Supporting Information

Stretchable Conductive Composites Based on Metal Wools for Use as Electrical Vias in Soft Devices

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Experimental

Fabrication of CEC Sheets. Conductive elastomeric sheets, containing <1% metal wool by volume, were fabricated by first pouring uncured Ecoflex 00-30 (Smooth-On, Inc.) onto a sheet of metal wool (steel wool grade "0000," Steel Wool International; "Fine" aluminium pads item # 123170, McMaster-Carr; "Fine" bronze wool, Global Material Technologies Inc.) (**Figure S2A**). The polymer-wetted metal wool sheet was placed between two metal plates with additional weights placed on top and cured in an oven at 60 °C for >2 hrs (**Figure S2B**). After curing, the excess Ecoflex 00-30 at the periphery of the encapsulated metal wool was trimmed with scissors to generate the composite sheet (**Figure S2C**). In the case of CEC sheets used for resistance measurements (**Video S3**), a region of metal wool at the periphery of the sheet, on the edges perpendicular to the majority fiber axis, was left uncoated to create exposed electrical contacts.

Fabrication of an Elastomeric Sheet with a CEC Via as used in Figures S4, S5, S6, and S7. A mold for constructing the device was 3D printed using ABS plastic (Stratasys Dimension Elite) (**Figure S8A**). Sulfur-free clay (Sculptex Medium Modeling Clay; Reynolds Advanced Materials) was placed in a recess at the base of the mold and steel wool (grade "0000," Steel Wool International) was placed on top (**Figure S8B**). Clay was used to affix the steel wool to the mold. It also functioned to mask the metal fibers at the base of the mold so that they remained uncoated by elastomer, thereby minimizing the resistance of the final device. Uncured Ecoflex 00-30 (Smooth-On, Inc.) was then added to the mold (**Figure S8C**) followed by curing in an oven at 60 °C for >2 hrs (**Figure S8D**). The cured material was demolded and the excess steel wool was trimmed with scissors to create the finished device (**Figure S8E**).

Fabrication of the Elastomeric Sheet with Four CEC Disks shown in Figure 3. A length of steel wool (grade "0000," Red Devil) (**Figure S9A**) was rolled in the direction of its minor fiber axis to create a cylinder of steel wool whose fibers were aligned with the axis of the cylinder (**Figure S9B**). This cylinder was then placed in a 15 ml polypropylene conical tube with Ecoflex 00-30, cured at 80 °C for >40 min, and sectioned into disks with a razor blade (**Figure S9C**). The resulting CEC disks (**Figure S9D**) were subsequently embedded in sheets of Ecoflex 00-30 (**Figure S9E**), generating an elastomeric sheet with regions of steel fibers traversing the width of the sheet (**Figure S9F**).

Fabrication of the Soft, Solderless Breadboard. A mold for constructing the device was printed in 3D using ABS plastic (Stratasys Dimension Elite) (**Figure S10 A and B**). Steel wool (grade "0000," Steel Wool International) was inserted into all of the recessions of the mold to create the electrical peg connectors for hard electrical components; it was also placed between selected recessions to create the electrical connections between peg connectors (**Figure S10C**). Uncured Ecoflex 00-30 (Smooth-On, Inc.) was added to the mold (**Figure S10D**) followed by curing in an oven at 60 °C for >2 hrs (**Figure S10E**). After curing, the device was demolded to create the finished, soft, solderless breadboard (**Figure S10F**).

Fabrication of the Soft Touch Sensor. A rectangular prism shaped nickel plated neodymium magnet (K&J Magnetics) was placed underneath a glass plate and a section of ferromagnetic steel wool (grade "0000," Steel Wool International) was placed on top of the glass plate (**Figure S11A**). Placing a magnet underneath the glass plate served to both affix the steel wool pad to the plate prior to the addition of elastomer and subsequent curing, and to pattern the steel wool pad into a rectangular shape. Uncured Ecoflex 00-30 (Smooth-On, Inc.) was then poured onto the glass plate (**Figure S11B**) followed by curing in an oven at 60 °C for >2 hrs (**Figure S11C**). After curing, excess elastomer was trimmed from the edges of the sheet with a razor to form a square sheet of cured elastomer with a square CEC pad at its center. A smaller square plastic sheet was placed on top of the cured sheet to act as a mask before uncured Ecoflex 00-30 was poured on top (**Figure S11D**). The mask was removed, leaving behind a bead of uncured elastomer at the edges of the cured elastomer sheet. A second square sheet of cured elastomer with a CEC pad at its center was placed on top (**Figure S11E**), and the layered construct was cured in an oven at 60 °C for >2 hrs (**Figure S11F**) creating an air tight seal between the sheets. Finally, a steel cannula (Hamilton Company) was used to puncture a hole into the layered construct so that an air supply line (Tygon tubing, ID = 1/32", OD = 3/32", Wall = 1/32", Saint-Gobain Performance Plastic) could be inserted into the gap between the cured elastomer sheets, producing the finished soft touch sensor.

Fabrication of the Soft Strain Gauge. Silicone-based conductive carbon grease (MG Chemicals) was printed on a cured sheet of Ecoflex 00-30 (Smooth-On, Inc.) using a pressurized syringe mounted in an Aerotech ABG1000 gantry system (**Figure S12A**). The carbon grease was extruded from a 410 µm diameter orifice at a driving pressure of ~446 kPa (given in units of absolute pressure) using a print speed of 0.75-1.25 mm/s. This left a carbon grease filament of ~650 µm in diameter. Using the gantry system, the carbon grease was printed in vertical stacks of six filaments, producing a free standing line of grease ~3.9 mm in height. An optical breadboard was used to hold steel wool (grade “0000,” Steel Wool International) fiber bundles in contact with the grease (**Figure S12B**). More uncured Ecoflex 00-30 was poured on top to encapsulate the grease and steel wool connections followed by curing in an oven at 80 °C for >40 min (**Figure S12C**). The sensor was cut free from the excess elastomer on the periphery with a razor. This left a block of Ecoflex 00-30 with a CEC at either end that was in conductive contact with the central channel of carbon grease (**Figure S12D**).

Characterization

X-Ray CT. Micro x-ray computed tomography experiments were performed on an X-Tek HMXST225 x-ray imaging and computer tomography system using a molybdenum reflection target, an accelerating voltage of 75 kV, and a filament current of 126 μA.

Mechanical Testing. All one-dimensional elongation and compression experiments were performed using an Instron model 5566.

Thermal Imaging. Thermal imaging was performed on a FLIR T640 0.10. Images and videos were collected with an emissivity of 0.95, a reflected temperature of 20 °C, an object distance setting of 0 m, a relative humidity of 50%, and an atmospheric temperature of 20 °C.

Supporting Videos

Video S1. Micro x-ray computed tomography of a CEC sheet.

Video S2. Thermal imaging of a 4 x 70 x 70 mm steel wool CEC sheet when a current of 5.0 A was transmitted parallel and perpendicular to the majority fiber axis for 10 sec.

Video S3. Resistance of a 2 x 82 x 89 mm steel wool CEC sheet as it was folded and stretched.

Video S4. A LED circuit was created using the surface of a conductive sphere, a button battery, a LED, and an elastomeric sheet with four steel wool CEC disks (portions of the play back are sped up).

Video S5. A LED was illuminated using biased copper wires and a soft, solderless breadboard made from steel wool CEC fiber bundles embedded in an elastomer.

Video S6. A LED circuit was opened and closed using a soft touch sensor.

Video S7. The change in resistance of a soft strain gauge was measured during several cycles of elongation.

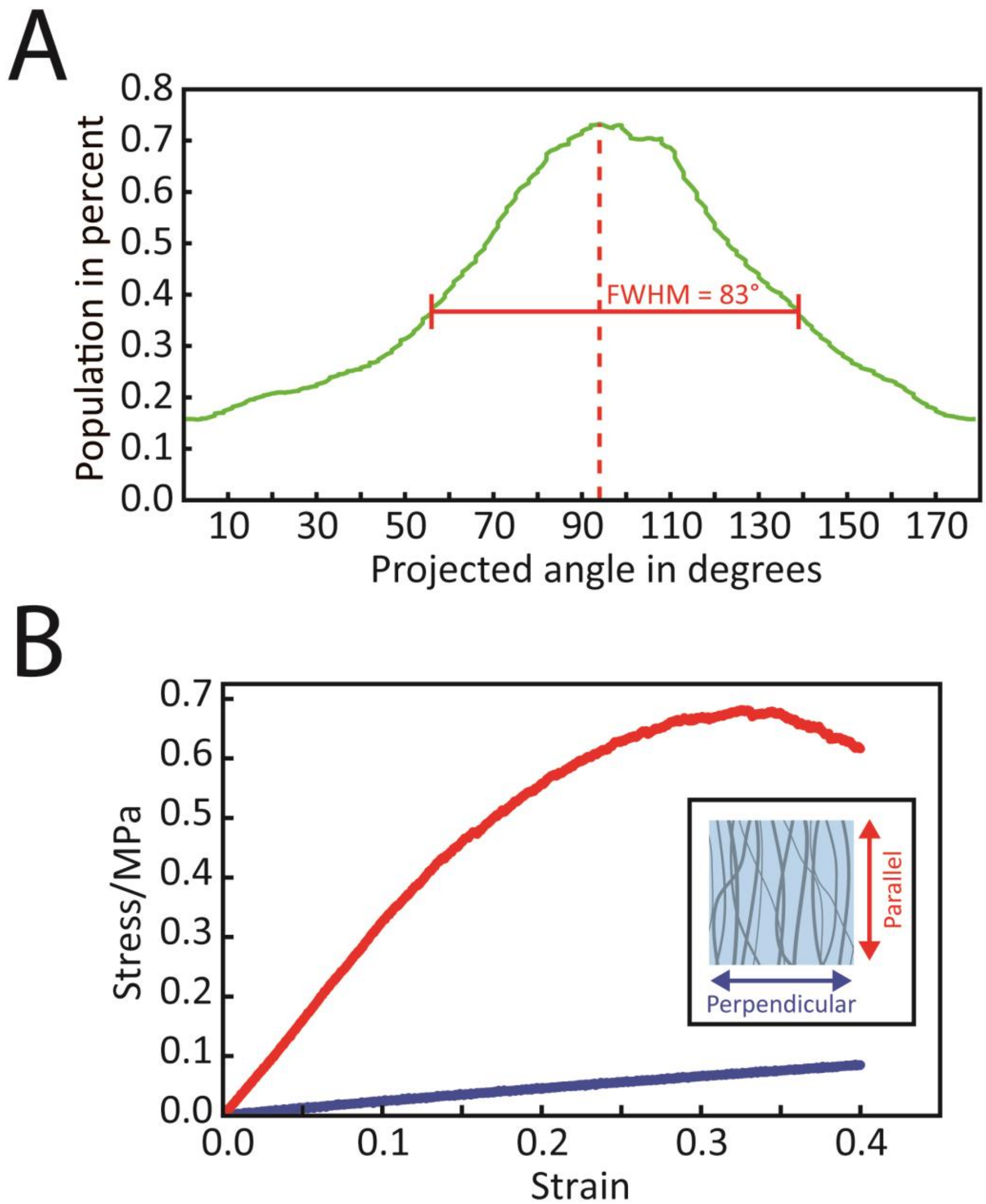

Figure S1. Materials Characterization. (A) Analysis of micro x-ray computed tomography data collected on the steel wool composite sheet shown in Video S1. The graph shows the population distribution for the orientation of steel fibers in the wool relative to the majority fiber axis (denoted here as 94°). (B) Stress vs. strain plot for representative steel wool composite sheets pulled parallel (Red) and perpendicular (Blue) to the majority fiber axis. Stress and strain data are provided based on measurements of engineering stress and engineering strain. The CEC sheets were elongated at a rate of 5 mm/min.

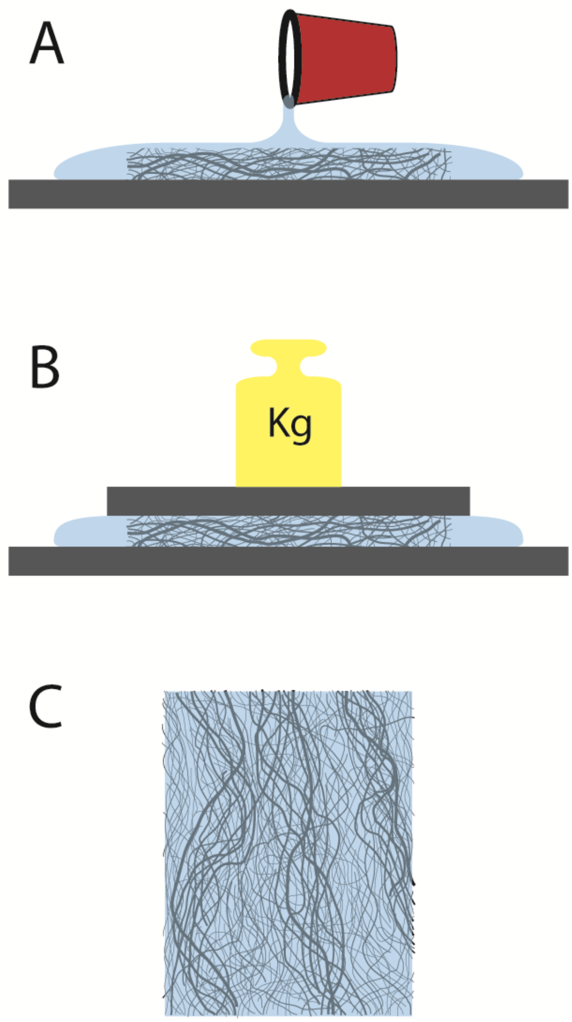

Figure S2. Fabrication of a CEC Sheet. (A) A sheet of metal wool was placed on a metal plate and soaked in uncured elastomer. (B) The soaked metal wool sheet was cured in an oven while being pressed by a top metal plate and additional weights. (C) The cured product was trimmed with scissors to generate the final CEC sheet.

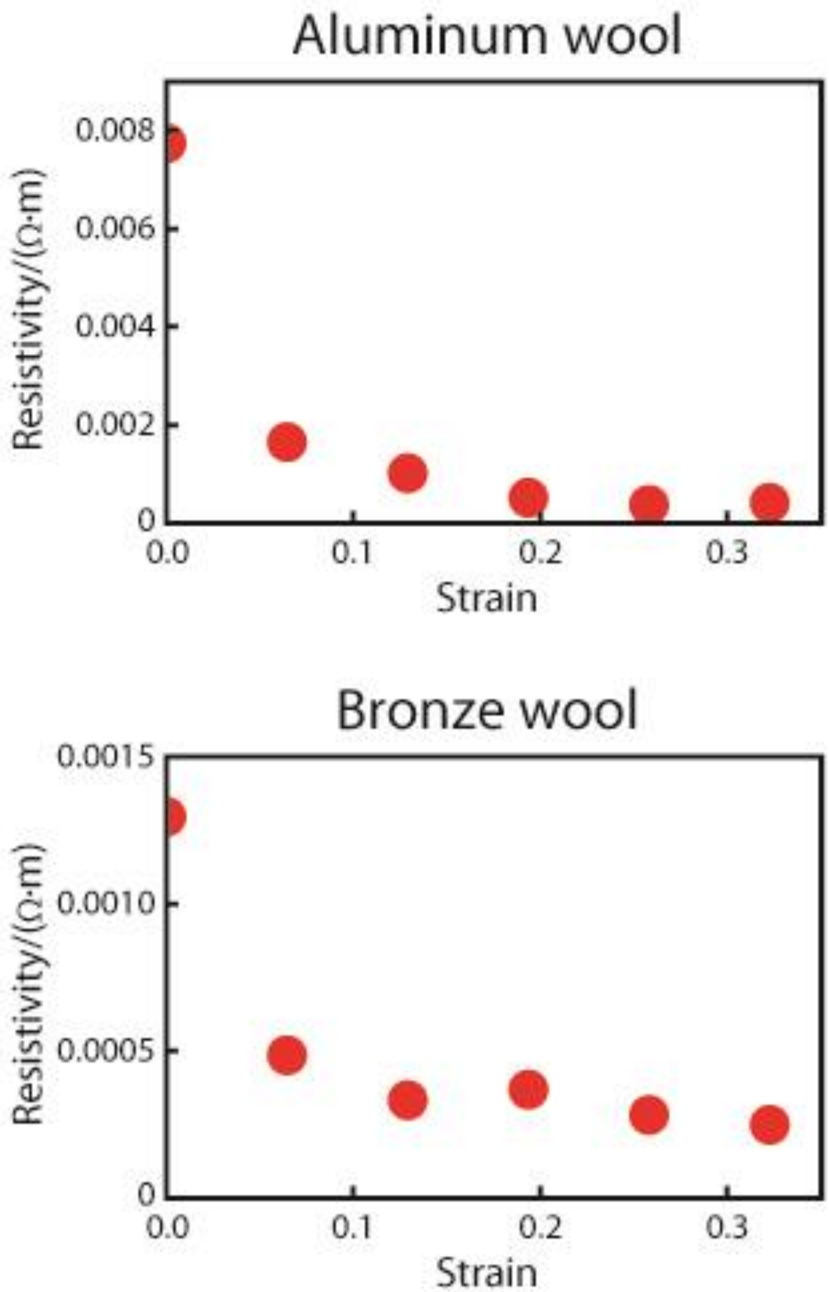

Figure S3. Resistivity Measurements. Plot of resistivity vs. strain for two representative CEC sheets made from aluminum wool (Top) and bronze wool (Bottom). The sheets were elongated in the direction perpendicular to the majority fiber axis as current was transmitted in the same direction as the elongation. Strain data is provided based on measurements of engineering strain.

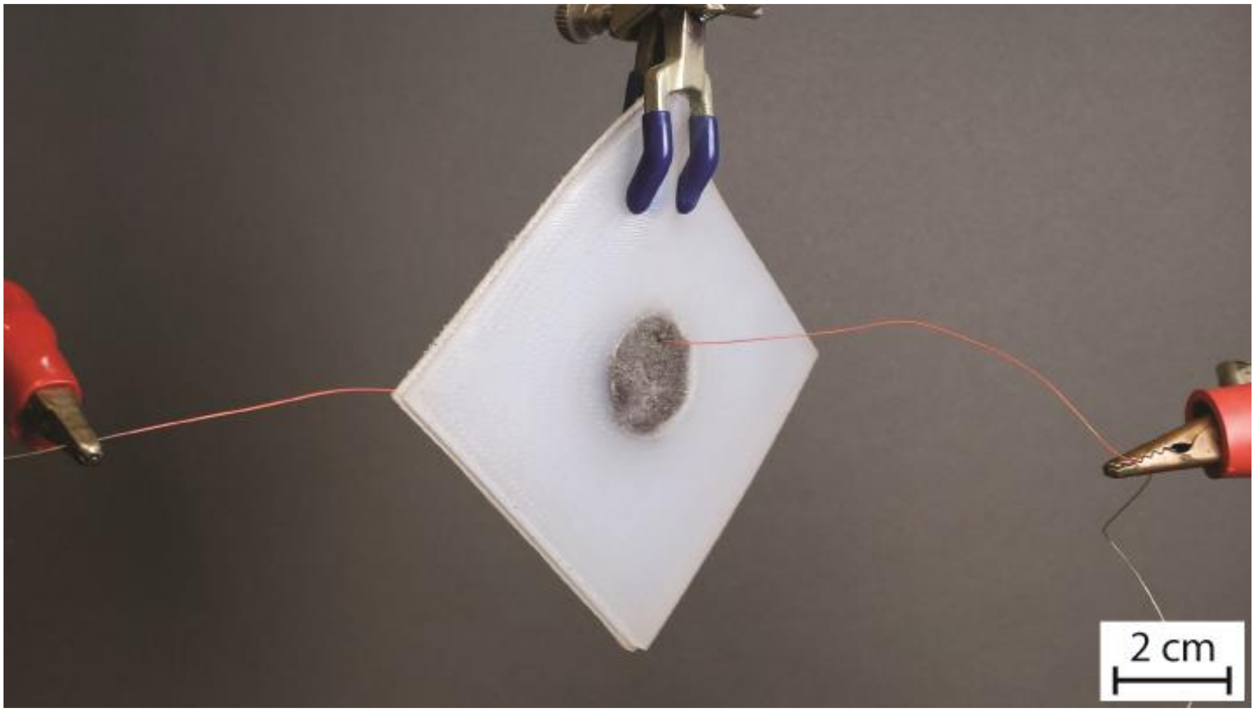

Figure S4. Creating a Conductive Path. Photograph of an elastomeric sheet with a disk shaped steel wool conductive CEC path at its center. For this demonstration, resistive nickel-chromium wires were inserted into the two opposing faces of the CEC to provide a visual indication of the flow of electrical current. The CEC is passing a current of 2.5 A across the elastomeric sheet as evidenced by the blackbody radiation being emitted from the wires used to supply and drain the current.

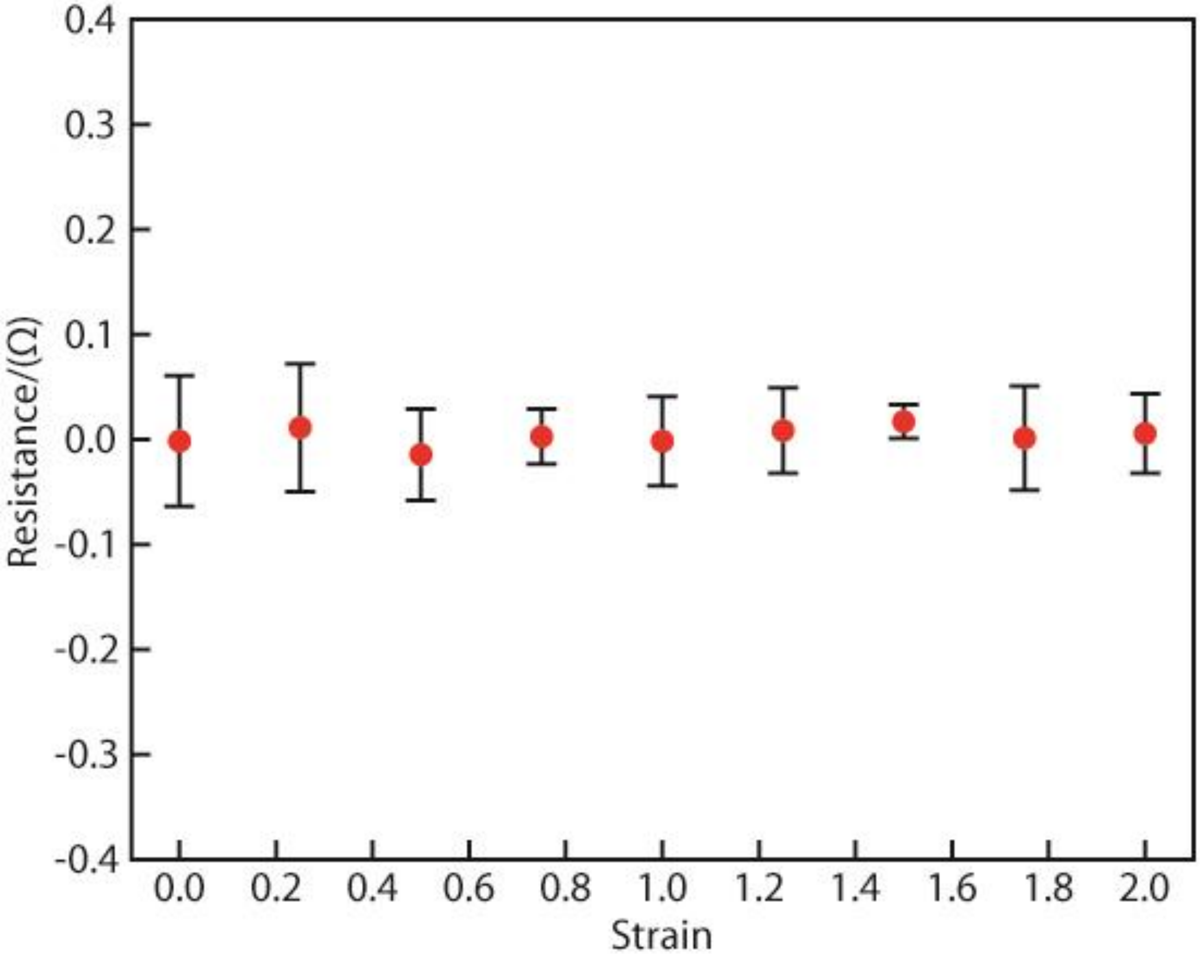

Figure S5. The Effect of Strain on the Resistance of a CEC Via. Plot of the average resistance (red dots) of n = 7 CEC disk shaped vias embedded in elastomeric sheets as the system was strained. Sheets were extended perpendicular to the majority fiber axis of the CEC disk and parallel to the long axis of the elastomeric sheet with a distance of 70 mm between the clamps. Samples were extended at a rate of 60 mm/min. Strain data is provided based on measurements of engineering strain. The standard deviation in resistance values is depicted by the bars associated with each red dot. Note some resistance values are reported as less than zero due to measurement errors induced by changes in the resistance of the electrical connections between the sample and the ohm meter over the course of the experiment.

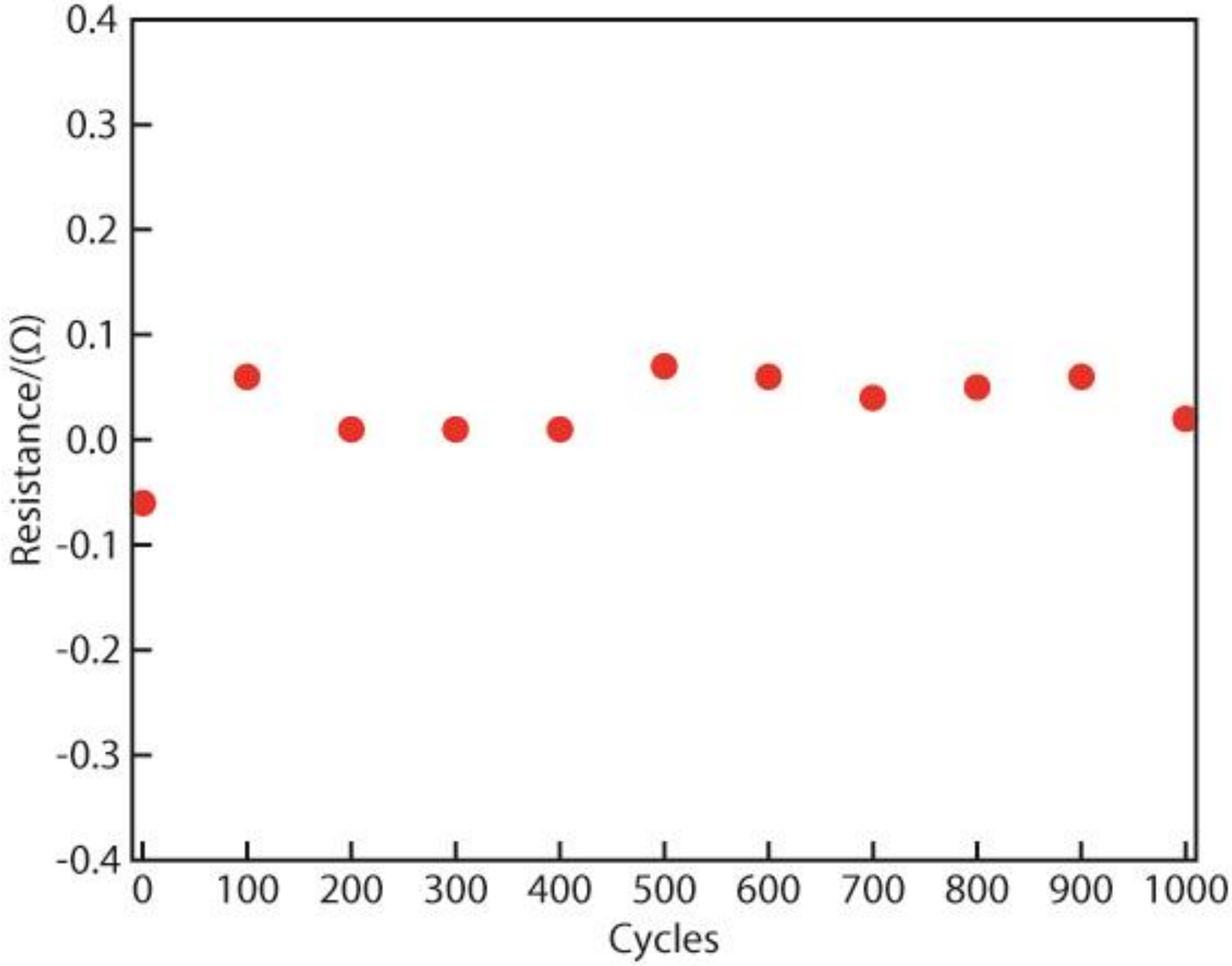

Figure S6. The Effect of Cyclic Fatigue on the Resistance of a CEC Via. Plot of the resistance (red dots) of a single CEC disk shaped via embedded in an elastomeric sheet as the system was cycled 1000 times to an elongation of 100%. The sheet was extended perpendicular to the majority fiber axis of the CEC disk and parallel to the long axis of the sheet with a distance of 70 mm between the clamps. The sample was cycled at a rate of 500 mm/min. Note some resistance values are reported as less than zero due to measurement errors induced by changes in the resistance of the electrical connections between the sample and the ohm meter over the course of the experiment.

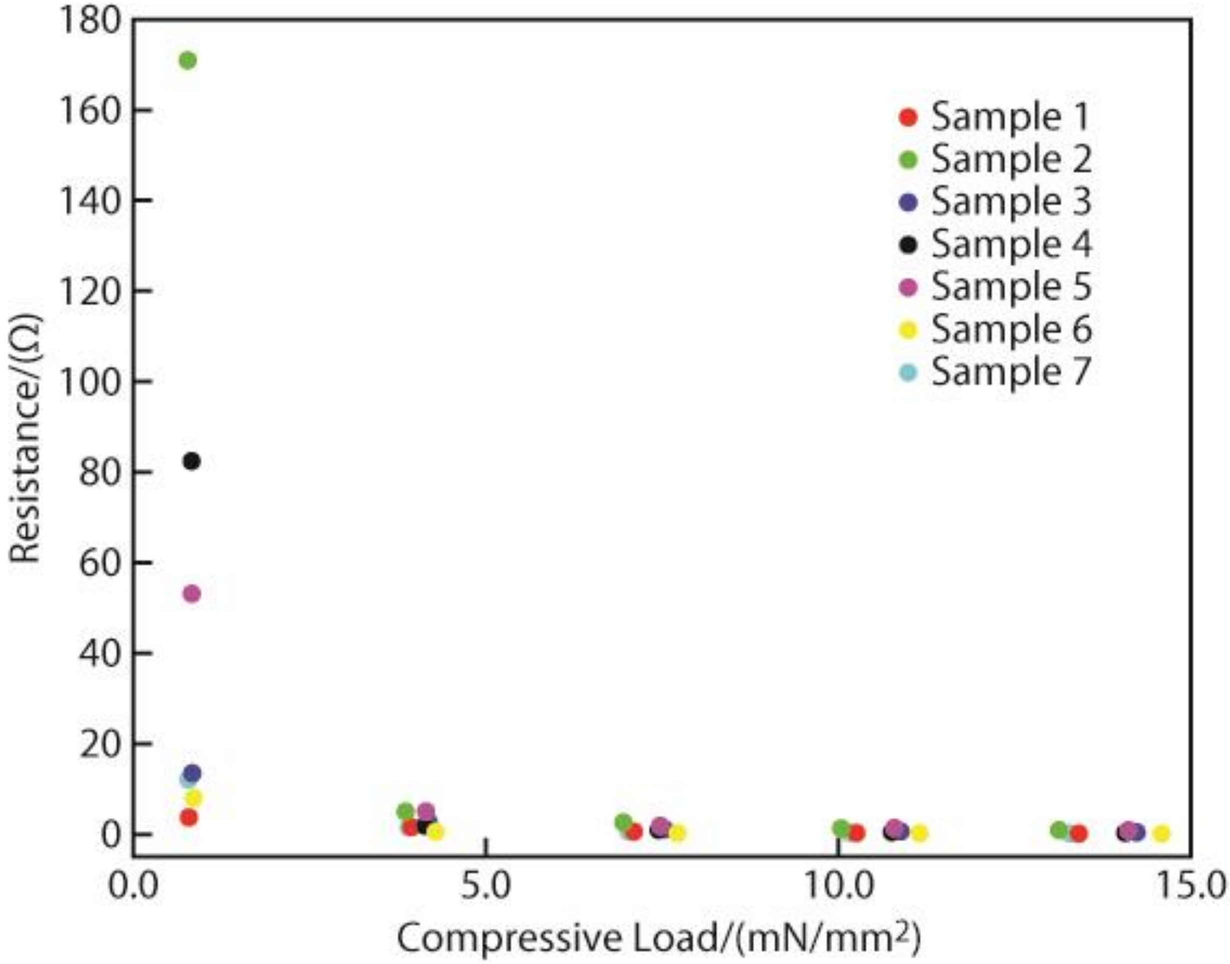

Figure S7. The Effect of Compression on the Resistance of a CEC Via. Plot of the resistance of n = 7 CEC disk shaped vias embedded in elastomeric sheets as a function of compression. Samples were compressed parallel to the majority fiber axis of the CEC disks and perpendicular to the long axis of the elastomeric sheets. The samples were compressed at a rate of 0.5 mm/min. Note some resistance values are reported as less than zero due to measurement errors induced by changes in the resistance of the electrical connections between the samples and the ohm meter over the course of the experiment.

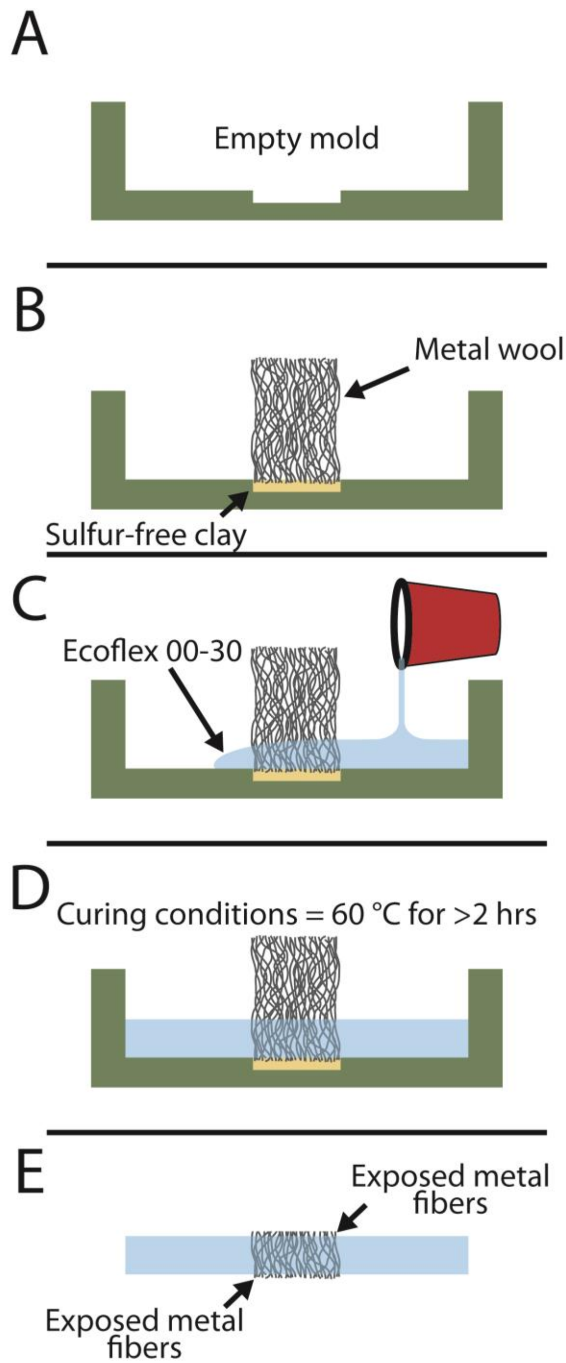

Figure S8. Fabrication of an Elastomeric Sheet with a CEC Path as used for Figures **S4**, **S5**, **S6**, and **S7**. (A) Illustration of the empty mold. (B) A steel wool slab was inserted into a clay filled recession at the center of the mold. The clay was used both to position the slab and to prevent coating of the end of the slab with elastomer. (C) Filling of the mold with uncured elastomer. (D) Curing of the elastomer. (E) Final elastomeric sheet with steel wool CEC path.

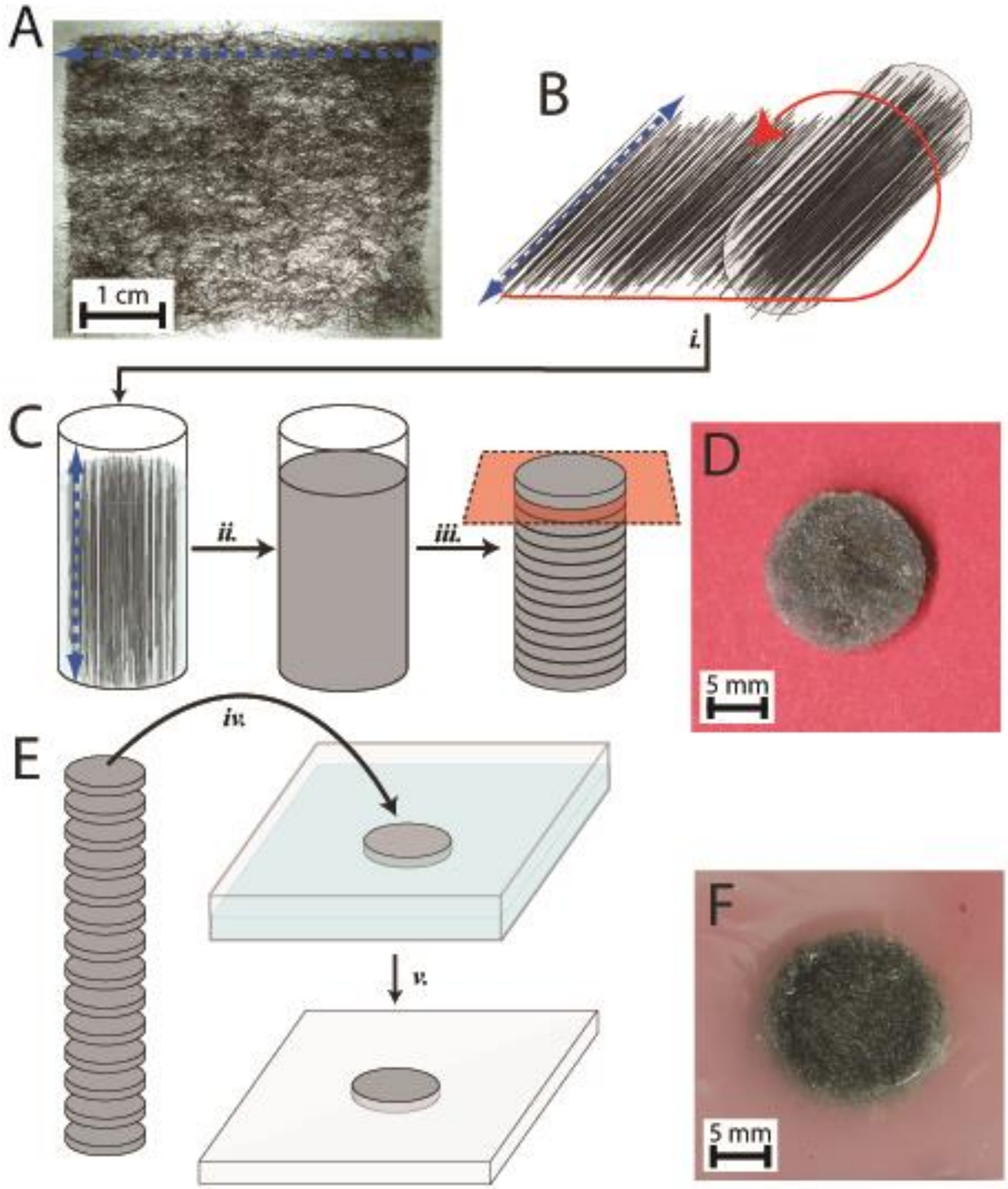

Figure S9. Fabrication and Embedding of Steel Wool CEC Disks in Elastomeric Films used for Figure 3. (A) Optical micrograph of steel wool. The blue dotted line shows the axis along which the majority of the fibers were oriented. (B) Schematic illustrating how the steel wool was rolled up. (C) The roll was placed into a cylindrical mold (*i.*) and impregnated with Ecoflex 00-30 that was cured at 80 °C for >40 min (*ii.*) and sectioned with a razor blade into disks (*iii.*). (D) A photograph of a CEC disk. (E) A disk was placed in a second mold (*iv.*) that was filled with Ecoflex 00-30 up to the top edge of the disk and cured at 80 °C for >40 min (*v.*). (F) The resulting CEC disk was embedded in an elastomeric film.

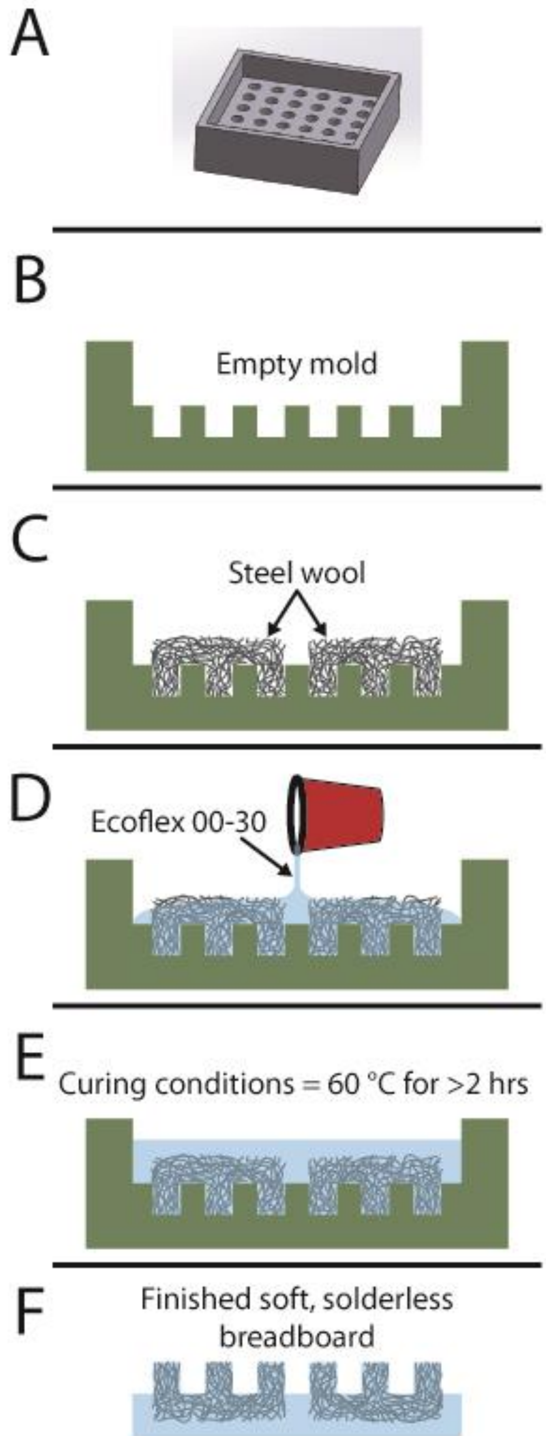

Figure S10. Fabrication of the Soft, Solderless Breadboard. (A) Perspective view of the mold. (B) Cross section of the mold before part fabrication. (C) Placement of steel wool to create conductive paths and connectors for electrical components. (D) Addition of uncured elastomer. (E) Curing of the elastomer. (F) Finished soft, solderless breadboard.

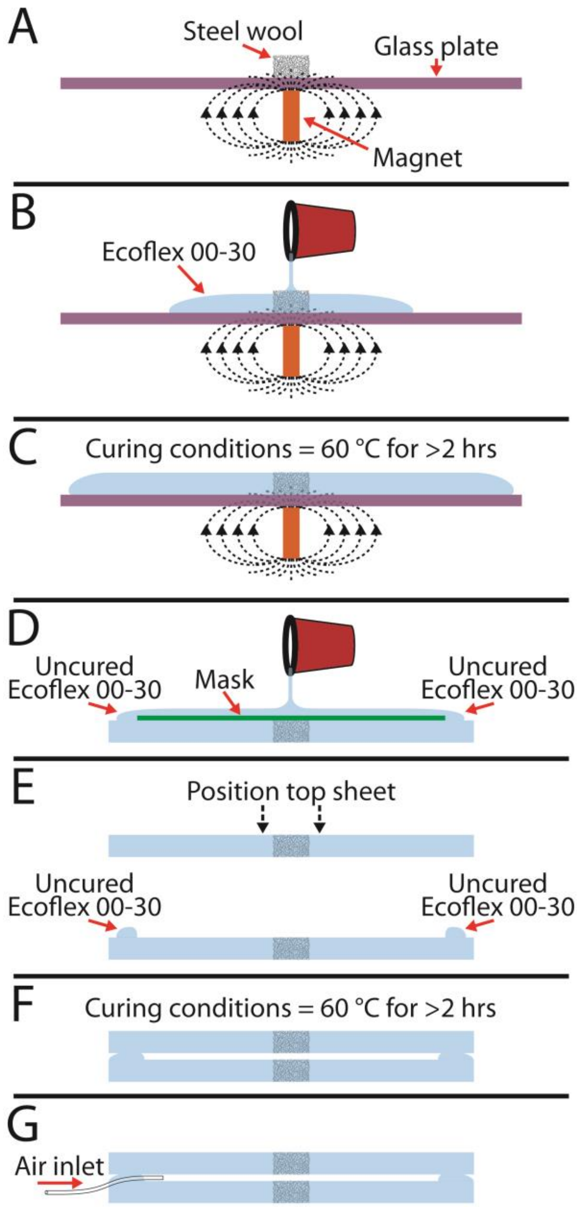

Figure S11. Fabrication of the Soft Touch Sensor. (A) Pinning of a steel wool pad to a glass plate with the aid of a magnet. (B) Addition of uncured elastomer. (C) Curing of the elastomer to create an elastomeric sheet with embedded CEC pad. (D) A square mask made from a plastic sheet was placed over a cured elastomeric sheet with embedded CEC pad and more uncured elastomer was added. (E) The mask was removed to reveal a square filament of uncured elastomer at the periphery of the sheet upon which a second elastomeric sheet with embedded CEC pad was placed. (F) The layered device was cured to make an air tight seal between the top and bottom sheet. (G) An air supply line was inserted between the sheets for device pressurization.

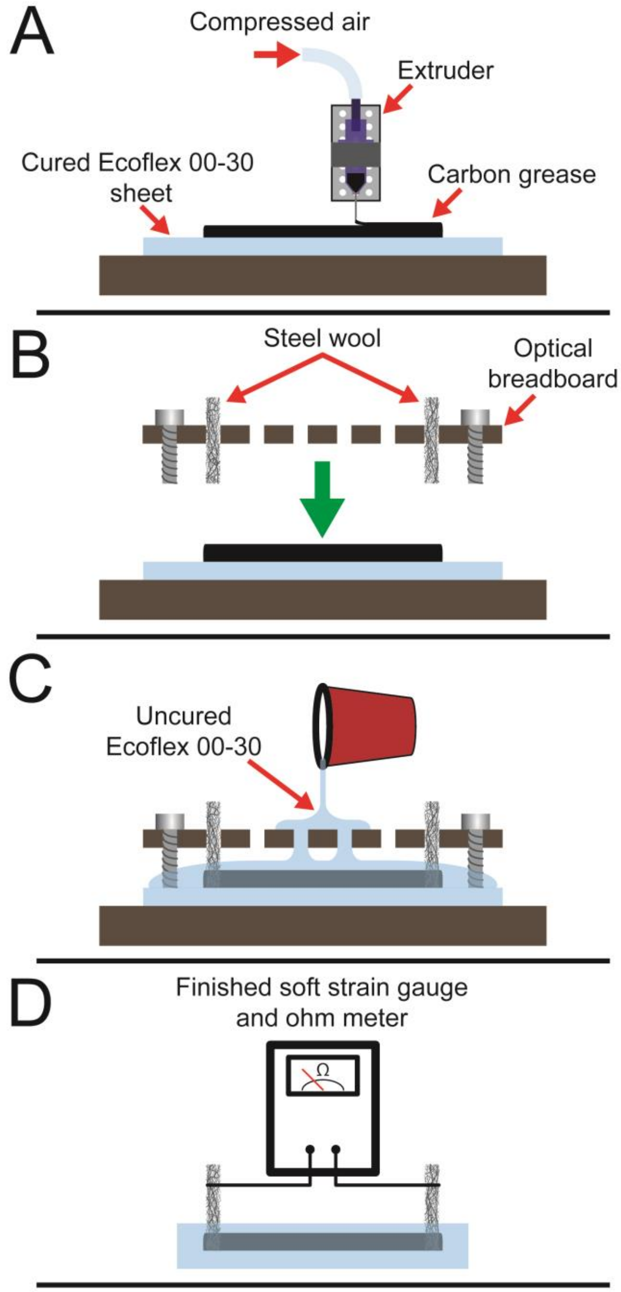

Figure S12. Fabrication of Leak-Resistant Electrical Connections for Embedded Carbon Grease Channels. (A) Layers of conductive carbon grease were deposited, via extrusion printing, on a sheet of Ecoflex 00-30 to form a linear filament of grease. (B) An optical breadboard, impregnated with steel wool fiber bundles and spacer bolts, was placed over the printed filament of grease mating the grease to the fiber bundles. (C) Uncured Ecoflex 00-30 was used to coat the grease filament and fix the position of the steel wool fiber bundles upon curing. (D) Finished sensor wired to an ohm meter.