Dielectric elastomers actuators are compliant capacitors which can convert electrical energy into mechanical energy [1]. The simplest device consists of a thin elastomer sheet sandwiched between two compliant electrodes. In actuation mode, a voltage is applied to the electrodes and the attractive Coulombic force between the opposing charges squeezes the elastomer causing it to expand perpendicular to the applied electric field. Since they are electrically driven, the response speed of DEAs is usually limited by the viscoelastic response of the constituent polymer.

In terms of ease of delivering power, as well as response speed, DEAs are some of the most promising technologies for the emerging field of soft robotics [2]. However, existing DEA technologies are severely limited in three key areas. First, most elastomers require some amount of mechanical pre-strain in order to achieve large deformation. Typically the strain is maintained by application of a rigid frame that improves the performance of the elastomer, but negates most of the benefits associated with a soft, compliant actuator. Second, the fields required for actuation are high, in the 20-200 V/micron range, causing the actuation voltage to be relatively high (3 - 20 kV). While the DEAs themselves require low power inputs, the high voltage requirement greatly limits where DEAs can be used and how portable they can be, since high voltage power supplies are generally bulky and heavy. Third, since DEAs are compliant capacitors, the strain in the electrodes has to match the strain in the elastomer. There are extremely few materials which can conduct electricity, bond well to an elastomer, not add any significant stiffness to the substrate, and survive many repeated actuation cycles.

From the onset, I approached the problem with the goal of making dielectric elastomer actuators into artificial muscles more suitable for soft robots. The major impediment is the need for pre-strain and subsequent use of a rigid frame. To avoid the pre-strain while preventing electromechanical instabilities, I built upon earlier work from Prof. Pei's group at UCLA [3] and expanded the library of useful polymers to include materials that were less viscoelastic. The most suitable elastomers I found were liquid acrylic oligomers which cure under UV light. As a liquid, the material can be spin coated to the desired thickness, in repeated fashion, to create a multilayer device. Each constituent layer is thin, and, at constant field, needs a small applied voltage to actuate. However, most electrode materials are not compatible with this fabrication method, because they bond poorly to the elastomer. Without a strong bond, the electrode delaminates from the elastomer before the next layer is formed. The other extreme is undesirable as well: electrodes that bond very strongly to the elastomer require high energy input to deform, and increase the voltage requirement.

To solve the electrode compatibility problem I looked towards transparent DEA devices, such as tunable soft lenses developed in the Clarke research group [4]. The transparent electrodes used single wall carbon nanotubes (SWCNTs) in minuscule quantities (~ 10 mg/m^2) to create an ultra thin conductive layer on the surface of the elastomer. The SWCNTs have a unique aspect ratio, as thin, long fibers, and can form percolative networks that stay conductive even when the substrate is stretched. Most appealing, in a percolative network a large area of the underlying elastomer is not covered, and that polymer can form strong bonds to the adjacent elastomer layers. While the elastomer and electrode are individually compelling materials, their combination makes them uniquely suitable for DEA powered soft robotics.

My work was well received by both the Materials Science community, as well as the Robotics community. The initial demonstration focused on a presenting a clear and concise method, as well as a library of materials [5]. One of the biggest downsides of acrylic elastomers is the slow response of the material due to viscoelasticity. I was able to improve on the state of the art by finding a material that responds thirty times faster that state of the art. The novel elastomers have a response speed on par with human muscle. Once the method and material workspace were established, I shifted my focus to demonstrations of artificial muscle capability.

DEA powered robots tend to occupy one of two extremes: either very large systems that can carry their own power supply [6] or small systems that are primarily made from rigid components [7]. Meanwhile, soft robots powered by other means, such as using compressed air to drive pneumatic actuators, move relatively slowly, at less than a tenth of a body length per second. To show the unique potential of our combination of materials I focused on crawling locomotion in an inchworm inspired robot. The most challenging aspects were the small size (centimeter scale), the requirement to keep the robot primarily soft and the push for high speed movement. Using a combination of polyurethane and acrylic elastomers, I built a high speed, primarily soft inchworm inspired robot [8]. My robot was capable of moving at almost one body length per second, on par with natural systems and an order of magnitude faster than comparable robotic systems.

I plan to continue to focus on soft robotic demonstrations as part of my PhD work, while also evaluating other applications, such as biomedical applications, haptics, wearable devices, and energy harvesting for future work in academia. The high voltage requirement of dielectric elastomers makes untethered robots extremely challenging, because high voltage power supplies are generally bulky. By focusing on materials that can be made thinner or by boosting the dielectric constant, the robot can be powered by a lower voltage, opening the space of available miniaturized electronics. Smaller robots have enormous potential in biomedical applications, exploration or swarm systems. The two dimensional character of the multilayers makes them inherently suitable for low profile, wearable actuator or sensing devices. There the challenge lies with increasing the bandwidth to match what human mechanoreceptors can detect. Finally, as dielectric elastomers are transducers, given a mechanical input they would be able to convert it into electrical power. Tough, resilient elastomers could then be deployed in environments rich in mechanical energy, such as in wave harvesting systems, to produce renewable energy. I strongly believe that the key to broader adoption of dielectric elastomers lies with expanding the range of useful materials to make stronger, faster, more adaptable artificial muscles and using them to improve the quality of human life.

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List of publications authored while supported by the Link Foundation Fellowship:

1. Duduta, Mihai, R. Wood, and D. Clarke. "Flexible, stretchable electroadhesives based on acrylic elastomers." Proc. SPIE. Vol. 9798. 2016.
2. Duduta, Mihai, Robert J. Wood, and David R. Clarke. "Multilayer dielectric elastomers for fast, programmable actuation without prestretch." Advanced Materials 28.36 (2016): 8058-8063.
3. M. Duduta, D. R. Clarke, R. J. Wood, “A high speed soft robot based on dielectric elastomer actuators”, International Conference on Robotics and Automation ICRA, Singapore, (2017).
4. E. Hajiesmaili, M. Duduta, D. R. Clarke, “Shape-morphing dielectric elastomer actuators using inhomogeneous electric field”, Society of Engineering Sciences 54th Annual Technical Meeting, 2017.
5. M. Duduta, E. Hajiesmaili, K. Cheng, R. J. Wood and D. R. Clarke, “Graphene Based Hybrid Electrodes for Multilayered Dielectric Elastomer Actuators”, Materials Research Society Meeting, Boston, 2017 - submitted.

The support of the Link Foundation helped me focus on teaching and consolidated my interest in pursuing a career in academia. At Harvard's School of Engineering and Applied Science I was fortunate to have three distinct teaching experiences. In consecutive semesters I was a teaching assistant for a very large undergraduate course: *Science and Cooking*, then for my advisor's *Introduction to Heat Transfer*, and lastly a head teaching fellow for *Science and Cooking*. The three teaching opportunities came with very different expectations. As a TA for Science and Cooking my main role was to keep an laboratory section interesting and safe for students so good verbal communication, quick thinking and a friendly approach were paramount. My hard work paid off, and I earned one of the highest scores for a teaching assistant at Harvard that semester and a Derek Bok Center Excellence in Teaching Award. Working with Prof. Clarke on a smaller, engineering focused class, I was expected to hold a weekly recitation primarily aimed at helping students with their problem sets. The most rewarding part of teaching a class for engineering majors was getting to answer their deeper scientific questions, often going beyond the scope of the class. Lastly, as a head teaching fellow returning to *Science and Cooking*, my main challenges were logistical: I had to prepare homework and exam questions, help organize laboratory sections, coordinate guest lectures from famous chefs and even respond to unusual circumstances, such as a bomb threat. I found the role to be less exciting because there were fewer direct interactions with students and most were heavily focused on grades and performance. Still, being the primary resource for a class for more than one hundred and fifty students was gratifying and excellent preparation for running my own class one day.