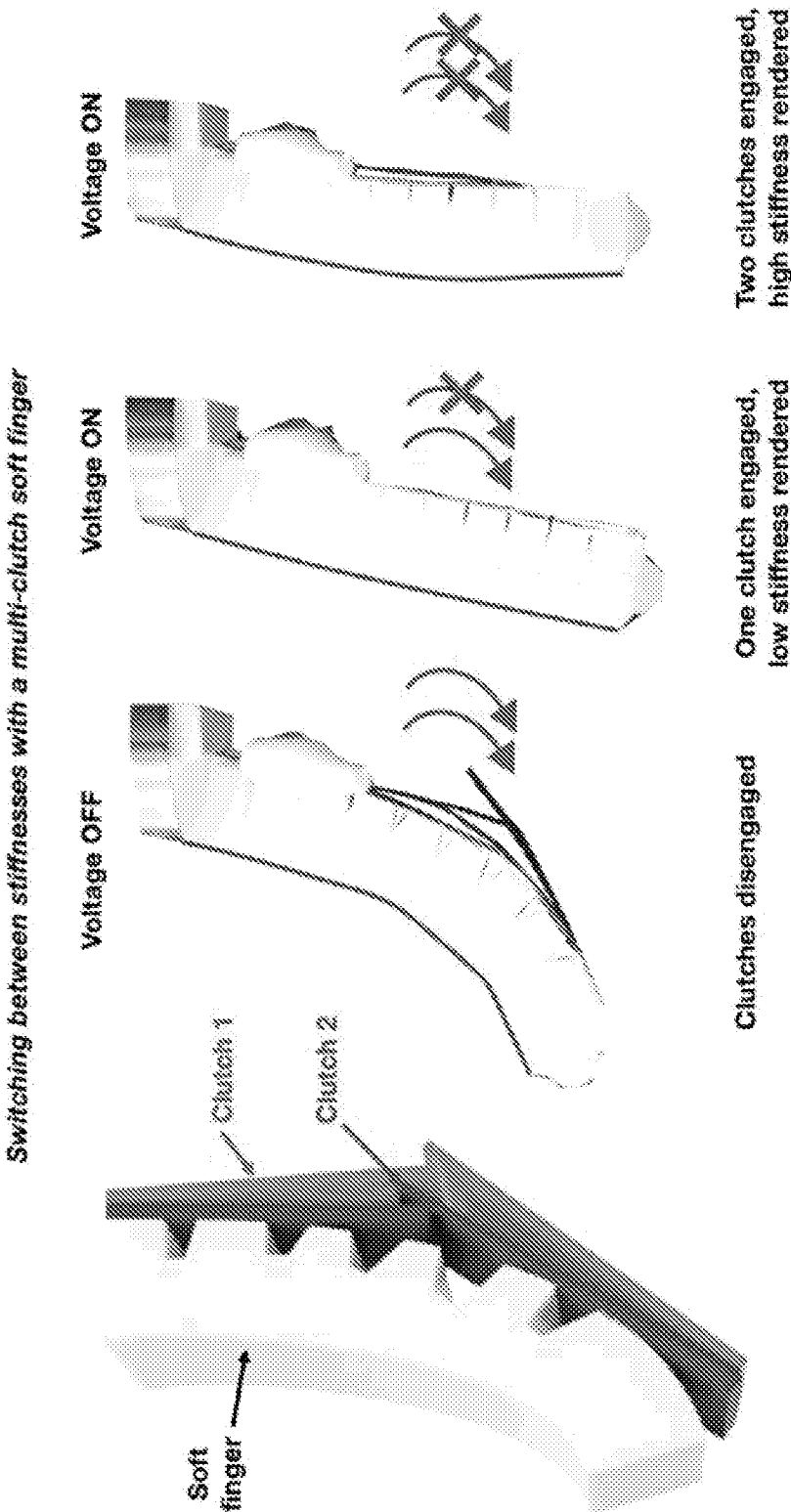


FIG. 23

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US 23/72929

A. CLASSIFICATION OF SUBJECT MATTER

IPC - INV. H02N 13/00, H01H 59/00 (2023.01)

ADD. F16D 27/02, F16D 37/02 (2023.01)

CPC - INV. H02N 13/00, H01H 59/00

ADD. F16D 63/002, F16D 28/00

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

See Search History document

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

See Search History document

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

See Search History document

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2021/0271326 A1 (ECOLE POLYTECHNIQUE FEDERALE DE LAUSANNE (EPFL)) 2 September 2021 (02.09.2021), entire document	1-2, 3/(1-2)
A	US 2,897,934 A (Fitch) 04 August 1959 (04.08.1959), entire document	1-2, 3/(1-2)
A	US 2022/0202104 A1 (NIKE, Inc.) 30 June 2022 (30.06.2022), entire document	1-2, 3/(1-2)
&, P	WO 2022/241326 A1 (ESTAT ACTUATION, INC.) 17 November 2022 (17.11.2022), entire document	1-2, 3/(1-2)

☐ Further documents are listed in the continuation of Box C.☐ See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"D" document cited by the applicant in the international application

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search

19 December 2023 (19.12.2023)

Date of mailing of the international search report

JAN 31 2024

Name and mailing address of the ISA/US

Mail Stop PCT, Attn: ISA/US, Commissioner for Patents

P.O. Box 1450, Alexandria, Virginia 22313-1450

Facsimile No. 571-273-8300

Authorized officer

Kari Rodriguez

Telephone No. PCT Helpdesk: 571-272-4300

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US 23/72929

Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. ☐ Claims Nos.:
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:

3. ☒ Claims Nos.: 4-7, 11-18
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

*- See Extra Sheet *-

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.
2. ☐ As all searchable claims could be searched without effort justifying additional fees, this Authority did not invite payment of additional fees.
3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:
4. ☒ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:
1-3

Remark on Protest

- ☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.
- ☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.
- ☐ No protest accompanied the payment of additional search fees.

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US 23/72929

This application contains the following inventions or groups of inventions which are not so linked as to form a single general inventive concept under PCT Rule 13.1. In order for all inventions to be searched, the appropriate additional search fees must be paid.

Group I: Claims 1-3, directed to an electroadhesive clutch, comprising: a first electrode, a second electrode, and a spacer.

Group II: Claims 8-10, directed to a method, comprising: estimating a predicted force capacity of an electroadhesive joint.

Claims 4-7, 11-18 were found to be unsearchable because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a). Also, Claim 18 recites that it depends "from claims 15-18"; for purposes of this Invitation, claim 18 is interpreted as depending from claims 15-17.

The inventions listed as Groups I-II do not relate to a single general inventive concept under PCT Rule 13.1 because, under PCT Rule 13.2, they lack the same or corresponding special technical features for the following reasons:

SPECIAL TECHNICAL FEATURES

The invention of Group I includes the special technical feature of an electroadhesive clutch, comprising: a first electrode, a second electrode, and a spacer, not required by the claims of Group II.

The invention of Group II includes the special technical feature of a method, comprising: estimating a predicted force capacity of an electroadhesive joint, not required by the claims of Group I.

COMMON TECHNICAL FEATURES

Groups I-II share the common technical features of an electroadhesive device.

However, this shared technical feature does not represent a contribution over prior art as being anticipated by US 2,897,934 A to Fitch, which Fitch teaches an electroadhesive device (Fig. 1-6; col 1, ln 14-18, "This invention relates to electroadhesive devices wherein the operation depends upon the electroadhesive forces between a conductive member and a co-operating semi-conductive member under the influence of an electrical potential difference").

Therefore, Groups I-II lack unity under PCT Rule 13 because they do not share a same or corresponding special technical feature.