A soft and dexterous motor

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We present a soft, bearing-free artificial muscle motor that cannot only turn a shaft but also grip and reposition it through a flexible gear. The bearing-free operation provides a foundation for low complexity soft machines, with multiple degree-of-freedom actuation, that can act simultaneously as motors and manipulators. The mechanism also enables an artificial muscle controlled gear change. Future work will include self-sensing feedback for precision, multidegree-of-freedom operation. © 2011 American Institute of Physics. [doi:10.1063/1.3565195]

Electric motors, whether inductive, capacitive, or ultrasonic are orders of magnitude more rigid than living organisms. Their subassemblies include magnets and metal windings (induction motors), piezoceramic friction plates (ultrasonic motors), and metal frames that support roller bearings. Motion is typically limited to only one linear or rotary degree-of-freedom. By comparison, the human hand, while unable to match the precision and high torque capabilities of motor technology, can manipulate an object between thumb and forefinger, rotating it by moving thumb and fingers in opposing directions or repositioning by moving thumb and fingers together. The hand’s ability to manipulate and move an object in 6 degrees-of-freedom provides inspiration for the development of a soft machine technology that can do the same. To achieve such freedom and dexterity we seek an analog for living muscle.

One actuator technology with performance metrics similar to natural muscle is the dielectric elastomer actuator (DEA). A DEA is composed of a polymer dielectric sandwiched between flexible electrodes.1–3 When a voltage is applied, the charge accumulating on the electroded faces gives rise to an electrostatic Maxwell pressure that results in out-of-plane compression and in-plane expansion, and that can produce active strains greater than 30%.1–3

DE artificial muscles are being considered for robotics, haptics, medicine, and optics.4–7 Due to their high energy density, DE have the potential to give robots animal-like performance capabilities.8,9

While many applications employ them as linear actuators9–15 DE can also be used to produce rotary motion.16–18 The first reported DEA based rotary motor, by Kornbluh et al.16 mechanically converted the linear motion of one or two DEA roll actuators to rotary motion. The device used a rocker arm, whose axis coincided with the axle of a central wheel and that transmitted torque to the wheel through a one-way roller clutch. In another design, by Anderson et al.,17 the ordered electrical charging/discharging of electroded sectors of a stretched membrane was used for turning a shaft using a rigid orbiting gear or a sliding eccentric shaft in a cranklike arrangement.18 These motors require rigid sliding bearings to support their shafts and are limited to rotary motion. To achieve the gripping and turning action of thumb and forefinger, a more flexible mechanism is required.

To mimic the action of fingers and thumb we inserted a soft and flexible gear between antagonistic DE muscles. The central gear can be contracted like a sphincter [Fig. 1(a)] or made to assume an elliptical profile by charging opposing membrane sectors. Subsequent stepping of actuation around the membrane will then cause the axis of the ellipse to rotate; rolling the contact surface between gear and shaft and turning the shaft in a nonslip drive [Fig. 1(b)]. The gear literally grips and turns so that there are no rigid bearings required; providing an opportunity for additional motion freedoms. For instance, by varying the relative voltages the unconstrained axis of rotation can be repositioned up, down, or side-to-side [Fig. 1(c)].

Membrane motors were fabricated from 3M VHB4905 acrylic tape (3M, Mich., USA) prestretched four times

FIG. 1. (Color online) A schematic of the actuation modes for the soft motor. (a) Mode I: simultaneous actuation of all sectors. (b) Mode II: turning the central shaft. (c) Mode III: repositioning the shaft sideways through differential actuation of electroded sectors.
shaft was measured from videos analyzed using MATLAB and an upper bound of 2500 V. Rotational speed of the rotor at 0.4 Hz and was increased in 0.4 Hz steps up to 3.2 Hz. The signal from online movie that depicts the artificial muscle motor as it rotates and tilts a shaft.

equibiaxially and fixed on a ringlike rigid acrylic frame with 200 mm inner diameter. A toothless gear was assembled at their center. This consisted of two VHB 4905 rings joined onto each side of the stretched membrane. The rings had an inner diameter of 19 mm, an outer diameter of 31 mm, and were 0.5 mm thick. Membrane material within the gear’s inner diameter was removed, causing it to stretch, expanding until the circumferential stiffness of the gear balanced the tensile stress within the membrane. The inner surface of each gear was coated with a thin layer of silica sand (Ceramic Microspheres EX150/500) to eliminate sticking between the central gear and the shaft. Conducting carbon grease was painted on six electrically isolated sectors of each membrane (60° sector with 5 mm separation).

Two motor membranes with gear inserted were spaced 85 mm apart so that they supported opposing ends of a shaft. Membranes were charged using a square-wave voltage signal delivered using two high voltage control units (Biomimetics Laboratory, NZ). To produce rotary motion the six sectors of the membrane were activated in the following cycle: AD $\rightarrow$ DABE $\rightarrow$ BE $\rightarrow$ BECF $\rightarrow$ CF $\rightarrow$ CFAD $\rightarrow$ AD [refer Fig. 1(b)]. The actuation frequency of the wave form, $f_a$, started at 0.4 Hz and was increased in 0.4 Hz steps up to 3.2 Hz. The voltage wave form had a lower bound of 0, 500, or 1000 V and an upper bound of 2500 V. Rotational speed of the rotor shaft was measured from videos analyzed using MATLAB (The MathWorks, Inc.).

A photograph depicting two motor membranes gripping opposing ends of a shaft and tilting it (mode III) is depicted in Fig. 2. This configuration could also turn the shaft giving it five degrees-of-freedom: two translational and three rotational. An online movie depicts the motor in operation.19

Speed was frequency dependent; the counter-rotating shaft speed increased with actuation frequency but above 2.2 Hz the shaft ceased to travel any faster and in fact the rotational speed reduced with rising actuation frequency (Fig. 3). Raising the baseline voltage also reduced shaft speed.

Equation (1), based purely on the geometry of this non-slip coupling that relates gear circumference ($C_g$), shaft circumference ($C_s$), and membrane actuation ($f_a$) to shaft speed ($f_s$), can be used to explain this phenomenon as follows:

$$ f_s = f_a \left( \frac{C_g - C_s}{C_s} \right). $$

Applying a voltage to all sectors as illustrated in Fig. 1(a), will cause the flexible gear to contract. From Eq. (1) we see that a reduction in circumference, $C_g$, will effectively reduce the shaft speed thus providing an electroactive gear change mechanism.

Increasing the frequency of membrane actuation above 2.2 Hz has a similar effect. This drop in performance, associated with the viscoelastic behavior of the membrane material20,21 resulted in a slower response of the elastomer at higher frequencies. Viscoelasticity not only limited the speed of membrane response to the step voltage change but also, slowed the return of each membrane sector to its rest position between actuation cycles, thereby reducing the effective circumference of the flexible gear $C_g$.

The performance of the DE membrane motor could be improved with the substitution of a less viscoelastic elastomer. One material commonly used for DE artificial muscles is silicone.2,21 Silicone is also easy to mold thus it is possible to manufacture membrane and gear as a single part.

Another way to improve the motor is to use lower voltages. The Maxwell pressure on the membrane is proportional to the dielectric constant and the square of the electric field.1–3 There are clear roads for achieving a high Maxwell pressure at low voltages. This could include raising the dielectric constant.22 And through the use of a thinner membrane, we could achieve a high electric field but with much reduced voltages. Multiple stacked layers of membrane could also be used to boost torque.18

The membrane motor is nonferrous, nonmagnetic, simple to manufacture, and suited to low speed applications, and could, for instance, be used under magnetic resonance imaging guided surgical procedures. These characteristics and advantages are shared with piezoelectric ultrasonic (PU) motors.23 PU motors can be precision controlled, and another feature that we would seek to emulate. However, the DE membrane motor can also be made from materials that are orders of magnitude softer than piezoceramics and this coupled with the bearing-free drive opens the door to multidegree-of-freedom operation.

To be truly dexterous the motor should be able to sense and control its position. We will investigate doing this by
resistive and capacitive self-sensing.\textsuperscript{24–30} This would make the device useful for manipulation tasks, enabling the motor to hold shaft position or to move the shaft to a desired location despite unexpected and random variations in external loadings. An example for such a control system is our own muscle, with its embedded nerves, which through proprioception, enables us to touch our nose with eyes closed. Imparting self-sensing capability to the motor will enable it to perform dexterous tasks with feedback control so that the soft motor can become an extension of our hands.


\textsuperscript{8}J. D. Madden, \textit{Science} \textbf{318}, 1094 (2007).


\textsuperscript{11}See supplementary material at \url{http://dx.doi.org/10.1063/1.3565195} for motor video.


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