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Review:

Artificial muscles for wearable assistance and rehabilitation*

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Abstract: Traditional exoskeletons have made considerable contributions to people in terms of providing wearable assistance and rehabilitation. However, exoskeletons still have some disadvantages, such as being heavy, bulky, stiff, noisy, and having a fixed center of rotation that can be a burden on elders and patients with weakened muscles. Conversely, artificial muscles based on soft, smart materials possess the attributes of being lightweight, compact, highly flexible, and have mute actuation, for which they are considered to be the most similar to natural muscles. Among these materials, dielectric elastomer (DE) and polyvinyl chloride (PVC) gel exhibit considerable actuation strain, high actuation stress, high response speed, and long life span, which give them great potential for application in wearable assistance and rehabilitation. Unfortunately, there is very little research on the application of these two materials in these fields. In this review, we first introduce the working principles of the DE and PVC gel separately. Next, we summarize the DE materials and the preparation of PVC gel. Then, we review the electrodes and self-sensing systems of the two materials. Lastly, we present the initial applications of these two materials for wearable assistance and rehabilitation.

Key words: Artificial muscle; Smart material; Dielectric elastomers (DE); Polyvinyl chloride (PVC) gel; Actuator; Wearable assistance; Rehabilitation
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1 Introduction

Aging is accompanied by a series of muscle problems (Candow and Chilibeck, 2005), and may also increase the probability of some diseases such as stroke (Kelly-Hayes, 2010), which affects basic daily activities such as walking, eating, and shopping. Fortunately, with the development of robotics, many exoskeletons have been invented to solve these problems (Weber and Stein, 2018), and these have dramatically reduced the burden on physical training therapists. However, traditional exoskeletons made of steel are very heavy. In addition, drive motors and reducers mounted on the exoskeletons act directly on human joints, which is distressful for elders and patients. Furthermore, most exoskeletons have a fixed center of rotation, whereas human joints do not. When people wear the exoskeletons, the resulting misalignment restricts their movement, which causes discomfort, and may inflict secondary damage to the patient (He et al., 2017).

Pneumatic actuators, which can provide a higher force and are flexible, behave like natural muscles and have been widely used in wearable assistance and rehabilitation robots (Dzahir and Yamamoto, 2014). However, these actuators require external air compressors that are heavy, large, and noisy. Moreover, the response speed of the actuator is usually limited by the airflow capability of the tube.

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In recent years, a soft exosuit that considers muscle synergy has been presented by Harvard University. It has been used to assist walking and rehabilitation (Asbeck et al., 2015; Awad et al., 2017). Unlike traditional exoskeletons, the exosuit has no rigid frame, consists mainly of webbing straps and looks like a piece of clothing. However, the exosuit still requires heavy motors and reducers to drive Bowden cables that are connected to the webbing straps.

Artificial muscles based on smart materials, which are lightweight, mechanically flexible, and quiet, have drawn much attention for use as soft actuators in recent years (Lee et al., 2017; Mirvakili and Hunter, 2018). The actuating method is determined by the material; for example, the thermally responsive method is used for shape memory alloys (SMAs), the electrically responsive method for dielectric elastomers, and chemically responsive method for hydrogels (Hines et al., 2017). However, the response speed of most materials is very slow, which is a challenge for wearable assistance applications. Fortunately, some electroactive polymers (EAPs) have both fast response and large deformations, which make them most closely resemble biological muscles (Bar-Cohen et al., 2017).

In this paper, we focus on two kinds of EAPs, dielectric elastomers (DEs) and polyvinyl chloride (PVC) gels, which hopefully will be applied to wearable assistance and rehabilitation in the future (Carpi et al., 2014; Li and Hashimoto, 2017). For DEs and PVC gels, we first introduce the working principles. Then, the materials and electrodes are reviewed. Lastly, we present self-sensing systems and some applications for wearable assistance and rehabilitation.

2 Dielectric elastomer actuators

DEs are a class of EAPs that can convert electrical energy into mechanical energy through the electrostatic interaction between two electrodes. The material dates to the 18th century in a letter by the Italian physicist Alessandro Volta who mentioned that a shape change in a solid dielectric with electric charge was observed in a Leyden jar (Carpi et al., 2010). About a hundred years later, in 1880, Röntgen discovered that a natural rubber sheet became thin and long when electric arc sprayed on it (Keplinger et al., 2010). This is a milestone experiment for electroactive DEs. However, it was not until the beginning of the 21st century that the electroactive DEs ushered in a boom (Gu et al., 2017b).

2.1 Working principle

The DE actuator is composed of a thin elastomeric film with compliant electrodes on both sides. When a voltage is applied to the electrodes, the upper and lower electrodes attract each other (this is called Maxwell or electrostatic force), resulting in a reduction in film thickness and an expansion in area (Fig. 1). When there is no voltage applied to the electrodes, the DE film quickly returns to its original shape.

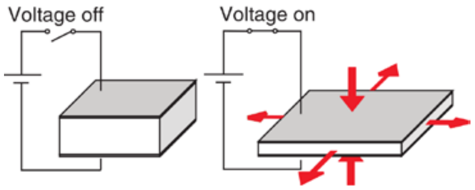


Fig. 1 Working principle of the DE actuator

The Maxwell force, which is determined by the total permittivity of the material and the electric field strength (Pelrine et al., 1998), can be expressed as

$$p = \varepsilon_0 \varepsilon_{\rm r} E^2 = \varepsilon_0 \varepsilon_{\rm r} (V/d)^2, \tag{1}$$

where p represents the Maxwell pressure, ε_0 is the vacuum permittivity, $\varepsilon_{\rm r}$ is the material permittivity, E is the electric field strength, V is the applied voltage, and d is the thickness of the film.

For an actuation strain less than 10%, the value of the change in thickness can be obtained through the principle of linear elasticity (Pelrine et al., 1998):

$$s_d = -\frac{p}{Y} = -\frac{\varepsilon_0 \varepsilon_{\rm r} (V/d)^2}{Y}, \tag{2}$$

where s_d is the change in thickness and Y is the elastic modulus of the material.

When the deformation of the material is large, the stress–strain curve is no longer linear. This means that the elastic modulus of the material has changed, and Eq. (2) is no longer applicable. DE is considered a super-elastic body, and many nonlinear models have been developed based on this property, such as the Mooney–Rivlin model (Goulbourne et al., 2005; Kim et al., 2018), neo-Hookean model (Li et al., 2011; Yang et al., 2017), Ogden model (Kofod, 2008; Sharma et al., 2017), and Yeoh model (Wissler and Mazza, 2005; Tran et al., 2017). Some researchers have used viscoelastic models to describe DE actuators (Hong, 2011; Kollosche et al., 2015; Patra and Sahu, 2015; Liu and Zhou, 2018; Zou and Gu, 2018). The review articles by Wang and Qu (2016), Zhu et al. (2016), Gu et al. (2017a), and Kadooka and Taya (2018) present more specific descriptions of DE actuator models.

The nonlinear models can better predict large deformations of the materials, but none of the models are applicable to all cases because the materials and test conditions are different. Suo (2010) developed a theory within the framework of continuum mechanics and thermodynamics to describe the general model of DE, and made good progress.

2.2 DE materials

Over the past two decades, many dielectric materials have been studied. Among these materials, acrylics and silicones have been the subject of most studies. Acrylic elastomers, whose area strain can reach 1692% (Li et al., 2013), are the most promising materials for applications requiring large strain. The commercial availability of 3M VHB acrylic elastomers (VHB 4910 and VHB 4905) has also contributed to its popularity among researchers. However, these materials exhibit strong viscoelasticity (Hong, 2011), which limits the bandwidth of the actuator. Silicone elastomers overcome this shortcoming and exhibit a much faster response, but the actuation strain of silicone elastomers is much smaller than that of acrylic elastomers. Also, silicone elastomers have a lower dielectric constant and therefore require a higher driving voltage.

For a DE film with a thickness of 10 to 100 μm, the driving voltage generally ranges from 500 V to 10 kV (Brochu and Pei, 2010). The high driving voltage limits its application in many fields, especially in wearable assistance. Many studies have been focusing on new DE materials to reduce the driving voltage. According to Eq. (1), increasing the permittivity of materials can reduce the driving voltage. The most common way to increase the material's permittivity is to add a certain filler with a high dielectric permittivity to a matrix material, for example, adding carbon black to ethylene acrylic elastomer (Sahoo et al., 2012; Shakun et al., 2018), polydimethylsiloxane adulterated with multi-walled carbon nanotubes (Liu et al., 2015), and TiO_2 mixed in polydimethylsiloxane (Liu et al., 2013). Brochu and Pei (2010) and Romasanta et al. (2015) provided more information on the improvement of elastomer materials. Although material modification can reduce the driving voltage, it also introduces some unwanted properties to the material. For instance, fillers increase the elastic modulus of the dielectric material, which reduces the actuating strain. Furthermore, the use of fillers is accompanied by an increase in dielectric loss, and the materials are more easily broken down at lower driving voltages due to large leakage current. To obtain a better performance of elastomer materials, the quantity of filler needs to be well controlled.

2.3 DE electrodes

Electrodes are a critical factor in the development of DE actuators. The electrodes need to have good electrical conductivity and be sufficiently compliant not to generate opposing stress on the elastomer films. Metal films that have a high electrical conductivity are used as the electrodes of DE actuators. However, the deformation of the elastomer films is limited by about 1% because of the high stiffness of the metal films (Brochu and Pei, 2010). With the development of microfabrication technology, the metal films can be made into nanoscale electrodes. Thinner metal films provide less additional stiffness to the elastomer films, allowing them to produce greater strain for DE actuators (Rosset and Shea, 2013; Park et al., 2014). However, no matter how thin the metal electrodes are, the additional stiffness still limits the deformation of the actuators. Moreover, the microfabrication technology increases the difficulty of making DE actuators in the laboratory.

The most commonly used electrodes for DE actuators are carbon-based compliant electrodes, which can be divided into three main categories: (1) Carbon powders such as carbon black and graphite can be directly applied to DE films. These are especially suitable for 3M VHB acrylic elastomers that have strong adhesion on both sides. The carbon powders add no additional stiffness to the elastomer films; thus, the DE actuators can produce large strain. However, the conductive carbon powders will detach from the electrodes at high strain, which will shorten the life span of the DE actuators. (2) Carbon greases are the most popular compliant electrodes because they can adhere to the highest number of elastomer film types without additional stiffness. However, the conductive particles in carbon greases could diffuse into the elastomer films, causing a short circuit, and the greases will dry out after a long period of use, which reduces the life span of the DE actuators. (3) Carbon compound electrodes are mixtures prepared from carbon powders mixed into elastomer matrixes. Unlike carbon powders, the carbon compounds attach well to the surfaces of elastomer films without falling off for a long time. However, electrodes based on carbon compounds give the elastomer films additional stiffness, which limits its use for applications requiring high strain.

The electrodes mentioned above are all non-transparent. However, some particular applications require transparent electrodes (Chen et al., 2016). Yuan et al. (2008) developed a transparent electrode with single-walled carbon nanotubes. The strain of its DE actuator reached 200% under 5 kV. In addition, the transparent electrodes had self-cleaning characteristics, which extended the life span of the DE actuator by preventing electrode damage overall. Hydrogels have been studied as transparent electrodes, which could also produce high strain (Chen et al., 2014; Tang et al., 2018). However, similar to carbon powders, compliant electrodes based on single-walled carbon nanotubes and hydrogels still have trouble with being well bound to elastomer films.

2.4 Self-sensing

Humans have a variety of sensing systems that allow them to interact effectively with their surroundings. Traditional robots, such as wearable assistance and rehabilitation devices, are also integrated with a variety of rigid sensors to make the systems work successfully. If these rigid sensors were connected directly to the DE actuator, they would inhibit motion from the actuator and add undesired volume and mass. Fortunately, another advantage of the DE actuator is that it can be used simultaneously as a sensor in the actuating process, which is called self-sensing (Rizzello et al., 2016). The central working principle of the DE as a sensor is that the deformation of the DE film will lead to changes in the electrical characteristics of the DE actuator, such as capacitance, voltage, and current, such that by detecting these characteristics people can monitor the working status of the DE (Anderson et al., 2012; Zhang et al., 2017; Qin et al., 2018).

Jung et al. (2008) developed a self-sensing DE actuator without using traditional rigid sensors (Fig. 2). The DE actuator was in series with an external resistor, which could serve as a high-pass filter. They used a low-frequency signal for actuating and a high-frequency signal for sensing. Only the high-frequency sensing signal was obtained owing to the characteristics of the high-pass filter. The deformation of the DE film caused a change of the gained voltage from the high-frequency sensing signal. Therefore, the output sensing voltage could estimate the displacement of the DE actuator.

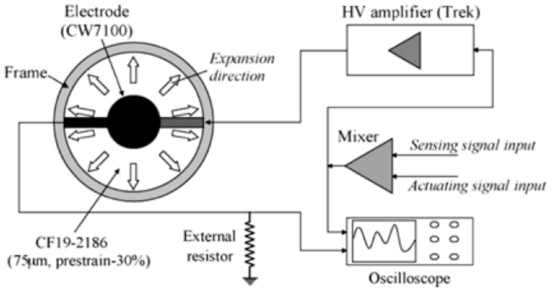


Fig. 2 Diagram of a self-sensing method for a DE actuator
A DC voltage is used for actuating and a low AC voltage for sensing (Reprinted from Jung et al. (2008), Copyright 2007, with permission from Elsevier)

O'Brien et al. (2007) presented a self-sensing DE actuator based on the measurement of electrode resistance. By comparing the performance of three carbon-based electrodes, they found that the carbon powders had the best performance for low noise and no hysteresis. However, the method showed the bandwidth of the self-sensing system to be about 0.2 Hz, and the maximum error was over 20%.

When the DE actuator is significantly deformed, various electrical characteristics such as capacitance and electrode resistance will change at the same time (Gisby et al., 2013). Thus, detecting one of these electrical properties does not accurately indicate the state of the DE actuator. Keplinger et al. (2008) proposed to use a high-frequency AC signal to measure the complex electrical impedance of the DE actuator. The gain and the phase of the signal were analyzed to represent capacitance and electrode resistance. Gisby et al. (2013) presented a self-sensing algorithm to estimate the change of the DE actuator capacitance combined with electrode resistance and leakage current through the DE film.

Force self-sensing methods are also being studied for DE actuators. Zhang et al. (2017) developed a DE actuator with a self-sensing structure for force feedback based on detecting capacitance. The actuator consisted of two regions, one for actuation and the other for sensing. The results showed that a long-term drift commonly appearing in self-sensing actuators was avoided in the actuator. Recently, Rizzello et al. (2018) designed a self-sensing DE actuator that detected displacement and force simultaneously, based only on the measurement of current and voltage.

2.5 Wearable assistance applications

DE actuators have the performance characteristics of light weight, fast response, acoustical silence, compact structure, and low power consumption, which are desirable for applications in wearable assistance and rehabilitation. However, there are few studies on DE actuators for applications in these areas.

Carpi et al. (2008, 2014) developed a hand rehabilitation device based on a DE actuator (Fig. 3). The DE actuator was made primarily of silicone films and custom-made silicone/carbon-black mixture electrodes. A multi-layer stacking mechanism was used to achieve a large actuating displacement. A plastic layer was used to protect users from high voltages. The device could implement flexions and extensions of human fingers. The stiffness of the device was regulated by the driving voltage. However, the device was still heavy owing to its many auxiliary structures such as an aluminum rod with a pulley for position adjustment, and a load cell for force detection. Furthermore, the purely active force was below 1 N at 5 kV.

Pourazadi et al. (2014, 2015) designed an active compression bandage (ACB) based on the DE actuator for patients who suffered from disorders associated with the lower extremity venous system (Fig. 4). The DE actuator was composed of silicone elastomers and compliant electrodes made from a mixture containing carbon black in ethanol. The ACB included three DE actuators for compressing the ankle, mid-calf and knee areas of the calf. Stretchable fabrics covered the DE actuators to prevent electric shock. The results showed that the ACB could provide the same pressure as the traditional compression socks, and that the applied electrical field could modulate the pressure of the ACB. However, a high driving voltage was needed to actuate the DE films, which had a thickness of 1.34 mm. Recently, they developed an electrical model between the DE actuator and a human body to protect patients from the danger of exposure to high voltage (Pourazadi et al., 2017).

Fig. 3 A DE actuator for hand rehabilitation (Reprinted from Carpi et al. (2008), Copyright 2008, with permission from SPIE)

Fig. 4 A DE actuator for lower extremity (human calf) rehabilitation (Reprinted from Pourazadi et al. (2014), Copyright 2014, with permission from IOP Publishing Ltd.)

3 PVC gel actuators

PVC is a highly commercial, low-priced material widely used in industry. PVC is a typical insulating material, and most products made of PVC, such as water pipes, plastic doors, and windows, are very hard. However, when enough plasticizer is added to PVC material, it becomes flexible and has an electrical response (Zulhash et al., 2001). The flexible PVC is called PVC gel. The PVC gel has attracted many researchers to study its various applications, such as contraction multi-layer actuators (Yamano et al., 2009; Li et al., 2015; Li and Hashimoto, 2017), varifocal lens (Hirai et al., 2009; Bae et al., 2015; Xu et al., 2016; Cheng et al., 2018a), and vibrotactile actuators (Park et al., 2016, 2018).

3.1 Working principle

Similar to the DE actuator, the PVC gel actuator consists of a thin PVC gel film with electrodes on both sides. However, their electrical response behavior is different. When the electric field is charged, the DE actuator responds with a reduction in thickness and an expansion in area, while the PVC gel actuator appears to bend toward the electrode anode (Fig. 5). When the electric field is discharged, the PVC gel returns to its original shape immediately.

The phenomenon of PVC gel bending toward the anode electrode has been explained by some researchers. Xia et al. (2010) used a pulsed electroacoustic method to measure the space charges for the PVC gel actuator. The results showed that when the electric field was charged, electrons were injected from the cathode into the PVC gel, and they migrated toward the anode. The accumulation of electrons on the surface of the anode promoted electrostatic adhesion of the gel, resulting in creep deformation of the anode electrode. The microstructure of PVC gel was studied by Ali et al. (2011). They put forward that in the PVC gel structure, each PVC chain is loosely connected by physical crosslink points, and the inner space of the PVC chain matrix is filled with plasticizers (Fig. 6). In the absence of an electric field, the dipoles in the PVC gel are arranged randomly, while in the presence of an electric field, the orientation of polarized plasticizer molecules and the dipole rotation of PVC chains pull the PVC gel toward the anode.

In summary, there are two different simultaneous working principles for the PVC gel actuator (Park et al., 2016; Li and Hashimoto, 2019). First, similar to the actuating method of DE, when an electric field is applied, there is a Maxwell force between the anode and cathode electrode of the PVC gel actuator.

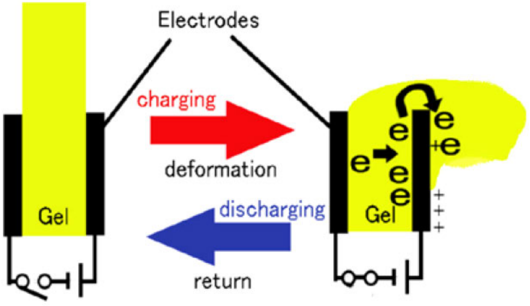


Fig. 5 Working principle of PVC gel actuator (Reprinted from Yamano et al. (2009), Copyright 2009, with permission from IEEE)

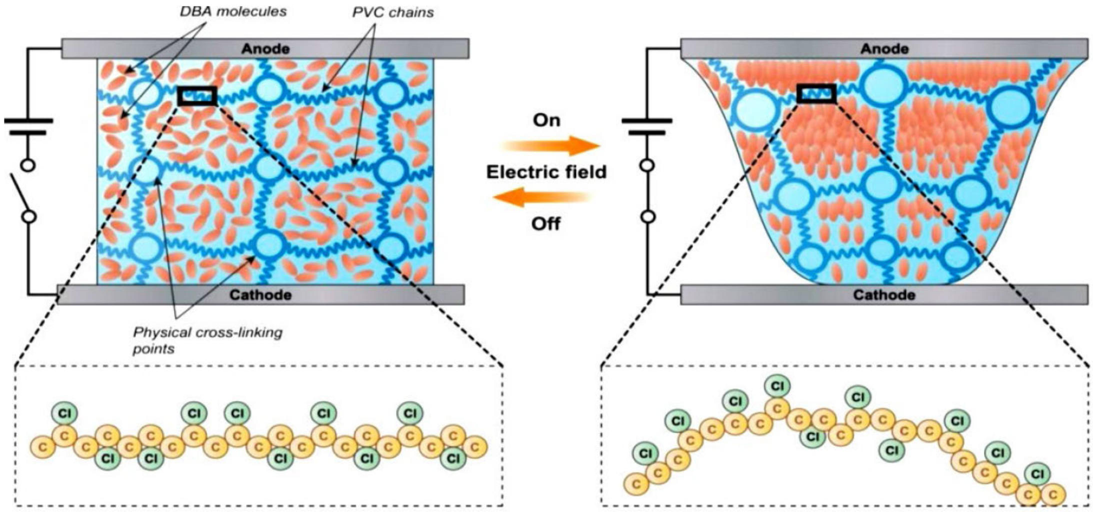


Fig. 6 Schematic diagram of the microstructure change of the PVC actuator before and after energization (Reprinted from Ali et al. (2011), Copyright 2011, with permission from American Chemical Society)

Second, the electrons accumulating on the PVC gel in the presence of an electric field create a local Maxwell force between the gel and the anode electrode.

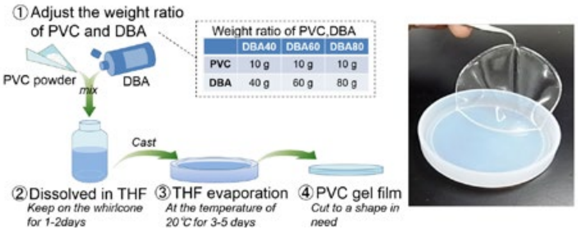
3.2 Preparation of PVC gels

The PVC gel is made from PVC powders, plasticizer and tetrahydrofuran (THF) solvent. PVC powders of different degrees of polymerization (DP) can be used for PVC gel preparation, such as DP1000 (Zulhash et al., 2001; Cheng et al., 2018b), DP1300 (Xu et al., 2016), DP3200 (Ogawa et al., 2009; Li et al., 2015; Li and Hashimoto, 2017), and DP3700 (Xia et al., 2010; Asaka and Hashimoto, 2018). The first plasticizer used to make PVC gel was dioctyl phthalate (DOP) (Zulhash et al., 2001). Currently, the dibutyl adipate (DBA) plasticizer is widely used for the preparation of PVC gel (Ogawa et al., 2009; Xia et al., 2010; Ali et al., 2011; Kim et al., 2015; Li et al., 2015; Li and Hashimoto, 2017; Asaka and Hashimoto, 2018). Some other plasticizers can also be used to make PVC gel, for example, acetyl tributyl citrate (ATBC) (Bae et al., 2015; Park et al., 2018) and dibutyl phthalate (DBP) (Xu et al., 2016).

The process of preparing PVC gel is primarily the solution evaporation method. The following is an example of the preparation using PVC powders (DP3200) and DBA plasticizer (Fig. 7). First, the quantity of PVC powders and DBA plasticizer needs to be calculated and weighed. Then, the PVC powders and the DBA plasticizer are dissolved in excess THF solution and stirred until thoroughly mixed. Finally, the mixed solution is cast in a Petri dish at room temperature, and PVC gel is formed until the THF solvent has completely evaporated. To improve the performance of PVC gel, some researchers purified PVC powders before use (Zulhash et al., 2001; Hirai et al., 2009; Xu et al., 2016; Choi et al., 2017).

Ali et al. (2013) fabricated a PVC gel from PVC plastisol without using THF solvent. First, PVC resin was washed with methanol-water solution to remove emulsifiers. Next, a certain amount of DBA plasticizer was added to the purified PVC resin and stirred to form the PVC plastisol. Lastly, the PVC plastisol was placed in a Petri dish and cured in an oven at 150 °C for 30 min to form a PVC gel.

Some researchers have studied the preparation of PVC gel to improve its electrical response. Hirai et al. (2010) investigated the effects of adding ionic liquid to the PVC gel. The results showed that with less than 0.01 wt% of an ionic liquid, the PVC gel could have a similar response as a PVC gel without the ionic liquid at twice the driving voltage. However, when the amount of the ionic liquid was over 0.02 wt%, the PVC gel had no actuation response. Park et al. (2018) found that the performance of a soft vibrotactile actuator could be enhanced by adding silicon dioxide nanoparticles to the plasticized PVC gel. The dielectric loss and leakage current of the PVC gel decreased with an increase in silicon dioxide nanoparticles. However, the dielectric constant was reduced, and elasticity modulus was increased. Tokoro and Hashimoto (2014) developed a non-woven PVC gel actuator to reduce the applied voltage using the electrospinning method. They found that the PVC gel actuator exhibited a contraction strain of 20% under an applied voltage of 80 V. However, the recovery stress of the actuator was small, about 56.8 Pa at 80 V. In addition, the response speed of the actuator was slow, about 2 Hz.



Weight ratio of PVC,DBA

	DBA40	DBA60	DBA80
PVC	10 g	10 g	10 g
DBA	40 g	60 g	80 g

Fig. 7 The process of making PVC gels (Reprinted from Li et al. (2015), Copyright 2015, with permission from the authors, licensed under CC BY-SA 3.0)

3.3 PVC gel electrodes

The PVC gel can be actuated without compliant electrodes according to its actuating principle. The most common PVC actuator is a stacked structure (Yamano et al., 2009; Li et al., 2015; Li and Hashimoto, 2017). The anode electrode of the PVC gel actuator is a stainless mesh, and the cathode electrode is a thin foil (Fig. 8). When an electric field is applied, the PVC gel moves into the anode mesh, causing a decrease in actuator thickness. When no electric field is applied, the PVC gel quickly returns to its original shape via its elasticity. The performance of different rigid metal electrodes was studied by Asaka and Hashimoto (2018).

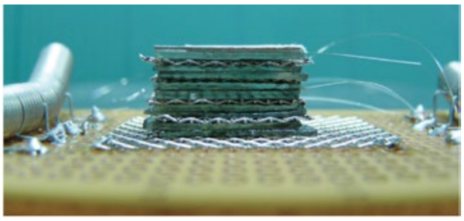


Fig. 8 The electrodes of a stack PVC gel actuator, where the anode is a stainless mesh and the cathode a thin foil (Reprinted from Yamano et al. (2009), Copyright 2009, with permission from IEEE)

Silicone greases as compliant electrodes were also studied in the PVC gel actuator by Li and Hashimoto (2019) to compare with the performance of the DE actuator. The results showed that the PVC gel actuator had a much lower driving voltage than the DE actuator. Furuse and Hashimoto (2017) provided a new idea for the electrodes of the PVC gel actuator. In their article, the conductive PVC gel, which was prepared from plasticized PVC solution filled with carbon powders, was cast again with standard PVC gel solution. Thus, the conductive PVC gel as the electrode was in the PVC gel called core-sheath PVC gel. Recently, Helps et al. (2018) developed fully soft PVC gel actuators by replacing the previous rigid metal electrodes with flexible conductive rubber electrodes via the custom shape of PVC gels.

3.4 Self-sensing

There is relatively little research on the PVC gel actuator when compared with the DE actuator, and research on the PVC gel for self-sensing is even less. Most PVC gel actuators have no sensing system (Li and Hashimoto, 2016, 2017; Park et al., 2018; Cheng et al., 2018a).

Hashimoto (2011) and Asaka and Hashimoto (2018) developed an equivalent circuit model for the feedback control of the PVC gel actuator using the electric impedance method. A DC voltage was applied to the PVC gel actuator for actuating, and a small AC voltage for measuring the electric impedance. The results showed that the model had a resistor in series with two parallel circuits, which were constructed with a capacitor and resistance due to the two arcs in the Cole–Cole plot. Because the response speed of the PVC gel actuator was low, the effect of the high-frequency part could be ignored. Thus, one parallel circuit in series with a resistor represented the mode of the PVC gel actuator, and the electric current served as the sensing signal for feedback control.

3.5 Wearable assistance applications

The PVC gel actuator has a very long life span (>5 million cycles), high output stress (>90 kPa), great strain (>10%), and fast response (about 9 Hz) (Li and Hashimoto, 2017), all of which can be judiciously applied in the wearable assistance and rehabilitation fields.

Li et al. (2015) designed a soft variable stiffness PVC gel actuator for walking assistance (Fig. 9). The actuator consisted of multiple-stacked PVC gels in series to achieve sufficient actuating displacement. The actuator was covered with an elastic fabric which was directly in contact with the human leg to protect the experimenter from its high driving voltage. Variable stiffness of the PVC gel actuator was achieved by turning on and off the applied voltage. Two types of efforts were required for the actuator to assist walking. First, joint torque was generated at the outside of the lower limb by tensile force while the actuator was working. Second, as in kinesiology-taping techniques, a compressive force was applied on the thigh and gave a stimulus to the nearby muscles. The total mass of the actuator was only 300 g excluding the power source. The results revealed that the activity of the rectus femoris muscle was reduced by about 6% compared with not wearing the PVC gel actuator. However, because of the disadvantages of the multilayer stacking structure, the larger force from a higher voltage would destroy the actuator. The total generating force of the PVC gel actuator was about 5.6 N under 300 V, which was far less than that of traditional exoskeletons.

To improve the actuating force for walking assistance, Li and Hashimoto (2016) developed a stretching-type structure for the PVC gel actuator (Fig. 10). Unlike the previous PVC gel actuator, the design of the structure was based on the recovery force of the actuator, which significantly greatly improved the robustness of the actuator. The response time of the recovery force was less than 100 ms, which was sufficient for wearable assistance. The actuator had two stretching-type structures connected in series to achieve a large displacement. The output force of the PVC gel actuator reached 94 N at 400 V, and the overall mass was only about 600 g. Recently, based on the stretching-type structure, Li and Hashimoto (2017) developed a portable control and power system to make the PVC gel actuator more convenient for daily use. Also, this actuator worn by a hemiparetic stroke patient was studied. The results showed that the step length of the patient increased, and muscular activity decreased, which demonstrated that the PVC gel actuator is promising for use in rehabilitation.

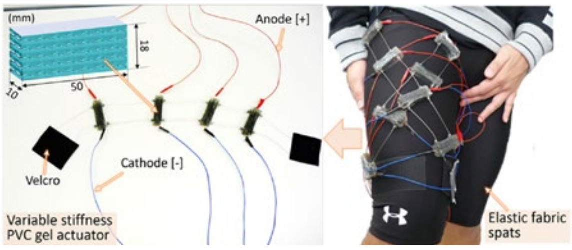


Fig. 9 A variable stiffness PVC gel actuator for walking assistance (Reprinted from Li et al. (2015), Copyright 2015, with permission from the authors, licensed under CC BY-SA 3.0)

Fig. 10 A stretching-type structure PVC gel actuator for walking assistance (Reprinted from Li and Hashimoto (2016), Copyright 2016, with permission from Elsevier)

4 Concluding remarks

Traditional exoskeletons can help people as wearable assistance and rehabilitation tools, but they lack the flexibility required to interact appropriately with humans, which is especially crucial for elders and patients. There is a need for the application of soft actuators in these fields. Soft actuators based on smart artificial muscle materials have attracted much attention from researchers. Some artificial muscle materials have surpassed natural muscles in some properties, but so far, no material has been able to surpass natural muscles in all properties. Among these materials, DEs and PVC gels are the closest to natural muscles; thus, they have advantages for application in wearable assistance and rehabilitation. However, research is still in its early stages, and some key challenges need to be addressed.

First, a high driving voltage is needed to actuate the materials, and this poses a great danger to human safety. For DE materials, the driving voltage required is in values higher than kilovolts, while PVC gels need a lower driving voltage but require at least a hundred volts. One way to significantly decrease the driving voltage is to reduce the thickness of the material films to a few microns, but this will create difficulty in making the actuators. Another method is to increase the dielectric constant of the materials by adding some substances during the preparation of the materials. However, these additives can change some other properties of the materials, such as increasing elasticity modulus and dielectric loss, leading to large current leakage when the materials are working, causing them to break down prematurely. Therefore, the amount of additives needs to be well controlled. Special materials preparation technology needs to be given particular attention because it can also significantly reduce the driving voltage. For example, the PVC gel produced by the electrospinning method could be driven below 100 V at the cost of reducing the output force and response speed (Tokoro and Hashimoto, 2014).

Second, compared to traditional exoskeletons, the output force and displacement of the materials are very small. The structure of the actuator requires a good design. Li and Hashimoto (2016) designed a stretching-type structure for the PVC gel actuator, increasing output force from 5.6 N to 94 N. The structural design for increased displacement has also been studied by some researchers (Kofod et al., 2007; Sun et al., 2016; Liu et al., 2018). On the other hand, the actuator can be tried first with applications to parts of the human body that require less force, such as human fingers.

Finally, most of the actuators lack feedback control. Rigid sensors are not convenient for use in soft actuators. Fortunately, the self-sensing properties of DEs have received much attention of researchers.

However, for PVC gels, there is little research on self-sensing methods. Research on PVC self-sensing systems can begin with the imitation of the self-sensing method of DE actuators because of the similarity in actuating principles. Another problem for PVC gels is that most of the PVC gel actuators use rigid electrodes, which is deficient for self-sensing. Compliant electrodes need to be developed for PVC gels. In the future, a better soft actuator will be integrated with a variety of self-sensing systems, such as displacement self-sensing and force self-sensing, to achieve better control.

In this review, we propose that DEs and PVC gels as two kinds of artificial muscles could potentially be applied in the wearable assistance and rehabilitation fields. Compared with PVC gel actuators, DE actuators require a higher voltage and prestrain but have higher response speeds. The specific application determines the choice between these two materials.

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