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Research Article

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Improvement Measures for Components of Dielectric Elastomers for Heavy Duty Uses Such as Robots and Power Assist Devices

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Abstract

Dielectric Elastomers (DE) are currently being rapidly researched and developed all over the world as a technology that has begun to be incorporated at a practical level. As a product, game vibrators using DEs are already on the market in the United States and Europe. However, much of the market demand is dominated by more output-focused applications such as DE power suits, DE motors, DE muscles for robots, and larger DE power systems. Attempts have been made to improve elastomers and use new carbon foam materials such as single-walled carbon nano tubes (SWCNTs) and multi-walled carbon nano tubes (MWCNTs) as electrodes for DEs to meet these demands. This paper discusses these issues.

Also, by reversing the movement of the DE, it is possible to generate electricity with high efficiency. By attaching the power generation system to the robot, which generates electricity from the movement of the robot, and charges the robot's battery of the robot, it becomes possible to move the robot more efficiently. This is also discussed in this paper.

Keywords: Dielectric Elastomers (DE), DE Actuator (DEA), Cnt, Ss Curve, Dynamic Viscoelasticity, Artificial Muscles, Actuators, Large Deformation, High Efficiency, DE Generators (DEG)

Introduction

Electroactive polymers (EAPs) are called "soft actuators" or "artificial muscles" because of their flexible movement. Regarding EAPs, the following is well known: 1) a DE type that uses electrostatic force between electrodes, 2) a wet type uses the mechanism of the movement of ions and water molecules in the polymer membrane, 3) the type changes the structure of the polymer (for example, use of liquid crystal) [1-6].

In 1990, S. Chiba and R. Perline started research and development of DEs, but now, research and development are rapidly progressing all over the world for the technology's practical use [1, 2]. As a product, game vibrators incorporating DEs have already been released in Europe, the United States and Japan [7].

Much of the market demand is dominated by more output-focused applications such as DE power suits, DE motors, DE muscles for robots, and larger DE power systems. To meet these demands, the elasticity of the elastomer is an important. In this paper, we will discuss the important factors for stress-strain (SS) curves, viscoelasticity tests, etc. of the materials of DEs.

Recent attempts have been also made to use new carbon foam materials such as single-walled carbon nano tubes (SWCNTs) and multi-walled carbon nano tubes (MWCNTs) as electrodes for DEs. It is also known that it is better to drive at a lower performance than the maximum performance in order to prolong the life of the elastomer. Recently, through research to maximize the performance of acrylic elastomers, S. Chiba and M. Waki succeeded in lifting 8kgf by 1mm or more at a speed of 88msec with a 0.15g elastomer [8, 9]. The edge of the DE was, however, reinforced so that it would not be destroyed by repeated loads, and the total weight was set to 0.97 g. As a result, the reality of robots, wearable powers, etc. is increasing. We will also discuss these issues in this paper.

Background of Dielectric Elastomers

The structure of a DE is simple and consists of a polymer film (elastomer), which is the main material, and two electrodes that sandwich it [1, 2, 8]. Also, the typical thickness of the elastomer is from about 500 μm to 1 mm. The DE electrode can use a very thin metal sheet (when a thin gold foil is used as an electrode and a potential difference is applied between the electrodes, the polymer film contracts in the thickness direction due to Coulomb force and expands in the plane direction (see Figure 1), or carbon particles can also be attached and used as an electrode.

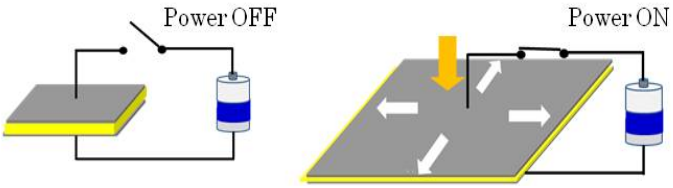


Figure 1: DE operating principle

Thus far, a lot of research and development for materials, systems and electric circuits has been done [2, 8-33]. For example, P. Hu et al. has tried to drive at a relatively low voltage using a silicon material [13]. He also fabricated soft silicone elastomers with no chemical cross-linking [14]. H. Kumamoto has studied the development of a small moving robot using deformable DEs for actuation without pre-stretch [15]. M. Carmel has studied enhancing the permittivity of DEs with Liquid Metal [16]. L. Romasanta et. al. and E. Hajiesmaili et. al. reviewed the SS curves, dielectric permittivity, dielectric loss and viscoelastic damping, etc. The content of those papers, including the kinds of materials, has not been fully analyzed for experimental results. E. Hajiesmaili et. al. additionally reviewed the use of carbon nano tubes (CNTs) for electrodes. However, the electrodes using CNTs shown there are quite thick, several hundred μm, and are not flexible and sufficiently stretchable electrodes. Chiba et al. have developed ultra-flexible, fully stretchable electrodes using single-walled carbon nanotubes, and they also developed DE actuator (DEA) drivers [17-20]. They can supply high voltage accurately and quickly. S. Hayat et al. also introduced the power supply for DEAs. Unfortunately, their design concept lacks safety and there are also doubts about efficiency. F. Albuquerque has researched on the effect of humidity, temperature, and elastomer material on the lifespan of silicone-based DEAs [21, 22].

L. Romasanta et al., L. Xu et al., J. Youn et al. introduced small DEA gripers. Their outputs are very small [17, 23, 24].

As mentioned in above, electrodes with a needle-like (or particle-like) material have the properties of being flexible, expandable and contractible, and able to maintain conductivity, which enables large changes in shape. Currently, 680% deformation (quickly deformed with an area ratio) is possible (see Photo 1) [25]. At the material level, DEAs have a fast response speed (above 100,000 Hz) and are also excellent as energy-saving actuators.

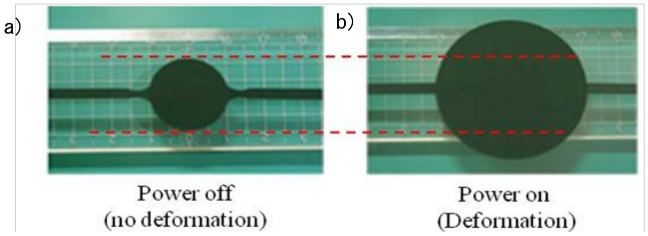


Photo 1: Deformation of a circular actuator (up to 680%): a) Power off/no deformation; b) Power on/deformation.

As mentioned above, it is now possible to lift a weight of 8 kg with a dielectric elastomer of 0.15 g with 88 msc by 1 mm or more (see Photo 2) [8, 9]. The polymer used for them was 3M VHB 4905 acrylic (see Photo 2), and the electrode material was a single-walled nanotube (ZEONANO®-SG101, Zeon corp., Tokyo, Japan).

This actuator can be used not only as a linear drive but also as a DE rotating body in the same way as a normal motor. This has been realized in automobile drive motors that are ultra-lightweight and have high output.

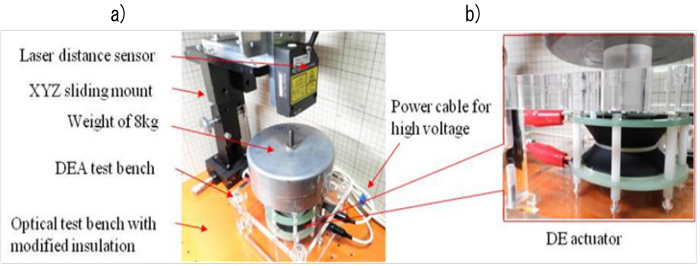


Photo 2: DE actuator (DEA) with a weight of 8 kg: a) 8 kg weight placed on DE actuator on a test bench, and b) DE actuator.

An interesting application of DEs is the control system of the Mars probe (see Photo 3). Martian planes must be lightweight in order to fly aerodynamically in the dilute atmosphere of Mars. Therefore, Mars planes need lightweight, high-power actuators. DE actuators are ideal for Martian planes. DE actuators are likely to be used as actuators for control surfaces (i.e., ailerons, ladders, elevators, and flaps) and Mars airplane propellers [12].

a) Image of an airplane exploring the surface of Mars ©JAXA

b) Mars exploration airplane wing and aileron controlled by a DE actuator in the 2mx2m low-speed wind tunnel experiment (JAXA: Japan Aerospace Exploration Agency).

Photo 3: Image of an airplane for the exploration of Mars and an experimental scene using JAXA's wind tunnel: a) Image of an airplane exploring the surface of Mars ©JAXA; b) Mars exploration airplane wing and aileron controlled by a DE actuator in the 2mx2m low-speed wind tunnel experiment (JAXA: Japan Aerospace Exploration Agency).

DE Actuator Mathematical Model

The strain (deformation) observed in the elastomeric membrane is mainly caused by the interaction of electrostatic charges between the electrodes [34]. Opposite charges on the two electrodes attract each other, and the same charges repel each other. This phenomenon can be derived by using a simple electrostatic model to derive the effective pressure generated by the electrodes of the elastomer membrane as a function of the applied voltage [30, 32]. Pressure ρ is

$$\rho=\varepsilon r\varepsilon oE^2=\varepsilon r\varepsilon o(V/t)^2 \qquad (1)$$

Here, εr and εo are the permittivity and the relative permittivity (dielectric constant) of the polymer in the free space, respectively, E is the electric field strength, V is the applied voltage, and t is the film thickness. The responsiveness of this polymer is similar to that of conventional electrostrictor polymers, and the pressure is proportional to the square of the electric field strength.

The pressure in Equation (1) is twice that of the equation for calculating the pressure of an air gap type electrostatic actuator using a steel plate! This is because the polymer has two modes in electrical / mechanical energy conversion, that is, (1): thickness direction and (2): expansion mode in the width direction.

Although the dielectric constant of air is 1, elastomers (polymers) generally have a dielectric constant of about 2.5 to 10, so the driving pressure is 2.5 to 10 times higher than the conventional method using static electricity. It can be doubled and increased. In addition, DE can use a high electric field, and in the laboratory, an electric field of about 1,000 to 2,000 V / 100 μm is used on a daily basis, and in the past, there have been cases where an electric field strength of 20,000 V / 100 μm or more was used.

In this way, the three effects of "two-mode interaction," "high dielectric constant," and "high electric field strength" greatly contribute to the driving pressure of the DE.

In Equation (2) above, the relationship with pressure becomes non-linear as the elongation increases, but in the case of small elongation, the elastic modulus Y is used and the elongation Sz of the thickness can be calculated from the following equation [23].

$$Sz=\rho/Y=(\varepsilon r\varepsilon oE^2)/Y \qquad (2)$$

If the material is stretched in the vertical (X) and horizontal (Y) directions in the same way, Sx = Sy, and the relationship between the thickness and the surface can be expressed by Equation (3) [30]. This equation (3) is also effective in the case of large elongation.

$$(1+Sx)(1+Sy)(1+Sz)=1 \qquad (3)$$

That is, the thickness Sz can be obtained by accurately measuring the vertical (X) and horizontal (Y).

DE research and development status

In this chapter, the various materials and DE shapes being studied thus far, and the development status of DEs applying them are discussed

Usefulness of CNT electrodes

First, Table 1 shows how much weight can be lifted with a stroke of 5 mm due to the difference in electrodes. The elastomer used is 3M VHB 4905 acrylic, and its weight is 0.1 g [11].

Table 1: Types of electrodes and weight that can be lifted

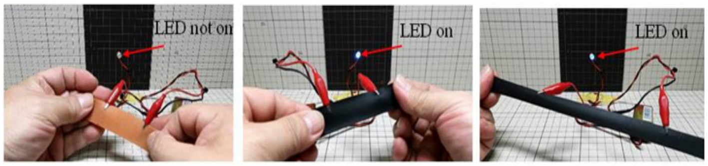
Electrode type	Weight that can be lifted with a stroke of 5 mm
Carbon Black	10N
Multi-walled carbon nanotubes (MWCNT)	16N
Single-walled carbon nanotubes (SWCNT)	22N

Note: The output and stroke are in inverse proportion to each other; the relationship is clearly expressed by table 1 showing the stroke of the SWCNTs and the weight that can be lifted, and photo 2, showing the stroke and the weight that can be lifted. In other words, in Photo 2, a 1mm stroke can lift a weight of 8kgf, but the stroke in Table 1 is 5mm, and the weight that can be lifted is about 2.2kgf. Regarding the relationship between the stroke and the weight that can be lifted, in the case of the SWCNTs shown in Table 1, the amount of acrylic used differs from Photo 2 by 0.05 g, but the difference is small, so we ignored it in this consideration).

Since these electrodes are not optimized, it seems quite possible to lift heavier weights. In addition, since these are single layers of DEs, by making them multi-layered, they are sufficiently close to the range necessary for robots and power suits. The difference in elongation due to the difference in electrodes is 1.2 to 1.6 times that for MWCNTs and 1.7 to 2.2 for SWCNTs, where 1 is the carbon electricity. These cases are also expected to grow further as they have not yet been optimized in detail.

Interestingly, with electrodes using MWCNTs or SWCNTs, DE is not destroyed even if it is pierced with a needle. Normally, a DE alone becomes one capacitor, so if it is scratched with a needle or the like, it will be destroyed. However, since CNTs have a column-like shape, each column is well dispersed and has a mesh shape. This means a needle would enter inside the mesh, and it will cause the mesh to burnt and it does not affect other parts. Further increasing the dispersion of CNTs on the elastomer, the columns of CNTs are very thin, and when the network structure is well constructed, it becomes difficult to see with the naked eye and appears transparent [33].

As mentioned above, the use of SWCNTs dramatically improves the performance of the DE, but there is one drawback. It needs to be well coated on the elastomer, but until now doing that has been difficult. Recently, S. Chiba and M. Waki have succeeded in spraying carbon nanotubes (CNTs) by treating and dispersing them by a special method (see Photo 4) [35]. The spray using ZEON's SWCNTs (see above) is particularly excellent [35]. By spraying this spray directly on various elastomers, it became possible to easily form DE electrodes.



a) **Before applying CNT spray** **b)** **After applying CNT spray,** **c)** **Even when stretched a lot the LED remains on the LED lights up.**

Photo 4: Ultra-flexible thin film electrode formation by CNT spray: a) Before applying CNT spray, b) After applying CNT spray, and c) Even when stretched a lot the LED remains on the LED lights up.

Voltages and circuits that drive DE

A DE is said to have a higher voltage than other soft actuators, but in order to achieve large force and elongation, it is necessary to increase the voltage or increase the current. Higher current is more dangerous to the human body, so the DE chooses higher voltage. It is a big feature of the DE that almost no current flows at 2,400V and 0.7µA (see Figure 2). However, in the case of Japan, there is a tendency to desire a low voltage, and the authors are dealing with it by reducing the thickness of the elastomer [33]. As an example, a 4 cm size DE sensor using 3M VHB 4905 acrylic has a film thickness of 40 µm and uses a voltage of about 3 V. As another example, a thin film (10 µm) was used for the microdevice, and a strain of 5% was obtained at 36 V. These voltages are within the range of conventional CMOS drive devices.

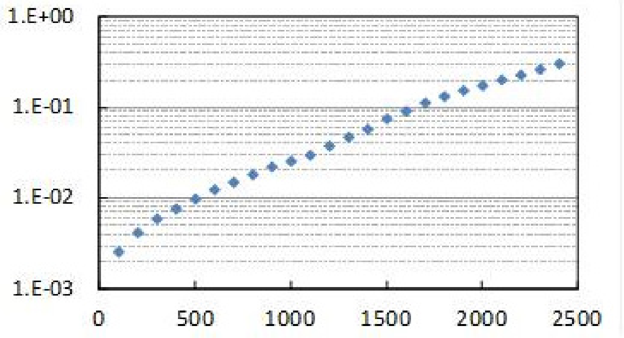


Figure 2: Relationship between DE input voltage and current

M. Rosenthal et al produced vibrating headphones for games. Photo 3 shows a circuit for driving the vibrating body [7]. Most of this circuit is the equalizer and equalizer circuit that controls the sound. The DE vibrating body uses 3 pieces of silicon with a size of 3mm x 25mm. It can be seen that the booster circuit is quite small. This size is 0.9 mm x15mm (see the section of the booster in Photo 5) This is because the current used is very small. The voltage is boosted from 5V to 1200V.

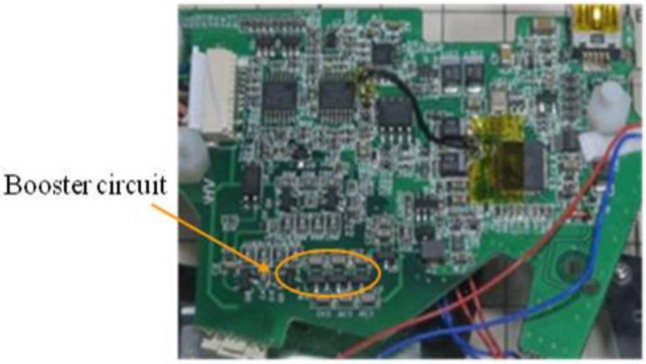


Photo 5: Booster circuit located inside the headphones:

At SPIE 2020, highly useful DE drivers and programmable sensor drivers were presented [11]. Photo 6 shows an image of the DE sensor being evaluated using the sensor driver.

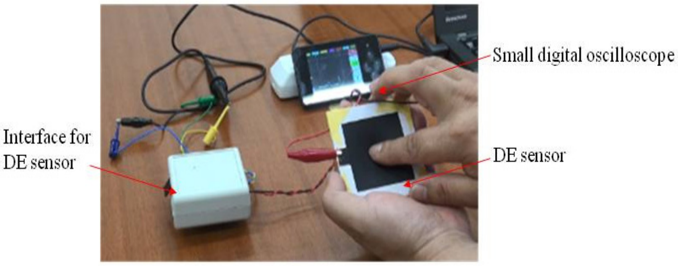


Photo 6: An image of the DE sensor being evaluated using the sensor driver.

Comparing and investigating both SS curves and dynamic viscoelasticity test results

First of all, the research target is artificial muscle, and it is better to examine the speed of the SS curve and viscoelasticity test from the operation speed required for robots and power assist devices. Figure 3 shows that the SS curve and Figure 4 shows dynamic viscoelasticity dependence on the test speed [36].

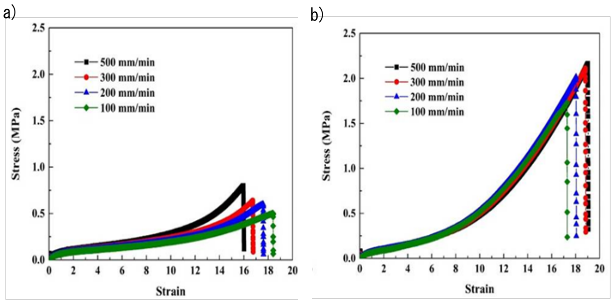


Figure 3: Relationship of stress-strain for tensile tests: a) 3M VHB 4905 acrylic, and b) A silicone elastomer made in Japan.

What is interesting here is that acrylic has higher viscoelasticity, so it depends more on tensile speed than silicon. This implication indicates that it is important to test with the response required for the artificial muscle. In other words, until now, researchers have overlooked the importance of viscoelasticity. This meaning is easier to understand by looking at the results of the dynamic viscoelasticity test in Figure 4.

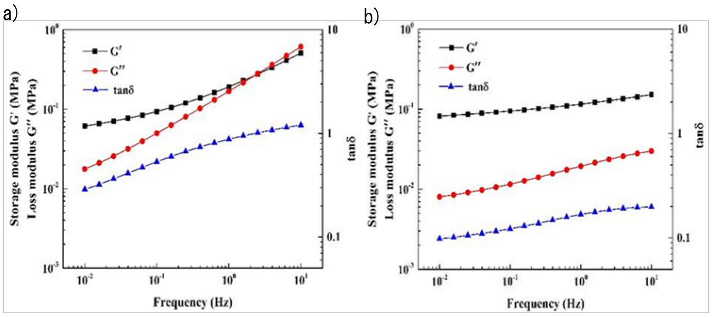


Figure 4: The frequency dependence of *G′, G″* and tanδ of a) the acrylic elastomer, and b) The silicone elastomer

From this figure, it is clear that acrylic is more affected by dynamic viscoelasticity than silicon. Therefore, when the driving voltage is increased and each elastomer is stretched, the silicon becomes harder, and as a result, the amount of stretching is smaller. Of course, it is also a fact that the difference in the dielectric constant and Young's modulus of both films is the cause (see Equations (1) and (2), but it can be explained from the above behavior. It can be seen from the SS curve in Fig. 4, the silicon curve stands up more. This does not mean that silicon has poor performance. It is a proposal that it is better to change the material depending on the application. Silicon has a faster drive speed and a higher rate than acrylic. Therefore, for applications such as robots, it is advisable to select the type of elastomer depending on where it is used. For example, in human muscles, there are slow muscles and fast muscles, each of which has an important mission. Moreover, Silicon can be used from a relatively high temperature to a considerably low temperature. Compared to acrylic, it could be a considerable advantage for devices that are used at higher or lower temperatures [37].

Studies on DE lifespan

Not much research has been done on the lifespan of a DE. It has been pointed out that acrylic is vulnerable to moisture, but recently research has shown that silicon is very vulnerable to moisture [22]. Silicon was thought to be resistant to moisture, so this is a bit disappointing.

Chiba et al. insert the DE element in a moisture-resistant polymer bag, seal it, evacuate the air, and use it in a vacuum state [29]. In addition, silica gel and nitrogen are also added to the above bag if necessary. These procedures have significantly improved lifespan. Especially in summer in Japan, the humidity is very high, and such measures are indispensable.

Other than the above, what can be done is to develop a DE with as high performance as possible and drive the DEs with a performance that is well lower than its maximum performance. Even with acrylic materials, there are recorded cases where the DEs were used up to 10 million times [22]. This is a value that is suitable on a commercial basis. Therefore, as shown above, a device that can lift 8 kg with only 0.15 g of acrylic material has been developed.

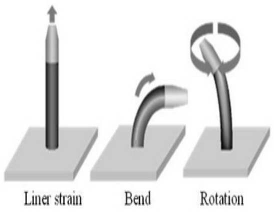
Even if the performance is sufficiently lower than this performance, the amount of acrylic used is very small, and the performance can be also improved by laminating. In addition, a DE is considerably cheaper than motors, so even if you increase the frequency of replacement, it seems to remain commercially viable.

Development of humanoid robots

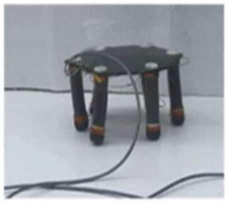
Next, the difference in performance depending on the shape of the DE will be described. First, although it is a roll type, a vertically long DE sheet is wound around a spring, a polymer core, or the like (see Figure 5). Since this is originally vertically long, it extends longer on its length. However, by winding it around a spring or the like, the wound layers affect each other by frictional force, and it is possible to extend the shorter length rather than the longitudinal direction, and as a result, the roll both ends of the roll extend [30]. This roll type has a bulky shape, like the muscles of an animal for humans, and is suitable for driving the arms and legs of robots, but it has a short lifespan due to stretching of the DE a lager. In addition, it's heavier, even if the size is not so big. Currently, based on a new concept, we are developing a roll type that is lighter and easier to bend.

By dividing this roll-shaped electrode into several parts, it is possible to create a roll actuator with three degrees of freedom that can not only extend vertically but also bend and rotate the roll (See the figure on the left of the first row and the right figure of the first row in Figure 5). Roll actuators with three degrees of freedom are ideal for robot hands and feet [34]. The figure on left of the second row, the figure on the right of the second row, and the figure on the left of the third row show an example of applying a roll to drive a finger.

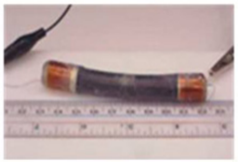
Figure 5 of show examples of applying them to the hands, arms and legs of a robot [24, 25].



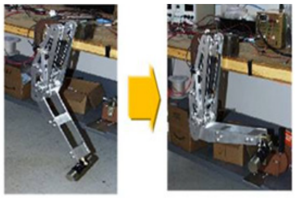
a) Roll actuator having three degrees of freedom



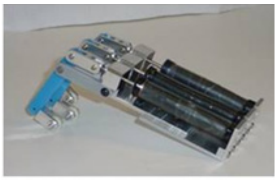
b) A leg robot that uses a roll-type actuator with three degrees of freedom (It was made for the exploration of Mars and able to crabwalk)



c) Roll-type DE alone



d) An example of applying the roll to robot arms and legs

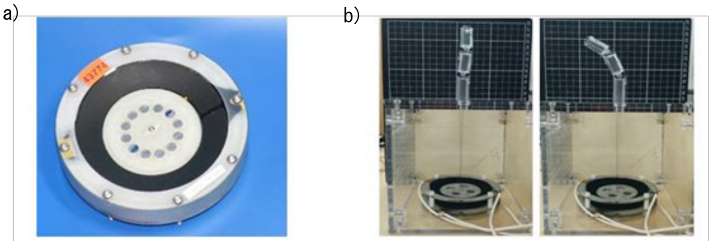


e) An example of applying a roll to drive a finger.

Figure 5: Roll type DE actuators and their applications: a) Roll actuator having three degrees of freedom, b) A leg robot that uses a roll-type actuator with three degrees of freedom (It was made for the exploration of Mars and able to crabwalk), c) Roll-type DE alone, d) An example of applying the roll to robot arms and legs, and e) An example of applying a roll to drive a finger.

Similarly, a finger model that uses a roll to drive a human-like finger with a tendon (rods) was also developed (see the figure on the left of the third row in Figure 5). This finger can be driven at 6Hz. The human finger is, by the way, 5 Hz [31, 32, 34]. Photo 5 e shows an example in which a roll-type actuator is placed in a frame and developed as a device for a robot's arm, power assist, etc. [32, 34,37]. However, as mentioned above, this is relatively heavy.

The diaphragm type uses a small number of DEs, is easy to multi-layer, and can exert power (see the figure on the left of the first row in Photo 7). In addition, since it extends in the direction perpendicular to the surface of the DE, it is ideal for driving the arms and fingers of a robot. Another feature of the diaphragm is that it has a hole in the center through which struts and arms can be passed, making it a power suit for robot arms and humans [38]. It is also convenient for wiring. In recent years, a finger model using Diaphragm DE has also been developed. This is a type that uses two diaphragms DEs, and it is a push-pull type that bends the finger with one diaphragm and returns the bent finger with the other diaphragm, not the mechanical movement peculiar to motor drive (see the figure on the right of the first row in Photo 7). Because it uses the principle of leverage, you can bend the fingers enough by just stretching the DE a few millimeters. Sine waves and such were used to reproduce movements closer to humans. This DE is a super energy-saving device with 0.7μA at 2400V [33].



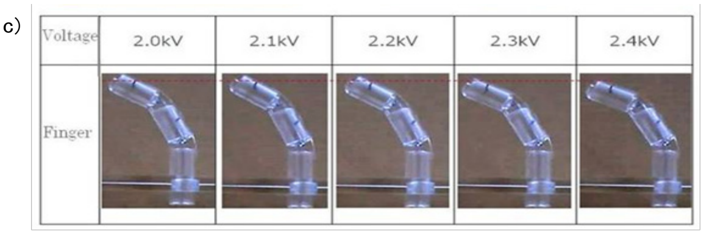


Photo 7: Finger models driven by diaphragm type DEAs: a) A diaphragm actuator, b) A finger model that combines the diaphragm DE up and down and moves alternately, and c) The movement of the artificial finger in response to voltage change.

Photo 7 shows that the diaphragm type DE finger model can move quickly and freely at different angles by changing the voltage [39].

A device that successfully combines the roll-type DE and diaphragm DE can be applied to powerful power suits, various robots including humanoids, and for rehabilitation and nursing care. However, for the time being, it would be better to start with a hybrid that uses an existing motor for areas that require more force and a DE for areas that require delicate movements. Figure 6 shows a performance comparison of the DE, electromagnetic motor, and pneumatic actuator technologies [39].

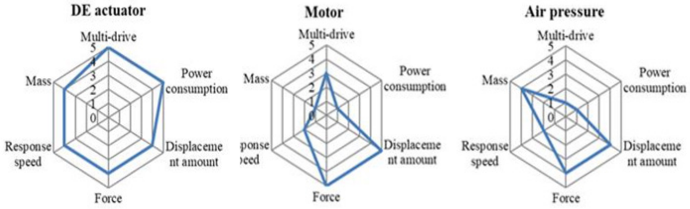


Figure 6: Performance comparison of the DE, electromagnetic motor, and pneumatic actuator technology

Robot drive battery backup DE power generation

Power can be generated by reversing the drive of the DEA. So far, a lot of research on DE power generation has been done [38-63]. As a backup power source for robots, it seems better to use the movement and vibration of the robot to generate electricity [60-62]. When running a humanoid robot, there is the risk that it may fall over due to large impact that occurs on the foot when stepping. However, by attaching the above-mentioned miniaturized device and adjusting the damping force by movement, a smart damper that absorbs the impact well becomes possible. At the same time, power generation is also possible with that setup. Figure 7 is an image diagram showing how a thin DE film can be attached to a robot or a human body to generate electricity. A DE film with a width of 5 cm and a length of 25 cm (about 0.5 g) can make about 100 mJ of energy if it stretches once per second [47].

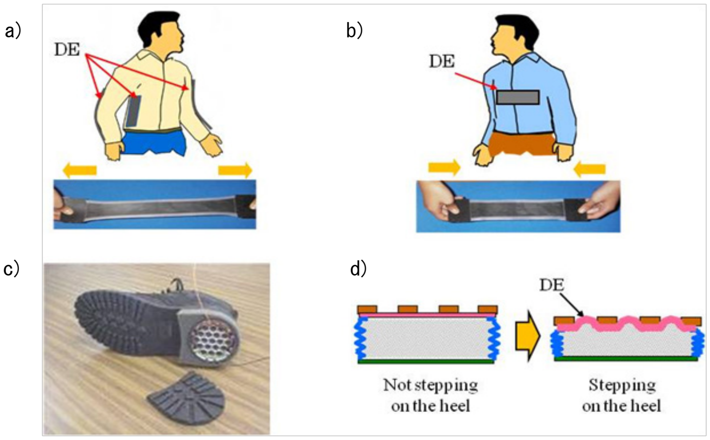


Figure 7: Power generation systems that can be attached to a humanoid robot or human body: a) A DE is Stretched, b) The DE returns to its original shape, c) A DE power generation device attached to the sole, and d) The DE power generation device.

It is also becoming a reality to use this same elastomer film as an actuator to assist the movement of robots and people [48]. That is, both the actuator and the power generation function are compatible. It is also possible to attach a DE power generation element to the sole of the robot or the sole of a person to generate power. As shown in Figure 7, when the robot starts walking, the robot's own weight deforms the power generation device and power generation becomes possible. In this device, a grid is placed on top of the DE, and when stepped on, the DE deforms more and produces more power. With 40g of DE per step, you can get about 1.5W [49].

Conclusion

Summarizing the above results, the following could be concluded:

- The use of CNTs, especially SWCNTs, for electrodes could dramatically improve DE performance.
- Elastomers with high dynamic viscoelasticity could undergo greater deformation.
- Silicone elastomers would be suitable for low and high temperature zones. It would be also suitable for applications that require quick response and where efficiency is desired.
- For robot applications, it could be better to use silicon as "fast muscle" and acrylic as "slow muscle".
- If a device could be created with the highest DE performance and driven with a performance well below that value, a sufficient commercial life level would be reached.
- DEAs could also be used as a power generation element. Using that function, power can be supplied to the backup power supply.

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