Stretchable conductive fabric simplifies manufacturing of low-resistance dielectric-elastomer-system electrodes

*David P. Allen[1]
Sophie E. Farmer[2]
Robert D. Gregg[1,2]
*Walter Voit[1,2,3]

Departments of:
[1]Mechanical Engineering,
[2]Bioengineering,
[3]Materials Science and Engineering
The University of Texas at Dallas

*Corresponding authors:
david.allen@utdallas.edu,
walter.voit@utdallas.edu

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Abstract

We made low-resistance electrodes for a dielectric elastomer system (DES) without the use of thin film deposition or wet lab processes by utilizing a stretchable conductive fabric, Less EMF Stretch Conductive Fabric (SCF), for electrode material. Carbon-based DES electrodes are easy to make, but they have high resistances (kilo ohms) that hamper dynamic operation and reduce energy efficiency. Metal and hydrogel DES electrodes have much lower resistances (tens to hundreds of ohms), but they require complex manufacturing processes, such as thin film deposition or wet lab synthesis. Conductive fabrics can have low resistance and they can be made into DES electrodes with merely a laser cutter and a dry lab environment, but their stiffness may hinder DES performance. This work reports electrical and mechanical properties of SCF and a more compliant, though less conductive fabric, MedTex P70+B, and describes the assembly and performance of DES variable stiffness modules using them.

SCF had low sheet resistance, less than 3.0 ohm/square even during 125 % biaxial stretch, and both fabrics stretched beyond 200 % uniaxial elongation before mechanical failure. The assembly of modules with conductive fabric electrodes was comparable in terms of difficulty to that with carbon powder electrodes, and produced functional modules. However, the stiffness of the fabrics diminished DES stiffness-reduction performance to merely 12.8 % and 13.4 % compared to the 24.5 % stiffness reduction a DES module with carbon powder electrodes achieved. Future work should investigate or develop more compliant conductive fabrics that would yield greater DES performance.

Keywords: dielectric elastomer, conductive fabric, electrode, manufacturing, assembly, fabrication

1 Introduction

Dielectric elastomer systems (DESs) show great promise for actuation, energy harvesting, and sensing applications in robotics, MEMS, and biomimetic engineering fields[1,2]. A DES consists of a dielectric elastomer (typically as a thin film or sheet) coated on two opposite faces with stretchable electrodes[3]. For most applications, these electrodes must exhibit four characteristics. First, they must be stretchable, able to expand in length and area, because DESs expand and contract during operation (with more than 100 % elongation in some cases[4]). Second, DES electrodes should be mechanically compliant so as not to restrict DES motion. Third, they need low electrical resistance to improve the system's dynamic response[5] and energy efficiency. Fourth, DES electrodes should be easy to manufacture. Presently, many DES electrode technologies are stretchable and compliant, but none have both low resistance and simple manufacturing.

Carbon-based electrodes are popular in part because they are simple to manufacture[6], but they exhibit high resistances. They can be manufactured by smearing carbon powder or grease onto the surfaces of dielectric elastomers directly. Electrodes made from carbon rubber require curing after application, but they are resistant to abrasion unlike carbon powder and carbon grease electrodes. The conductivity of electrodes in this class depends on contact between carbon particles that are loose powders (carbon powder), suspended in a viscous liquid (carbon grease), or embedded in an elastomer matrix (carbon rubber). Accordingly, carbon based electrodes have high resistances that increase dramatically and nonlinearly as the electrodes stretch[7].

Thin-film metal electrodes are attractive because of their low electrical resistance, but they must be manufactured with complex methods to be stretchable and compliant. Though metals are not inherently stretchable, thin metal films can bend, so thin-film metal electrodes are made stretchable by deposition in special patterns[8,9], onto patterned elastomers[10,11], or onto stretched elastomers that subsequently relax, buckling the film[12]. These deposition methods complicate the manufacturing process and all of them require expensive equipment for vapor deposition, sputtering, e-beam evaporation, and/or photolithographic processes.

Liquid metal electrodes are inherently stretchable and compliant, and they conduct well[13]. The assembly process for these electrodes has been demonstrated preliminarily, but it requires polymer film deposition and still has challenges to overcome[14]. Further, the liquid must be encapsulated to prevent leakage, and the stiffness of the encapsulation hinders the electrode's compliance.

Hydrogel electrodes offer transparency in addition to low resistance[15], but are manufactured in a wet lab. Hydrogels consist of an elastomer matrix that is swelled with a liquid, which is an inherently compliant and stretchable combination. If that liquid contains ions, then the hydrogel will conduct electric charges readily. Manufacturing hydrogel electrodes requires synthesis of the hydrogel with wet lab processes[16]. The liquid in hydrogels tends to evaporate, so hydrogels must be kept moistened during operation, which may not be convenient in DES applications, and encapsulation of hydrogels to

prevent evaporation decreases their compliance. Further, hydrogel electrodes operate in fairly narrow thermal windows so they are only useful in specialized applications.

Other processes for making DES electrodes, such as implanting metallic nanoparticles[17], depositing ink with metal flakes[18], or synthesizing silver nanowire composites[19], also offer low resistance, but at the expense of complex and possibly expensive manufacturing processes.

Stretchable, conductive fabrics offer the possibility of simplified manufacturing of low-resistance DES electrodes. The other low-resistance electrodes mentioned above, which are based on metals and hydrogels, all require thin-film deposition or wet lab processing. In contrast, conductive fabrics are commercially available and merely need to be cut to shape and adhered in place, which can be done with machine shop equipment and a dry lab environment. Only the manufacturing of carbon powder and carbon grease electrodes can match this simplicity, but those electrodes have high sheet resistances. However, only limited electrical and mechanical specifications for conductive fabrics are available from manufacturers, so further investigation is needed to determine whether they are viable DES electrode materials. The compliance of these fabrics is a primary concern because insufficient compliance will hamper the performance of DESs. Also, the changes in sheet resistance as the fabrics stretch must be determined.

This paper presents two conductive fabrics, Less EMF Stretch Conductive Fabric (SCF), which is more conductive, and MedTex P70+B (P70), which is thinner and more compliant, and describes their incorporation into DES variable stiffness modules. We selected these fabrics because they were among the thinnest, stretchable conductive fabrics available, and we expected them to have better compliance than thicker conductive fabrics. After comparing the manufacturing of DESs with conductive fabric electrodes to that of DESs with carbon powder electrodes, this work reports the sheet resistances of both relaxed and stretched SCF, and the stretchability and compliance of SCF and P70. Finally, it compares both fabrics' performance in DES variable stiffness modules to that of carbon powder electrodes.

2 Experimental results

Three DES variable stiffness modules, each having SCF, P70, or carbon powder electrodes, were assembled in a dry lab environment using machine shop tools. After describing the assembly process, this section gives the results of the three set of experiments in this work. 1) The sheet resistance of SCF when both relaxed and biaxially stretched was measured with a four-point probe. 2) Strips of SCF and P70 were subjected to tensile testing in a universal testing machine. 3) The DES variable stiffness modules were subjected to tensile testing while at 0.0 kV and 6.0 kV. Additional details on the DES module assembly process, conductive fabrics, and the testing methods can be found in Section 5.

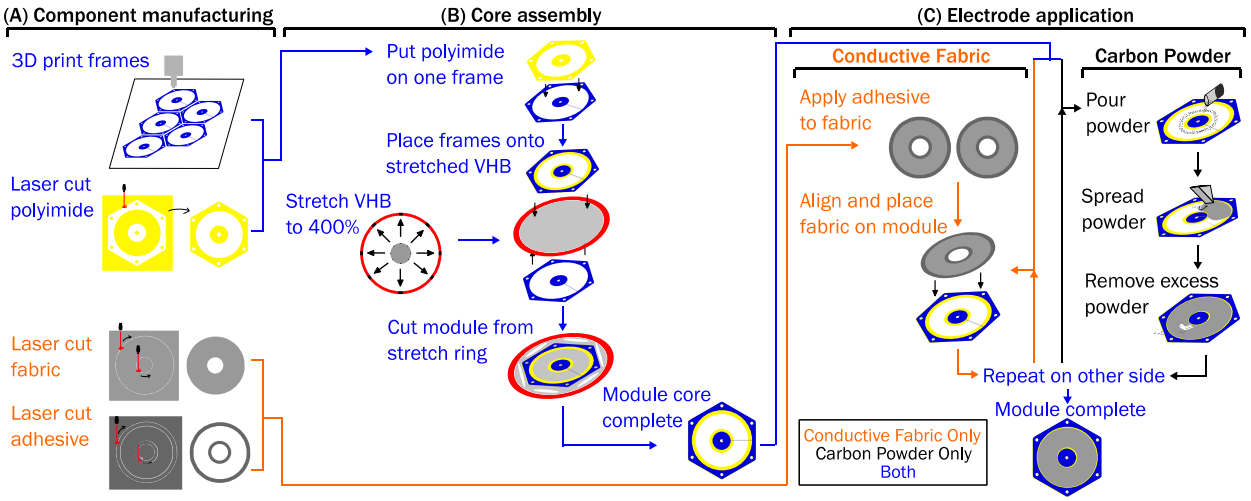

Figure 1: The assembly of DES modules with conductive fabric electrodes is comparable in terms of complexity to that with carbon powder electrodes as this assembly diagram shows. It requires merely shop tools that are much less expensive than advanced thin film deposition and semiconductor processing equipment, which are required for manufacturing some low resistance electrodes. The process also requires no wet lab synthesis or processing, so it can be performed in a relatively simple dry lab environment.

The manufacturing of DES variable stiffness modules was done in three phases: 1) component manufacturing, 2) core assembly, and 3) electrode application as depicted by Figure 1. Processes for the modules with conductive fabric electrodes are indicated by orange text and arrows, processes for the module with carbon powder electrodes by black, and processes for both types of modules by blue. Details of the individual processes are in the Experimental Methods section (Section 5) of the paper. The process for making conductive-fabric DES electrodes is straightforward and requires merely shop

Table 1: The sheet resistance of the Less EMF Stretch Conductive Fabric (SCF) decreased when the fabric was biaxially stretched. Measurements were made with a four-point probe on the top and bottom faces of three samples of SCF, in the machine and cross directions, at 100 % and 125 % biaxial stretch. The mean sheet resistance in the fabric's machine direction was less than and more sensitive to biaxial stretch than that in the cross direction.

	Sheet Resistance (Ω/□)				
	Machine		Cross		Direction
Sample	100	125	100	125	% Biaxial Stretch
Top face 1	1.81	1.11	2.01	1.65	
2	1.98	1.16	2.06	1.61	
3	2.46	1.32	2.66	1.93	
Bottom face 1	1.91	1.12	2.15	1.67	
2	1.76	1.22	2.07	1.62	
3	2.70	1.40	2.75	1.87	
Mean	**2.10**	**1.22**	**2.28**	**1.73**	

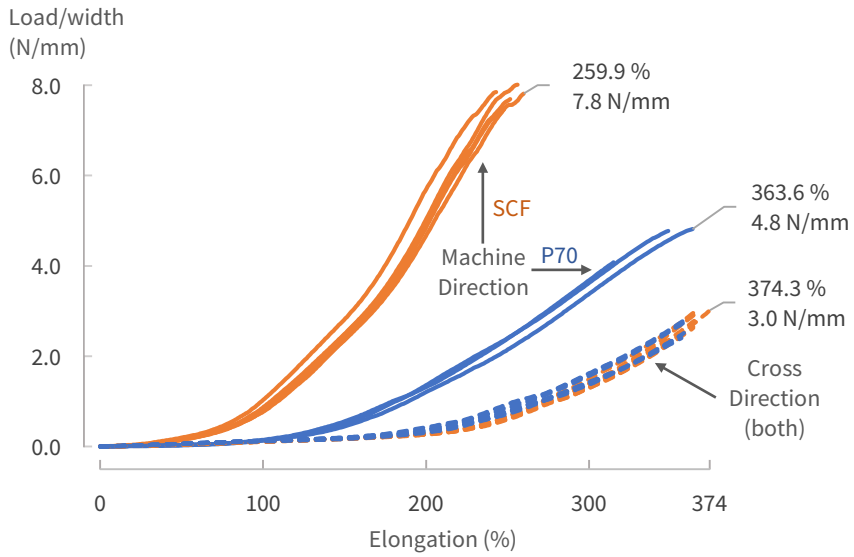

Figure 2: The tensile tests on the conductive fabric strips showed that both fabrics could elongate over 250 % in either direction. Load is normalized against fabric width (25 mm). In the machine direction, Less EMF SCF (SCF) was stiffer, and MedTex P70+B (P70) was more stretchable. Both fabrics performed nearly identically in the cross direction.

tools such as a laser cutter that are much less expensive than advanced thin film deposition and semiconductor processing equipment.

Sheet resistance measurements were made on three samples of SCF when they were relaxed and biaxially stretched 125 % (Table 1). Measurements were made on the top and bottom faces of the samples along the fabric's machine and cross directions. In all cases, sheet resistance was between 1.00 Ω/□ (ohms per square) and 3.00 Ω/□ and decreased with increasing biaxial stretch. The mean sheet resistances in the machine direction were lower than the corresponding values in the fabric's cross direction. Further, the mean sheet resistance in the machine direction dropped more with biaxial stretch than that of the cross direction.

Figure 2 depicts the results of the tensile tests conducted on strips of SCF and P70 fabric, which were 25 mm wide and cut in the machine and cross directions. Tensile test results typically have stress on the vertical axis, but because stress is actually carried by the individual fabric fibers, rather than the entire fabric cross section, we employ another normalized load measure for these results: load per fabric width (given in N/mm). Although this measure does not convey fundamental behavior, it is easily computed, and it is practical for this application because results can be compared between SCF and P70 and applied to other fabric widths.

All of the fabric strips cut in the machine direction broke at the edge of one of the grips, so if better protected from the grips, the strips might have been able to elongate more and bear more load than reported here. SCF elongated up to 260 % sustaining 7.8 N/mm before failure. P70 was more stretchable and compliant than SCF in the machine direction, reaching 364 % elongation before failing at 4.8 N/mm.

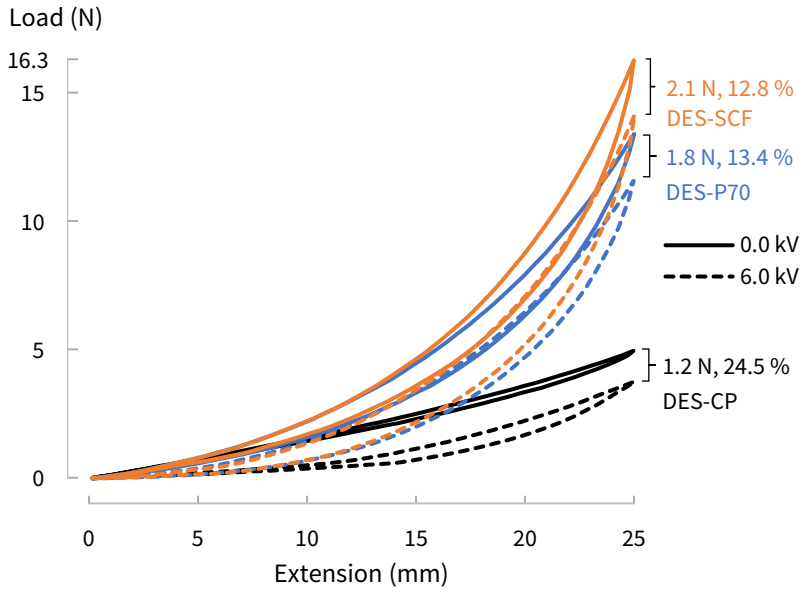

Figure 3: Tensile tests on DES modules showed that both of the modules with fabric electrodes were able to reduce their stiffness (defined as force/extension), but they reduced it proportionally less than the DES module with carbon powder electrodes did.

None of the fabric strips cut in the cross direction broke; they all stretched until the universal test machine reached its extension limit, and both fabrics behaved nearly identically in the cross direction. Maximum elongation was 374 % at 3.0 N/mm of load. The strips did not return to their original shapes after tension was released, so we infer that they exceeded their elastic limit.

Three DES variable stiffness modules, each having SCF, P70, or carbon powder electrodes (DES-SCF, DES-P70, and DES-CP respectively) were subjected to tensile tests while at 0.0 kV and 6.0 kV. The results of these tests (Figure 3) show that both of the modules using conductive fabric electrodes were able to reduce stiffness (defined as force/extension), dropping their force at max extension 2.1 N and 1.8 N for DES-SCF and DES-P70 respectively. These force drops were both greater than that of DES-CP, which only dropped 1.2 N at max extension. However, the fabrics nearly tripled the stiffness of the DES modules. This increase in stiffness diminished the relative stiffness reductions (the stiffness reduction divided by the original stiffness) to merely 12.8 % for DES-SCF and 13.4 % for DES-P70, compared to the 24.5 % achieved by DES-CP.

3 Discussion

Manufacturing conductive fabric electrodes was simpler than manufacturing other stretchable, low-resistance electrodes. It required no special equipment such as thin film deposition machines, no special environments like a wet lab or clean room, and no dedicated floor space. Compared to manufacturing carbon powder electrodes (as shown in Figure 1), manufacturing conductive fabric electrodes required additional laser cutting in the component manufacturing phase, but the electrode application phase was

more straight forward because it avoided the handling and spreading of loose carbon powder.

The conductive fabric electrodes were easy to operate, imposing no particular handling or operational difficulties during these tests. In contrast, carbon powder or grease electrodes are challenging to handle because the powder or grease will wipe off the DES.

SCF had low resistance, less than 3.00 Ω/□ of sheet resistance (as seen in Table 1), which is comparable to the resistances of other metallic DES electrodes. Although many types of DES electrodes increase resistance when stretched, the resistance of this fabric decreased under biaxial stretch (24.1 % in the cross direction and 41.9 % in the machine direction). Though stretching the fabric in one direction increases its sheet resistance, it appears that the decrease in sheet resistance due to stretching in the other direction outweighed the increase. The resistance of P70 was too high for our equipment to measure, and indeed the fabric is not marketed as conductive. Accordingly, though it conducted well enough to operate a DES, we cannot classify P70 electrodes as "low resistance."

The conductive fabrics were stretchable; they extended beyond 200 % elongation in both directions (and up to 374 % in the cross direction) before mechanical failure in the fabric strip tensile tests (shown in Figure 2). However, an electrode made from one of these fabrics could not repeatedly attain such elongation in practice because it would exceed the elastic limit of the fabric. A conductive fabric electrode that stretched that far would not return to its original shape, and may not be usable. Further testing is needed to find the usable elongation range of these materials, but the increases of slope in Figure 3 suggest that it may be near 60 % and 110 % elongation for the machine directions of SCF and P70 respectively, and near 200 % elongation for the cross direction of both fabrics. Manufacturer data for SCF in Table 2 states that SCF can elongate up to 100 % in the machine direction and up to 65 % in the cross direction.

The DES module tensile tests demonstrated that the conductive fabrics worked: the modules with conductive fabric electrodes softened when they were charged. This stiffness change is equivalent to actuation performance. A DES variable stiffness module becomes an actuator once subjected to an appropriate biasing force[20]. Softening the module causes actuation in the direction of the biasing force, and greater softening corresponds to greater actuation.

Although the compliance of these conductive fabrics was not so small as to prevent DES operation entirely, it hindered it greatly in this application, nearly halving the stiffness reduction achieved by DES-SCF and DES-P70 compared to that of DES-CP. DES-P70, which used the thinner, more compliant fabric, achieved a greater stiffness reduction than DES-SCF, which indicates a logical direction for further development. It may be possible to metallize thinner, more compliant fabrics that would yield greater DES performance and future work should investigate this possibility.

4 Conclusion

Until now, all low resistance DES electrodes, such as hydrogels and metal films, required complex manufacturing processes such as wet lab synthesis or thin film deposition. We made low-resistance electrodes for a DES variable stiffness module using merely shop tools in a dry lab environment by utilizing SCF for electrode material. Our measurements showed that SCF had less than 3.00 Ω/□ of sheet resistance even when it was biaxially stretched 125 %, and its sheet resistance decreased under biaxial stretch. Tensile tests demonstrated the stretchability of SCF and P70 and showed that P70 is more compliant than SCF. The DES variable stiffness modules that had electrodes made from these fabrics worked, reducing stiffness when charged to 6.0 kV. This result shows that conductive fabrics could be used to make dielectric elastomer actuators because a DES variable stiffness module becomes a dielectric elastomer actuator when it is subjected to a biasing force. However, the DES modules with conductive fabric electrodes did not perform as well as a DES module with carbon powder electrodes, reducing stiffness 12.8 % and 13.4 % compared to 24.5 %.

Conductive fabrics simplify the process of manufacturing low-resistance DES electrodes, which improve DES dynamic response and energy efficiency. This manufacturing advance brings practical DES devices a little closer to real world use in robotics and other fields. However, conductive fabrics lack the compliance necessary for high-performance DES devices as this work showed. Future work should attempt to metallize thinner, more compliant, stretchable fabrics, that could yield low-resistance DES electrodes suitable for high performance applications.

5 Experimental methods

We assembled DES variable stiffness modules to test the effectiveness of the conductive fabrics as DES electrodes and to investigate how conductive fabric electrodes affected the modules' assembly process. After explaining the basic design and function of the DES modules, this section will explain their assembly process, which is divided into component manufacturing, core assembly, and electrode application with both carbon powder and conductive fabric. Then, this section will explain the methods of the three groups of experiments in this work. In the sheet resistance tests, the sheet resistance of one conductive fabric in stretched and relaxed states was measured by a four-point probe. In the fabric tensile tests, a universal test machine tested strips of conductive fabric to determine their elongation and compliance. In the DES module tensile tests, a universal test machine tested DES modules to determine their stiffness reduction performance.

5.1 DES variable stiffness module preparation

The DES diaphragm design used in this work (Figure 4) is well known in the DES community, and was previously used for variable stiffness[21,22]. The module's diaphragm is a circular layer of VHB 4910 acrylic tape, stretched to 400 % of its original diameter. This double-sided tape adheres to the (comparatively) rigid ABS (Stratasys ABS-M30)

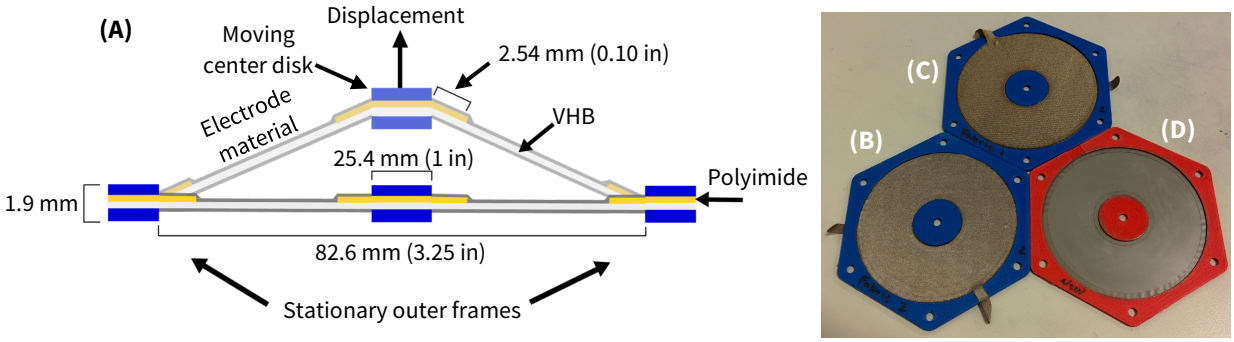

Figure 4: We assembled DES variable stiffness modules with conductive fabric electrodes and carbon powder electrodes for a performance comparison. (**A**) The center disk of the diaphragm deflects out of plane like the motion of a speaker cone. Picture of completed modules with (**B**) Less EMF SCF, (**C**) MedTex P70+B, and (**D**) carbon powder electrodes.

frame that maintains the tension of the diaphragm. 76.2 µm (3 mil) thick polyimide tape lines the inner and outer edges of the diaphragm providing reinforcement against the mechanical stress and electrical field concentrations there. The electrodes cover the upper and lower surfaces of the diaphragm. The adhesive surface of the VHB diaphragm holds carbon powder in place. It adheres to the conductive fabrics but not well enough to hold them in place during large displacements. Accordingly, an additional double-sided adhesive (Adhesives Research 8932EE, not shown in Figure 4) holds the edges of conductive fabric electrodes in place.

The DES module manufacturing process starts with the manufacture of module components (Figure 1A). This phase of the process can be done in large batches to leverage economies of scale. The polyimide tape is cut to shape with a laser cutter, and the module frames and center disks are printed from ABS-M30 by a Stratasys Fortus 400mc 3D printer. These components will be used in the core assembly stage regardless of which electrode will be applied later. Conductive fabric electrodes require additional laser cutting of the conductive fabric itself and the adhesive used to adhere it to the VHB elastomer diaphragm.

The core assembly process (Figure 1B) is the same for both electrode materials and is done by hand. After its backing is removed, polyimide tape is adhered to one frame and center disk. The VHB elastomer is marked with a circular stencil and then stretched until the markings on the elastomer align with the stretching ring. The elastomer is adhered to the ring with the marked region having 400 % of its original diameter. Both frames and center disks are then adhered to the stretched VHB elastomer. The module is cut away from the stretching ring, and excess elastomer is trimmed from its outer edges resulting in a complete module core. The module core will then be given either carbon powder electrodes or conductive fabric electrodes.

5.2 Carbon powder electrode application

Carbon powder electrode application (Figure 1C) is done by hand in three steps. The powder (graphite nanopowder, US Research Nanomaterials #US1058 in this work) is poured onto one surface of the VHB elastomer between the center disk and outer frame.

A soft applicator spreads the powder over the surface covering all of the VHB elastomer and polyimide tape thoroughly. Excess powder is first dumped off the module and then the remainder is blown off. These three steps are repeated on the other side of the module. Modules with carbon powder electrodes are complete when both sides are evenly coated with carbon powder and cleared of any excess. This phase of the assembly takes 7–10 minutes.

The application of carbon powder electrodes in this manner has two challenges. The first challenge is keeping the workstation and worker clean because the loose carbon powder tends to spread, stain, and contaminate the workspace. The second challenge is coating the diaphragm with a uniform layer of carbon powder. Non-uniform coatings may cause electric field concentrations that cause premature module failure. The care taken during the coating process to produce uniform coatings and avoid spreading carbon powder onto the work surface slows the process.

5.3 Conductive fabric electrode application

Conductive fabric electrode application (Figure 1C) is done by hand in two steps. The backing from one side of the adhesive rings is removed and they are then adhered to the edges of the conductive fabric electrodes. The remaining backing is removed from the adhesive on one electrode, and this electrode is applied to the elastomer diaphragm so that it covers the VHB elastomer and polyimide tape. This step is repeated on the other side of the module, and then the module is complete. The application of conductive fabric electrodes takes 5–7 minutes.

The application of conductive fabric electrodes does not present the challenges that carbon powder electrode application does. The conductive fabric application process does not require any special measures for cleanliness, and it produces a uniform coating. These advantages counter balance the extra time and effort consumed during the component manufacturing stage for additional laser cutting.

We utilized two fabrics for making electrodes in this work: Stretch Conductive Fabric (SCF) from Less EMF Inc. (catalog #A321) and MedTex P70+B (P70) from Shieldex. Table 2 gives the manufacturers' specifications for these two fabrics. Because these fabrics have anisotropic properties due to their construction, this work describes their properties in terms of machine and cross directions, and top and bottom surfaces. The cross direction is parallel to the width of a rolled bolt of fabric, and the machine direction runs along the length of the unrolled fabric, perpendicular to the cross direction. The cross and machine directions are parallel to the weft and warp of the fabric respectively. The "top" of a fabric is the surface that is exposed on the outside of a roll, and the bottom is that on the inside of the roll. The sheet resistance of a fabric is given in ohms per square (Ω/□), which is the resistance that would be measured between two bar contacts of equal length contacting the fabric parallel to each other separated by a distance equal to their length.

SCF is a blend of nylon and elastic fibers (composition not specified) coated with silver that stretches in both machine and cross directions. The manufacturer specifies a

Table 2: Manufacturer's specifications for the two fabrics studied in this work: Less EMF stretch conductive fabric (SCF), and MedTex P70+B (P70). Both fabrics are stretchable, silver-coated, nylon blends, but only SCF is advertised as conductive. P70 is advertised as an antibacterial fabric for medical use.

Parameters	SCF	P70
Sheet resistance (Ω/□)	< 1	
Elongation		
Machine	100 %	
Cross	65 %	
Composition		
Nylon (%)	76	79
Elastane/Other (%)	24	21
Thickness (mm)	0.40	0.35
Weight (g/m^2)	150	91
Operating temp. (°C)	−30–90	−30–90

maximum sheet resistance of 1 Ω/□ and indicates that sheet resistance increases when the fabric is stretched in one direction and decreases when the fabric is stretched in the other direction. The manufacturer suggests that it can be used for an antibacterial wound dressing (though it is not sterile) or for electrically shielding clothing. The silver coating can be damaged by some chemicals, particularly sulfur, fluorides, and water with low pH.

P70 is a nylon/elastane blend. It is coated with silver to give it antibacterial properties and polyurethane to reduce tarnishing. The manufacturer does not specify that the fabric is conductive or recommend it be used for electrical or shielding applications.

5.4 Sheet resistance tests on SCF

Electrodes for DES's must remain conductive as they stretch. Because the manufacturers of the conductive fabrics studied here did not supply resistance data for the fabrics when stretched, we gathered this data ourselves. To do so, we conducted a four-point probe sheet resistance test on biaxially-stretched fabric as suggested by Carpi et. al.[23]

We made our own four-point probe (Figure 5A) with the probes spaced far enough apart that it captured properties of the fabric rather than individual fibers (dimensions in Figure 5B). A Volteq HY3003D-3 power supply supplied current to the outer two probes, which were aluminum plates that each contacted the fabric on an edge of 25 mm width. The inner two probes had pointed tips, and they were connected to a Hewlett Packard 34401A multimeter that measured the voltage drop between them. A 3D printed structure held the probes in place with the dimensions shown in Figure 5B.

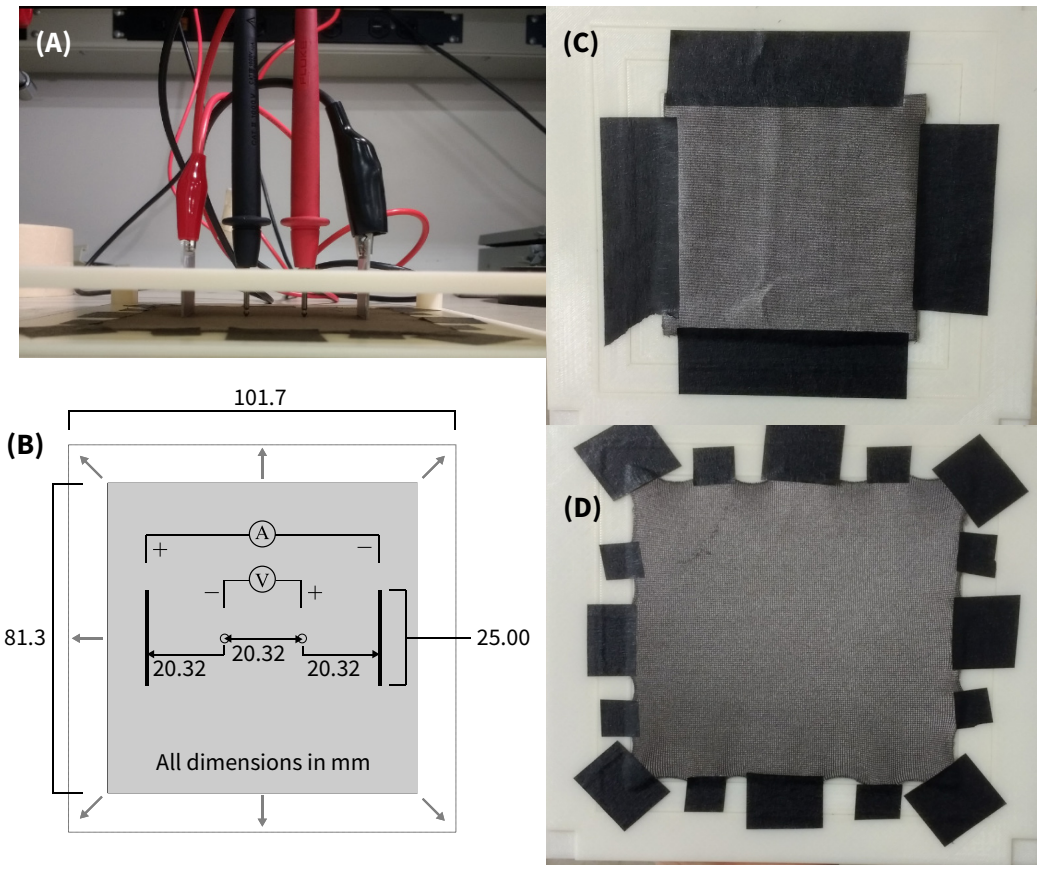

Figure 5: We built a four-point probe with large probe spacing to measure the sheet resistance of the conductive fabric. (**A**) Our four-point probe with a fabric sample, (**B**) Dimensions of the probe's electrodes and the samples, (**C**) A conductive fabric sample taped in place with no stretch, (**D**) A conductive fabric sample taped in place with 125 % biaxial stretch.

The samples were supported by a 3D printed base. All 3D printed parts were made with Stratasys ABS-M30.

To run the experiments, an 81.3 mm × 81.3 mm piece of fabric was taped to the base of the probe holder aligned with the holder's guide lines (Figure 5C). Then the top of the probe holder was put in place so that the probes contacted the fabric and ran in the machine direction. Next, the power supply was placed into current mode and adjusted so that it supplied 0.1 A. After a 30 s delay to allow the voltage to stabilize, the voltage drop was read from the multimeter. Eight of these measurements were obtained from each sample: the voltage drops on the top and bottom surfaces, in the machine and cross directions, with the sample relaxed and stretched. When stretched, the samples were stretched 125 % in length and width (Figure 5D). Three samples of SCF were tested in this manner. The power supply's maximum voltage was 40 V, and this voltage was insufficient to drive 0.1 A through P70, so the sheet resistance of this fabric was not tested.

Once we had the voltage values from the four-point probe, we used them to calculate the sheet resistance of the fabric. When the probes are equally spaced, the film thickness is less than 40 % of the probe spacing, and the film's edges are more than four times the probe spacing distance away from the probes, the film's sheet resistance, R_s, is given by

$$R_s = 4.53\frac{V}{I},$$

where I is the current through the sample, and V is the measured voltage[24].

5.5 Tensile tests on fabric strips and DES modules

We conducted two sets of tensile tests in this work. The first set stretched strips of conductive fabric to determine the fabrics' compliances and maximum elongations. The second set measured the force-displacement relationship for DES modules to determine their stiffness drop when charged. All of these tests were performed using a Lloyd LR5k universal test machine.

The fabric strip tests were conducted according to strip test 1C-E from the ASTM D5035 standard[25] at standard conditions. Thirteen 150 mm × 25 mm strips were cut from both fabrics, eight to measure behavior in the cross direction, and five to measure in the machine direction. The strips were covered with VHB 4910 adhesive tape on their clamped areas to protect them from the universal test machine grips. The ends of the strips were clamped in the tensile tester with 75 mm of free fabric between the grips and no pre-tension. The tests were performed at a constant speed of 5 mm/s until the fabric broke or the universal test machine reached its extension limit.

Individual DES variable stiffness modules were attached to the universal test machine with custom 3D-printed mounts. They were stretched at a constant speed of 1 mm/s for three cycles of zero to 25 mm to zero displacement. Due to viscoelasticity, the first two cycles were preconditioning cycles to allow the modules to settle to a steady behavior. The data from the third cycle is reported in Figure 3. Each module was tested at 0.0 kV and 6.0 kV. The voltage was supplied by a Matsusada EQ-30P1 high voltage power supply.

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