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REVIEW

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The Potential of Wearable Systems Using Dielectric Elastomers (DE)

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Abstract: Recent progress in dielectric elastomers has been remarkable. As an actuator, it is now possible to lift an 8 kg weight by more than 1 mm at a speed of 88 ms with a dielectric elastomer of only 0.15 g. As a sensor, it is capable of measuring from 0.01 N to 1,400 N with a very thin and small device, and can also use moisture sensors, stretch sensors, and tactile feedback. Therefore, by effectively combining these sensors, it is possible to create a wearable system with a fairly realistic sensation. In addition, dielectric elastomers are inexpensive, lightweight, have a simple structure, can be multi-layered, and are highly efficient. In the future, they are expected to be applied in various industrial machines. In this study, we analyzed the factors that improve the performance of dielectric elastomers and considered measures for industrialization. Based on this, various systems that can be applied to wearables have been considered.

Keywords: DE, DES, DEG, large deformation, CNT, large power, motion feedback, virtual reality

1. Introduction

Currently, wearable systems that support human movement are mainly driven by motors. However, motors are made of metal and require gears for control, which makes them even heavier [1]. The equipment used to increase air pressure is heavy, even in actuator systems that use air pressure.

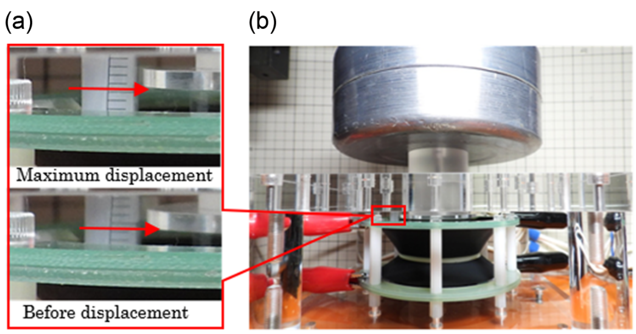
As a result, lightweight systems such as biological muscles are desired, and devices such as piezoelectric and electrostatic actuators have been developed. Piezoelectric devices have a sufficiently high drive speed and can produce a large output; however, they have a small extension. Electrostatic actuators do not produce much output [2].

A sensitive, fast, and flexible chemical sensor for moisture detection has also been developed using highly piezoelectric responsive Sm-PMN-PT ceramics (d33 = ~1500 pC N−1) [3]. Developments are also being made on wireless technology, such as Maxwell displacement current-driven wireless self-powered gas sensor arrays for passive breath analysis and exhaust gas monitoring. It can actively distinguish between minute amounts of ammonia and carbon dioxide, showing the feasibility of breath analysis and air quality monitoring [4]. In recent years, triboelectric nanogenerators have been investigated for intelligent wearable and implantable medical electronic devices that can dynamically monitor health information and treat diseases [5].

Actuators and sensors using dielectric elastomers (DEs) are inexpensive, lightweight, simple in structure, and multi-layered. They are also capable of large deformations and are highly efficient. Currently, a DE weighing only 0.15 g (0.94 g including the reinforcement on the outer periphery of the DE) can lift an 8 kg weight by more than 1 mm at a speed of 88 ms. The elastomer used is 3M4905 (acrylic), and the electrode material is single-wall nanotubes (SWCNT). Therefore, there are high expectations for its application to various industrial machines in the future (see Figure 1) [6]. In addition, DE generators can generate electricity in response to various external forces; therefore, they are attracting attention as wearable renewable energy systems.

However, the papers published so far have not fully examined the specific effects of various electrode materials, such as thickness, resistivity, and material type, on the characteristics of DEs using various elastomers, nor have they examined efficient circuits. Moreover, there aren't many examples of its applications either.

Figure 1
Diaphragm-type DE actuator capable of lifting an 8 kg weight (black part: diameter 8 cm): (a) DE actuator before (bottom) and after (top) actuation, (b) DE actuator actuated and stretched vertically



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In this paper, we explain, to the extent that we are currently aware, the current status of research and development of DEs using polymer (mainly elastomer) materials, the factors that have improved their performance, and discuss the possibility of applying them to wearable systems.

2. Background of DE Development and Recent Development Status

Research and development of artificial muscles began in earnest around 1949, with an attempt to use electricity to drive a polymer (Electroactive Polymer: EAP) [7]. Since then, the research and development of EAP actuators aimed at driving by electrical control has progressed. EAPs are also called "soft actuators", because they are made of flexible materials. Various types of EAPs have been developed. EAPs can be generally classified into three types: (1) wet type, which requires an electrolyte [7–14], (2) dry type, which does not require an electrolyte [6, 15, 16]; and (3) others (types that use light, air pressure, liquid crystal, heat, magnetic force, etc.,) [17–21].

As mentioned above, DEs (dry type) are currently the mainstream. Incidentally, in the late 1990s, Chiba, Pelrine, and others from the Stanford Research Institute (SRI International) in the US were the first to propose the principle of artificial muscles using DEs [22]. The driving principle is simple: Stretchable electrodes are attached to the top and bottom of a thin polymer (elastomer) film. When electricity passes through it, the Coulomb force acts on the polymer, causing it to be compressed vertically and simultaneously stretched horizontally. When the current stopped, the polymer immediately returned to its original length. DEs are actuators that use simple motions.

This can be expressed by the following formula:

$$\mathrm{P} = \varepsilon r \varepsilon o \mathrm{E}^2 = \varepsilon r \varepsilon o (\mathrm{V}/\mathrm{t})^2 \qquad (1)$$

where εr and εo are the permittivity of free space and the relative permittivity (dielectric contact) of the polymer, respectively; E is the applied electric field; V is the applied voltage; and t is the film thickness.

DEs have been investigated in actuators (DEAs) [6, 23–26], sensors [6, 27–30], and generators (DEGs) [6, 31–33]. In conjunction with these developments, much research has been conducted on elastomer materials for DEs and their improvements [6, 33–37], electrode materials [6, 33, 38, 39], high-voltage circuits and their composite systems [3, 30, 33, 40–44], and their applications [6, 22, 30, 33, 43–57].

Currently, DEAs can be processed into various shapes, such as sheets, rolls, and diaphragms. The sheet and roll types expand and contract horizontally, while the diaphragm type can drive the DE sheet, which has been slightly pre-strained horizontally, up and down.

As a result, actuators for a wide variety of applications are being developed, including robotic hands, feet, fingers, prosthetic hands (see Figure 2), prosthetic legs, power-assisted suits, vibrators, speakers, autofocus mechanisms for mobile phone cameras, Mars exploration vehicle controls, satellite antenna controls, rehabilitation devices for fingers paralyzed by stroke (see Figure 3), bedsore prevention devices, blood pressure monitors worn on fingertips, disposable catheters, and various other medical devices, as well as games [2, 6, 58]. Figure 2 shows a small robot hand (can also be used as a prosthetic hand using DEAs: (a) A model that bends and stretches the fingertip using a diaphragm-type DEA: It is the same as the principle that drives a human fingertip. Human tendons are wires, and the muscles that drive the wire are the DEA. (b) A hand model using roll-type DEA: It is also same as the principle that drives the human hand, metal rods (in this case, equivalent to the tendons) and roll-type DEA (equivalent to forearm muscles) enable finger flexion and extension. Compared to diaphragm-type DEAs, roll-type DEAs are heavier but have the advantage of greater output.

Figure 2
Small robot hands

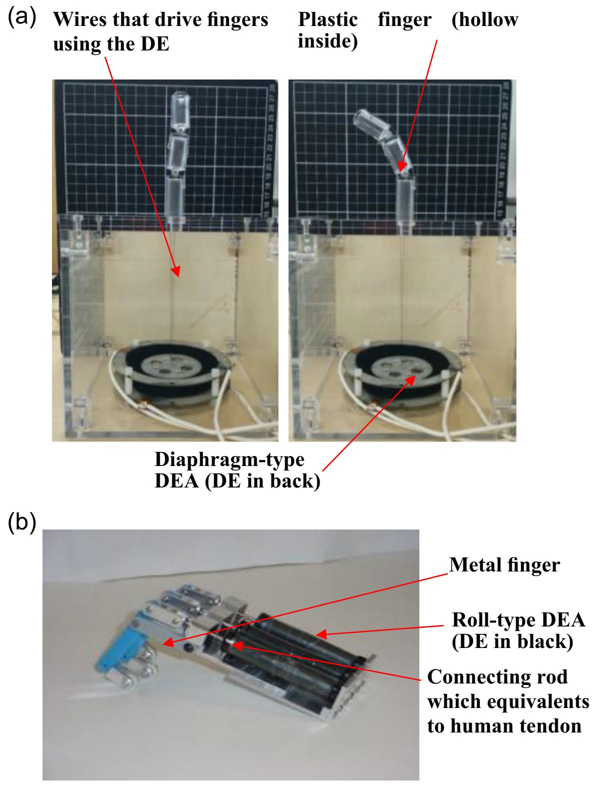
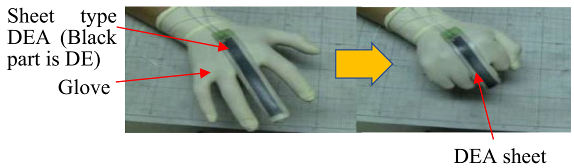
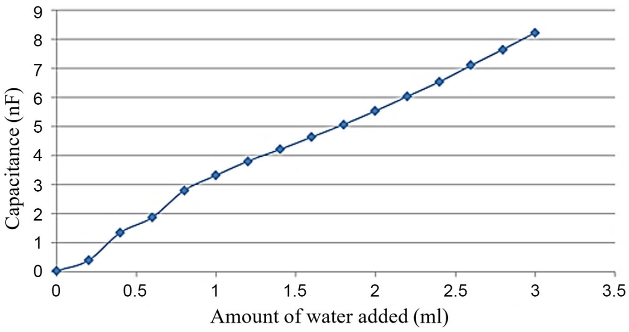


Figure 3
Rehabilitation glove



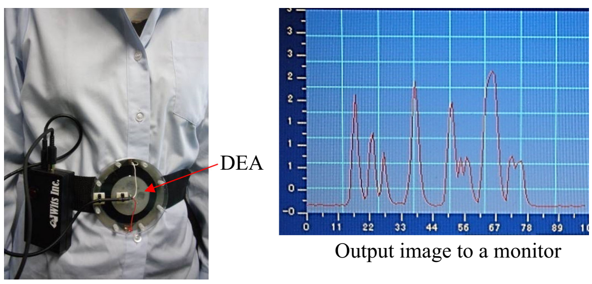
DE is expected to be used in various sensors [2, 6, 58]. It has the same structure as the DE actuator and is capable of sensing. The principle is that when a DE is deformed or stretched by an external force, the change in the capacitance is proportional to the change. Examples of DE sensor experiments include moisture sensors (see Figure 4), pressure sensors, stretch sensors, position sensors, vibration sensors, and wearable sensors that are used to alert people. Figure 4 shows a moisture sensor. The relationship between the amount of water injected and the change in capacitance of the DE sensor is almost linear because the electrodes of the DE are flexible. Diapers that change color when

Figure 4
Moisture sensor



there is urinary leakage are widespread. However, in China, there is a significant shortage of caregivers, so it is necessary for one person to grasp the condition of many elderly people at once. Thus, DE sensor systems that can remotely monitor their conditions are expected to be useful. Moreover, by attaching a thin transducer to the patient's abdomen and checking their breathing pattern while talking to them, this system could be used to diagnose dementia and provide rehabilitation even when the patient is far away from a doctor, and this is expected to be useful (see Figure 5).

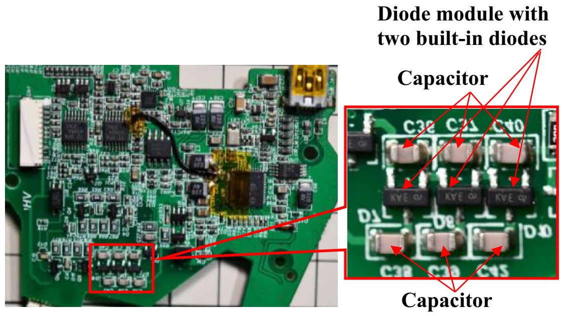
Figure 5
DEA that discerns dementia tendencies in people and the output images



DEA applications often use high voltages of over 1000 V. However, applications using voltages of over 1000 V are not very common. Therefore, the components that can be used in circuit design are limited. In particular, many semiconductors that support high voltages handle large currents and have large losses, making them less suitable for DE applications. One way to overcome these problems is to use multiple devices that are capable of withstanding a voltage of several hundred volts. A typical example is a high-voltage generation circuit using a Cockcroft-Walton circuit. This circuit uses AC waves or pulse waves of several hundred volts, and by repeating this multiple times, it is possible to generate DC high voltages of several thousand volts or more. The main components, capacitors and diodes, can use devices of several hundred volts. Figure 6 shows a high-voltage generation circuit using a Cockcroft-Walton circuit used in headphones equipped with a DE vibrator developed for gaming [58].

In this figure, the part shown in the red frame is the high-voltage generation circuit using the Cockcroft-Walton circuit. It is a 3-stage

Figure 6
Circuit board for headphones with a DE vibrator



Cockcroft-Walton circuit because it consists of 6 capacitors and diodes. Since the applied voltage to the DEA is 1.2 kV, the AC wave applied to the circuit is expected to be about 400 V. Chip parts are utilized for the areas where price and mass production are a concern. Other circuits are audio circuits and equalizer circuits, which make up the majority of the total.

As an example of a DEG circuit design, Mckay et al. [42] demonstrated the possibility of a DEG in which the elastic circuit elements in the film were installed. Anderson et al. [43] introduced soft DE electronics technology that can replace diodes in the DEG priming circuit. To improve the control of the DEG charge state, the diode can be replaced with active switches between the DEG and voltage source and load [42, 43]. van Kessel et al. [31] investigated a passive DEG power generation system that used only diodes at the generator level.

The DE pressure sensor (DEPS) is 2 cm in diameter and only 0.2 mm thick, but can measure pressures from 0.01 N to 1,400 N. The stretch sensor is 10 mm long, 20 mm wide, and only 0.2 mm thick, but can stretch more than 400% [2, 6]. They play an important role in virtual systems.

Figure 7 shows the prototype DEPS using improved hydrogenated nitrile rubber (HNBRs) (hereafter, improved HNBRs will be referred to as HNBRs). The method for this improvement is shown on page 7, center left. Electrodes were created using the CNT spray introduced above. The HNBR is extremely soft, so, by attaching this to a sheet (supporting

Figure 7
The prototype of a DEPS using the improved HNBR: (a) Photograph of the DEPS; (b) A cross-section of the DEPS

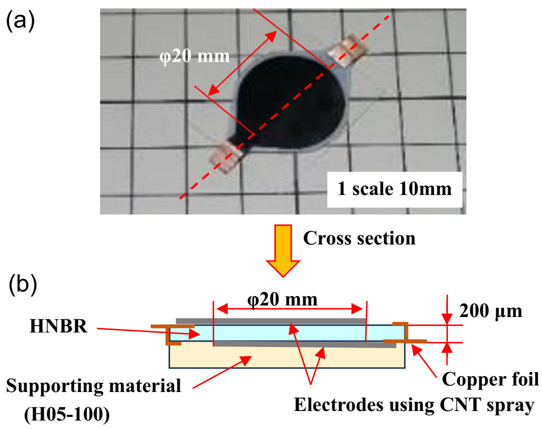
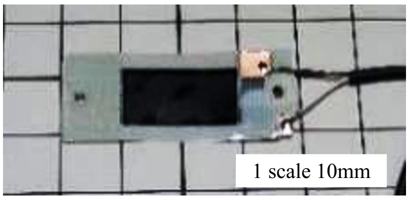


Figure 8
The prototype DESS



material) made of H05-100J manufactured by Exeal Co., Ltd., a structure can be deformed even with a small load. The H05-100J urethane material used here has a hardness of Asker C0/7, which is relatively soft. To confirm that the SWCNTs were uniformly sprayed onto the elastomer surface, four points on the surface of the DE sample were arbitrarily selected and observed using SEM. After creating the SWCNT electrode film on the elastomer, several locations were randomly selected and the thickness was measured with a Keyence double scan high-precision laser measuring instrument (LT-9500 & LT-9010M), all of which were 50 μm.

Figure 8 shows the prototype of the DE strain sensor (DESS) using the HNBR. The basic configuration is the same as the DESP described in Figure 7. However, in consideration of attaching it to a robot hand, the shape is a rectangle 10 mm in length and 20 mm in width, and no support material is used.

Changes in capacitance with an LCR meter while stretching were measured. The elongation was measured using a digital caliper, and the lengths were compared. In both cases, an electric current was applied to check the conductivity, and the LED was turned on. As a result, an elongation of 400% was measured. Figure 9 shows the change in the measured DESS capacitance. A is the point where the DESS displacement begins, and B is the point where the capacitance begins to change. The time from point A to point B was 50 ms, and it was confirmed that sufficient driving speed was obtained for use in a robot hand. Thus, the response speed of the DESS was 50 ms. The speed of DEPS was measured and found it to be 50 ms, the same as DESS, which is also fast enough.

Figure 10 shows an experiment in which a robot's fingers were driven using a DE motion feedback device [59]. The operator placed a glove equipped with a DEPS, DE stretch sensor, and DE touch

Figure 9
Changes in measured capacitance

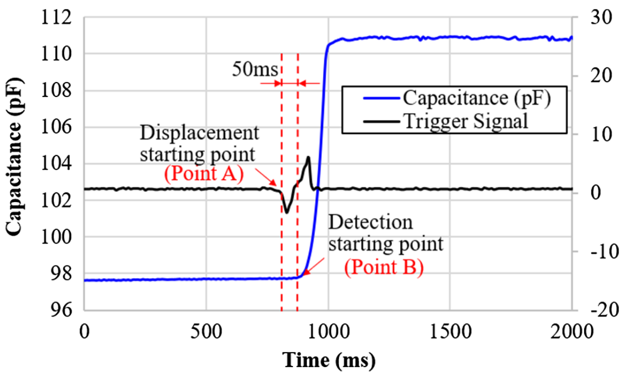
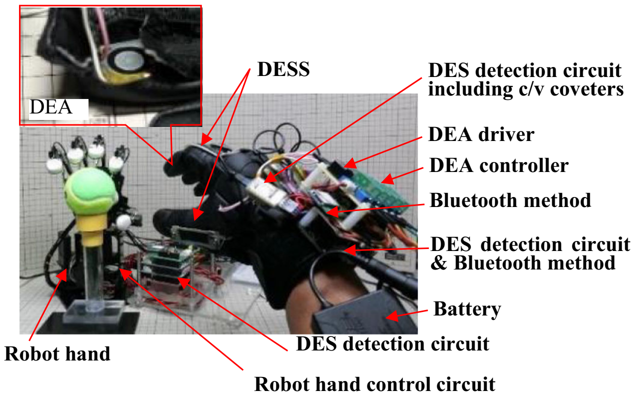


Figure 10
DE motion feedback system: The small diaphragm DE actuator on the top is a device that operates when the robot's finger touches a target part, creating a sense of touch



sensor (sensors that enable the operator's fingers to feel when the robot's fingers touch an object). It was confirmed that the operator's hand movements were transmitted to the robot, allowing the robot's fingers to be driven accurately. The driving speed was 50 ms.

DEGs have been developed in a variety of forms, including shoe-type power generation, solar power generation, wave power generation, fluid power generation such as water currents, wind power generation, power generation using vibrations from machines, bridges, and roads, power generation worn on the human body, and nanogenerators using frictional heat (6, 54, 56, 57, 62). Recently, a handheld generator was created by placing two 8 cm diameter DEs (see Figure 11) [33]. This made it possible to store the electricity generated by the DEG in a secondary battery. The circuit used in this study converts a high voltage of approximately 3,000 V output from the DE G to a few volts using a step-down circuit with multiple high-voltage capacitors to store the primary power. The energy-harvesting IC monitors the voltage of the electrical energy stored in the high-voltage capacitor; when it reaches 3.3 V, the output control switch is activated and 3.3 V is output to the outside. This makes it possible to convert the high-voltage intermittent electrical energy from the DEG into a stable 3.3 V voltage and supply it to other secondary batteries or sensor systems. Figure 11 shows the prototype DE power generation unit and the charging circuit for the small DE generator. The DE power generation unit is a short cylindrical device, as shown at the bottom of Figure 12. It consists of a cartridge with two diaphragm-type DEs with a diameter of 8 cm stacked on top of each other, and an acrylic rod

Figure 11
DE power generation unit and charging circuit for small DE generator

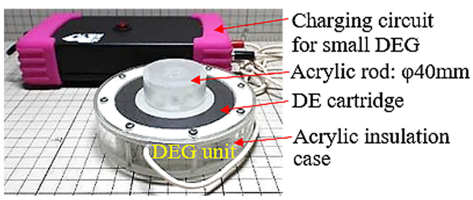
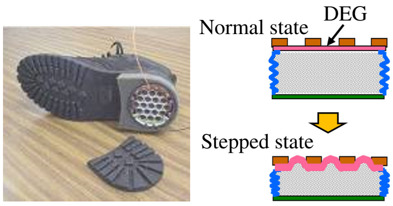


Figure 12
DE shoe power generation



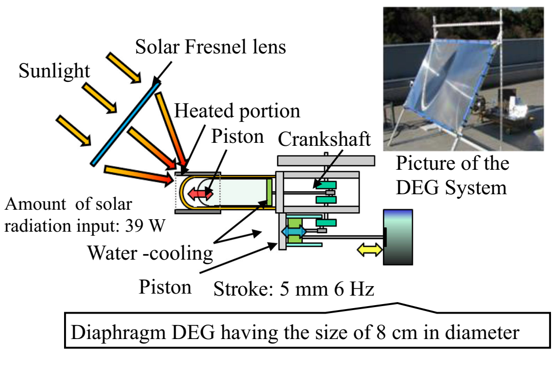
that generates electricity by pressing the DE generator. This example shows that the energy generated by attaching the sensor to a human or animal body can be charged. This is expected to help prevent cameras, smartphones, etc., from running out of the battery when active outdoors.

Previously, attempts were made to generate electricity by attaching DEGs to the soles of shoes or to the body (see Figure 12) [58].

A solar heat power generation system was developed as a unique example of DE power generation (see Figure 13) [58]. Figure 13 shows a DE Solar Heat Generator. Fresnel lens having the effective size of 1,000 mm × 1,350 mm and thickness of 3 mm. The capacity of the tube was about 44 cm^3. The piston stroke was 24 mm, and the diameter of the piston was 25 mm. This system has a higher power generation efficiency than solar power generation; however, the results are lower than those of normal DE power generation. The principle is that air is placed into a tube, which expands with the radiant heat of the sun to drive the DE. However, because the temperature of radiant heat is high, heat easily escapes, resulting in a decrease in efficiency. The use such as pentane (boiling point of 36 °C), which is expected to change in volume at room temperature or slightly higher, as a medium is being considered. If these are used, it may be possible to generate electricity exercise-induced changes in the body temperature of humans and animals. However, such media are toxic; therefore, caution is required when using them.

The energy conversion efficiency of a buoy-type wave power generation system equipped with DEGs is discussed [60]: The power generation unit is composed of a diaphragm DEG incorporating a 1.4 g acrylic (3M VHB4910) DE that moves vertically in response to waves. The diameter of the DEG is 8 cm, and carbon blacks are used as electrodes. For the experimental condition of the wave height is 0.03 m and the wave period is 0.98 s, the electric energy generation is 39.767 mJ. As a result, the electric energy was 39.767/0.98 s = 40.579 mW. Thus, the energy conversion efficiency is 40.579 mW /1.83 W = 0.02217 (2.217%). It is concluded that 2.217% of wave energy is converted to electric energy in the experiment for the wave height of 0.03 m and the wave period is 0.98 s. This means that, theoretically, placing 45 more DEGs per meter could absorb almost 100% of this wave energy and convert it into electrodes. The size of this DEG is small enough, so a large number of DEGs can be installed, and it can generate electricity 24 h a day, 365 days a year; if it is stored in a secondary battery, a considerable amount of electricity can be used. As mentioned above, the energy conversion efficiency of DEG is relatively small compared to wave energy. However, the maximum power generation capacity of DEG was 68.29 mJ and 39.767 mJ at a wave height of 3 cm. Therefore, the energy generation efficiency of DEG is 58.2%. In another experiment conducted by the authors using a wave tank with a length of 30 m, width of 0.6 m, and depth of 1.5 m, 90.6% was recorded at a wave height of 6 cm [60]. By the way, the champion data for LNG-fired power generation are 63.6% and were achieved by Tohoku Electric Power in 2023 [61]. However, existing wave power generation systems are limited by the direction and magnitude of the waves, and the system is complicated, which makes the construction cost very high. As Adderlini et al. [62] pointed out, the levelized energy cost of existing systems has not yet reached a level that can compete with fossil fuel power plants. In other words, the power generation efficiency is still low. Recently, the Hiratsuka Wave Power Plant in Japan claimed to have achieved 50% efficiency when waves were 150 cm high [63]. However, this can only be achieved if the waves are set to strike the reflector perpendicularly. The system uses a wave reflector that rocks back and forth with the energy of the incoming waves, driving a hydraulic cylinder that drives a permanent magnet generator, which converts the energy into electrical energy.

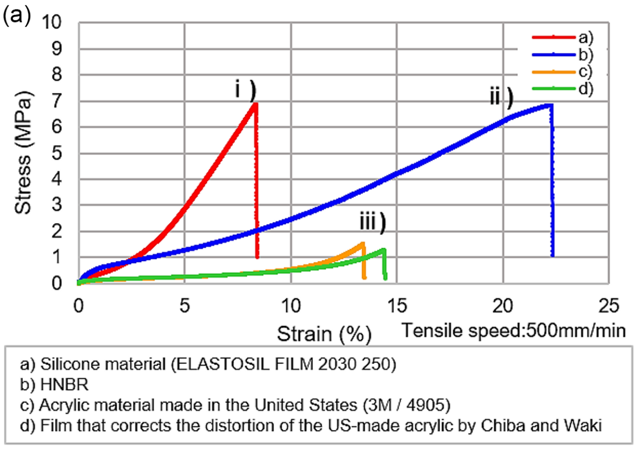
Figure 13
DE solar heat generator

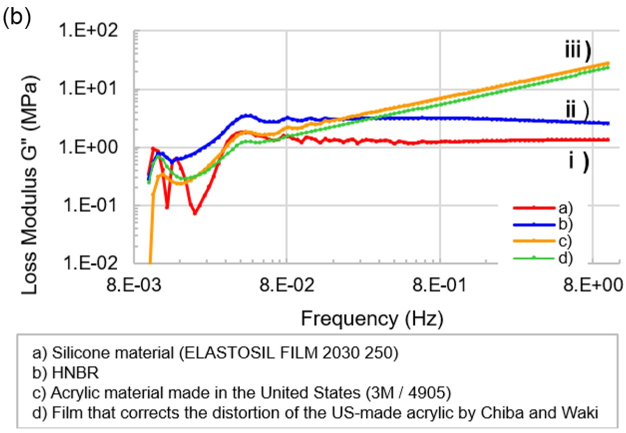


3. Factors That Improve DE Performance

Various materials have been investigated as elastomers to DEs. Examples include silicones, acrylics, polyurethanes, fluorosilicones, fluoroelastomers, polybutadiene, isoprene, and HNBR. From these studies, factors that affect the performance of a DE include the Young's modulus, electric field breakdown strength, Coulomb force-induced pressure, dielectric constant, and membrane thickness. DEs capable of large deformations and power outputs tend to have large values of electric field breakdown strength (Coulomb force-induced pressure), Young's modulus, or dielectric constant. However, simply increasing these parameters does not seem to significantly affect the performance of the DE. In other words, the elastomer membrane does not deform unless there is a large pressure caused by a larger Coulomb force (through the thickness) [2, 6]. This is because when a voltage is applied to the DEA, the membrane is pushed by the Coulomb force and stretches laterally; however, at the same time the membrane hardens. If the slope of the SS curve of the DE membrane is small or has a gentle curve, it does not immediately harden and may deform further. In other words, a large deformation can be obtained at relatively low pressure. Following this idea, in this review paper, we attempted to examine the above parameters using SS curve data and dynamic viscoelasticity data of actual elastomers [2, 6]. Figure 14 shows the SS curves and dynamic viscoelasticity measured using silicone, acrylic (including an improved version that removed membrane distortion), and HNBR.

Figure 14
(a) SS curves and (b) viscoelastic properties of the four films: materials used: (i) silicone ELASTSIL film/2030-250, (ii) HNBR, (iii) acrylic 3M4905, and strain-relieved film of 3M4905





The manufacturing process for DE has not yet been established. Although it depends on the application, a thin elastomer (50 µm to 1 mm thick) is used. Before spraying the electrodes, the elastomer is lightly pre-stretched, and then a carbon-based material is sprayed evenly on top to form the electrodes. As mentioned above, the electrodes are made by spraying carbon-based materials and applying them evenly. If applied poorly, the surface will be uneven and the electrolytic breakdown strength will decrease significantly. The easiest method that yields the best results is to spray the above materials using a solvent that matches them [6]. Through spraying, it is possible to apply a uniform and thin electrode to DEs of any shape. It should be noted that if the electrode is thicker, the membrane becomes harder and more difficult to stretch. Furthermore, what is important here is to check with a low-magnification microscope that the elastomer is free of scratches, distortions, and inclusions (including bubbles). In this paper, the acrylic elastomer is a commercially available thin sheet (3M 4905). The silicone film is also commercially available, and silicone ELASTSIL film/2030-250 is used. The HNBR is made by Zeon Corporation and is rolled to a thickness of 200 µm.

Silicone was the hardest membrane, followed by HNBR and acrylic. As shown in Figure 14, silicone membranes are harder than acrylic and HNBR; therefore, a large force is required to deform them. In other words, when a large force is applied, the membrane stretches, but the compression pressure is also large, which accelerates the stretching of the membrane and hardens it at the same time; thus, the deformation reaches a saturation state sooner, resulting in less stretching. Physically, such elastomers tend to exhibit low viscoelasticity (liquid-like properties) [6]. Figure 14(b) also shows that silicone is less affected by dynamic viscoelasticity than acrylic is. Therefore, when a voltage was applied, the membrane became harder and faster, and the degree of deformation decreased. Conversely, acrylic has a higher viscoelasticity than silicone; therefore, it can be more deformed and may have a greater dependence on the tensile speed [6]. Interestingly, the slower the pulling speed of the acrylic, the larger the maximum stress. Therefore, a larger deformation was obtained. Again, this was because of its high viscoelasticity (see Figure 14(b)). In addition, even with the same acrylic, one (orange) has residual distortion in the film owing to casting, etc., and the other (green) has the film distortion removed. Naturally, the type with distortion removed has a larger elongation than the type without distortion removal.

Here, we assume that the proportional relationship between force and elongation when pulling the elastomer is exactly the same. In other words, when the elastomer is pulled, it stretches according to the force; as a result, the following relationship holds [6]:

$$\sigma = \nu_m k_b T \left(\lambda - \frac{1}{\lambda^2} \right) \tag{2}$$

Here, ν_m is the total number of molecular chains contained in a unit volume, kb is the Boltzmann constant, T is the temperature, R is the gas constant, and λ is the change length of the elastomer. Therefore,

$$\nu_m k_b\ T = \frac{\nu_m}{N_A} N_A k_B\ T = \frac{\rho R T}{M} \tag{3}$$

This can be transformed, as described above. Here, ρ is the density, and M is the molecular weight of the polymer chain between the mesh and the mesh structure; that is, the polymer has a three-dimensional mesh structure formed by the bridge. From the above equation, we can see that the stress increases when the molecular weight between the mesh sheets is small; that is, the degree of cross-linking increases. Based on this equation, the above phenomenon can be explained.

In addition, there is a method of mixing elastomers with substances with high dielectric constants to increase the electrolytic breakdown strength of the membrane; however, this is a double-edged sword, and mixing them makes the membrane harder, so care must be taken. Moreover, the movement of DE can be improved by applying pre-strain to the membrane to reduce the initial membrane reaction [2]. This was inconvenient for the experiments because if the elastomer was stretched several times, it would not return to its original length. However, after Chiba et al. [2] confirmed that if an elastomer was stretched from a slightly stretched state at first, it would return to its original length, research into applying pre-strain was initiated. All the membranes mentioned above are elastomers available on the market. There are many cases of new elastomers being developed, but unfortunately, none of them can be said to have been very successful. The original HNBR introduced in this review paper is rubber that is placed between the engine and the body of a car to absorb vibrations. It can withstand high temperatures and is resistant to oil, making it ideal for DEs in automobiles. However, it is not suitable for DEs. Therefore, the amount of cross-linking agent in original HNBR was reduced and some of the bonding at

Table 1
Electrode type and weight that DEA can lift

Electrode type	Weight that can be lifted with a stroke of 5 mm (N)
Carbon Black	10
MWCNT	16
SWCNT	22
Selected SWCNT	29

Note: The selected SWCNTs were separated using a fixed-angle rotor ultracentrifuge for a slightly longer time, resulting in the selection of SWCNTs with smaller diameters and possibly an increased amount of metallic CNTs [2].

the double bonds was cut off, resulting in an elastomer that is softer than silicone and has good DE performance, as shown above.

The type of electrodes and the method of fixing them to the elastomer also play a major role in the performance of the elastomer. First, we consider the type of electrode [6]. Choosing one with high conductivity naturally improves the performance of the DE. However, if a metal is chosen, it is not suitable for DE because it is hard and does not stretch. If a metal is used, it is better to stretch the gold as thin as possible or to use liquid metal. However, even if it is stretched very thinly, the deformation of the DE is approximately 5%. Leakage is a concern in the case of liquid metal. Table 1 compares the numbers of newtons of weight that can be lifted by 5 mm using carbon grease, carbon black, multi-walled nanotubes, SWCNTs, and selected SWCNTs as electrodes. This result clearly shows that the DE performance improves when electrodes with high conductivity are used. The same was true for energy generation, with the selected SWCNTs being the best (see Table 2).

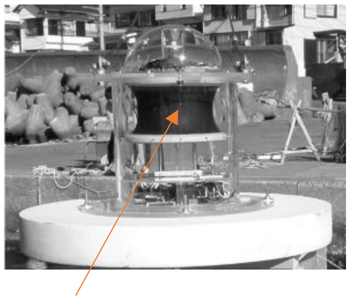
Table 2
Differences in energy obtained from different electrode materials

Electrodes	Energy obtained (mJ)
Carbon Black	274
MWCNT	445
SWCNT	630
Selected SWCNT	819

A drape-type DE was used for power generation evaluation. A drape-type DE is a cylinder that is pulled slightly vertically and has a small depression at the center to create a drum-like shape. Its dimensions were 120 mm in height and 260 mm in diameter from top to bottom. Figure 15 shows a photograph of a drape-type DEG attached to a wave power generation buoy. This drape is a hollow type, and the black part in the center of this photograph is the drape-type DEG. The elastomer used is 4.6 g of 3M4905. The electrodes used for comparison were the same as those used in the DE actuator (see Figure 15). As a result, there was a difference of approximately three times between the selected SWCNT and carbon black.

The important thing here is how to apply these materials to membranes, as described above. If applied poorly, the surface will

Figure 15
A photo of a drape-type DEG mounted on a buoy



Hollow type DE drape roll
φ260mm×120mm
Weight: 4.6g

be uneven and the electrolytic breakdown strength will decrease significantly. The easiest method that yields the best results is to spray the above materials using a solvent that matches them [3]. Through spraying, it is possible to apply a uniform and thin electrode to DEs of any shape. It should be noted that if the electrode is thicker, the membrane becomes harder and more difficult to stretch.

Kornbluh et al. [64] pointed out that the main factor in improving the lifespan of a DE is that if it is used below its maximum performance, it can be used tens of millions of times without any problems. Thus, it is very important to improve the performance of DE [6, 64]. In addition, some materials are sensitive to moisture; therefore, it is easy and effective to add a jacket to DE. In addition, the 8 cm diameter circular DE that author made more than 15 years ago is sandwiched between acrylic plates; however, it still works fine even in the hot summer weather. We think this is because it is sandwiched between acrylic plates and is not affected by the humidity in the air.

Guo et al. [65] indicated that conventional DE materials suffer from electromechanical instability, which reduces their performance and limits their application in soft robotics. To overcome this, it was found that there is great potential to fabricate DEs with a sufficient life span and high performance by using the factors and methods to improve the performance of DEs described in this section.

Finally, cost-effectiveness and scalability have not been fully considered. These will need to be considered when applying to actual applications. When deciding on the actual application, cost-effectiveness should be determined by setting a price that is acceptable to the market and at the same time taking into account the performance desired in the market. CNTs are generally said to be expensive, but depending on the size of the DE, the amount used as an electrode is quite small. Carbon black is also inferior to CNT in terms of conductivity. However, the price is quite low, and it is possible to improve performance by devising the structure of the DE. For example, the membrane size for the sensor is also small and quite thin, so the price of these is not high at all. Regarding scalability, DEs can be shaped into any shapes and are easy to stack.

4. Conclusion

In this study, the current status of research and development of DE using polymer (mainly elastomer) materials and factors for improving its performance were examined, and the following were found:

1) If the slope of the SS curve of the DE film is small or gentle, it may not immediately harden even when electricity is applied to the DE, and the deformation continues further.
2) Elastomers with high dynamic viscoelasticity are likely to deform more significantly. However, in this case, pre-straining the film can achieve a more stable movement.
3) From the results of the SS curve, the hardness of the film affected the elongation. Therefore, it is desirable to sufficiently remove the distortion when forming a film.
4) Care must be taken when adding cross-linking agents or substances to improve the dielectric constant. If used incorrectly, the film becomes harder, and the performance decreases.
5) Using electrode materials with higher conductivity will improve the performance of the DE.
6) When attaching electrode materials to elastomers, it is best to select a method that allows uniform and thin electrodes. When using carbon-based materials, it is best to spray them with an appropriate solvent.
7) To extend the life of a DE, you can increase its maximum performance and then operate at a level well below that performance, which will significantly extend its life.
8) The use of DEs is effective in wearable systems. DEs are lightweight, small, deformable, responsive, and capable of generating large forces. Therefore, they can be used not only as actuators but also as various sensors. Furthermore, it is now possible to attach them to shoes as small generators and store electricity in small secondary batteries dedicated to the DEG.
9) With the emergence of the above devices and DEA that can reproduce sensations such as touch, virtual experiences are expected to become more realistic. In addition, with the availability of 5G, it is becoming possible to perform some examinations and surgeries even if the patient and doctor are far away from each other. Moreover, when operating machines or equipment that are located far away, the sensation of driving is motion-fed back, resulting in a more realistic driving sensation.

Recommendations

In this study, we demonstrated that DEs function as actuators, sensors, and generators, and that they are inexpensive, lightweight, simple in structure, multi-layered, can produce high output, and are highly efficient. They are also ideal for use in wearable devices. Furthermore, with the emergence of DE actuators that can reproduce tactile sensations, it is expected that the combination of these devices will make virtual experiences more realistic. In addition, with the spread of 5G, it is becoming possible to perform some examinations and surgeries, even if the patient and doctor are far apart. Furthermore, when operating machines and equipment in remote locations, the driving sensation is motion-fed back, providing a more realistic driving sensation.

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Ethical Statement

This study does not contain any studies with human or animal subjects performed by any of the authors.

Conflicts of Interest

The authors declare that they have no conflicts of interest to this work.

Data Availability Statement

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

Author Contribution Statement

Seiki Chiba: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration. **Mikio Waki:** Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing – review & editing, Visualization.

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