Simple and Reliable Fabrication Method for Polydimethylsiloxane Dielectric Elastomer Actuators Using Carbon Nanotube Powder Electrodes

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1. Introduction

Soft robotics are receiving increased attention due to their compliance and safety for diversified human services. One major challenge is the establishment of a simple design and fabrication method for soft actuator technologies. Currently, there are electromechanical types of soft actuators including soft pneumatic actuators, stretchable pump, and dielectric elastomer actuators (DEAs). Soft pneumatic actuators can generate high-pressure actuation. This may expand the soft actuator application in some areas that require high-pressure actuators. However, soft pneumatic actuators require additional equipment such as air hoses and a compressor that may lead to a complex design for actuators. The stretchable pump utilizes electrohydrodynamics (EHD) to generate pressure difference between the fluid inside the device. Recently, rapid fabrication methods for EHD pump have been established using do-it-yourself-like method (DIY-like). The fabrication process includes cutting the copper sheet and assembling the pump manually which only requires 1 h to produce five pumps. This typical rapid prototyping is essential to boost innovation in the soft actuator area. In contrast with two other devices, DEA is a newly developing technology which is simpler than EHD (that requires dielectric liquid) and pneumatic actuators (that require air compressors). Further researches are required to understand the potential performance and application of DEAs. Typical strategies similar to the previously reported research in EHD pump that can achieve fast, reliable, and low-cost fabrication of DEAs are essential to accelerate the DEAs research area.

Dielectric elastomer actuators (DEAs) are energy efficient, compact, and operate silently. DEAs consist of an elastomer membrane sandwiched between two stretchable electrodes. Optimizing the quality of both the elastomer and the stretchable electrodes is essential to improve the DEAs performance. Herein, novel strategies are reported to achieve fast, reliable, and low-cost fabrication of DEAs. The strategies utilize a soft brush to directly pattern carbon nanotube (CNT) powder on the elastomer membrane and tune the mechanical and surface-adhesiveness characteristics of a polydimethylsiloxane (PDMS) membrane by altering the mixing ratio of the curing agent and base polymer. A uniaxial engineering tensile test on PDMS indicates that a softer material is formed when less curing agent is used. The softer PDMS has a sticky surface, which allows the CNT powder to be physically bound to the surface. Field-emission scanning electron microscopy (FE-SEM) images prove that the strong CNT network is formed on the surface of the elastomer. The electromechanical investigation also indicates that the electrical conductivity is improved for a stickier PDMS surface. The optimal performance of PDMS 30-1 in static and cyclic DEA tests shows that the brushing of CNT combined with soft and sticky elastomer membranes can increase the DEA performance.
DEAs convert electrical energy into mechanical energy. Their basic structure consists of a soft elastomeric membrane with compliant electrodes patterned on both sides (Figure 1). When DEAs are subjected to a DC electric field, opposite charges accumulate at the two electrodes, compressing the elastomer membrane. As the elastomer membrane is incompressible, this compression squeezes the elastomer membrane in the z-direction and expands the elastomer in the in-plane direction.\cite{16} The electromechanical response of DEAs mainly depends on both the applied external electric field and the electrical properties of the elastomer. These two variables are summarized in the Maxwell pressure ($P$) correlations and are expressed in terms of the vacuum permittivity ($\varepsilon_0 = 8.85 \times 10^{-12}$ F m$^{-1}$), relative dielectric constant of the elastomer ($\varepsilon_r$), voltage ($V$), and membrane thickness of the elastomer ($z$) (Equation (1)). In the case of an actuation strain below 20%, Equation (2) describes the deformation of the dielectric membrane in the z-direction, where $S_z$ is the actuation strain in the $z$-direction and $Y$ is the elastic modulus.\cite{16}

\begin{equation}
P = \varepsilon_0 \varepsilon_r \left( \frac{V}{z} \right)^2
\end{equation}

\begin{equation}
S_z = \varepsilon_0 \varepsilon_r \frac{V^2}{Yz^2}
\end{equation}

Based on Equation (2), we found that DEAs depend much on the material mechanical characteristics ($Y$). In DEAs, the mechanical characteristics of the device are affected by the elastomer used to compose the DEAs and the stretchable electrodes patterned on the elastomer. High-performance DEAs require elastomer membranes that can sustain a large area expansion strain without damage or loss of electric charging on the electrodes. Currently, commercially available acrylate-based polymers (e.g., VHB) are commonly used for DEAs due to their large area strain and relatively high dielectric constants. However, commercial acrylate-based (VHB) polymers exhibit a long relaxation time and a long recovery time of several hundred seconds due to their high viscoelastic nature. Furthermore, VHB elastomers must be carefully treated as they are sticky and easily broken under a highly prestrained condition.\cite{16,17} To achieve a fast response and reproducible DEAs, acrylate-based polymers must be replaced by another elastomer with negligible viscoelastic characteristics. Polydimethylsiloxane (PDMS) is an elastomer exhibiting extremely small viscoelastic characteristics.\cite{18} Other benefits of fabricating devices with PDMS include economical, biocompatible, and stretchable.\cite{19}\cite{19} These characteristics allow devices to be fabricated to meet various design requirements.

To maximize the DEAs actuation performance, the stretchable electrodes should be able to preserve their electrical conductivity while sustaining large deformations and durability for millions of cycles. Many research groups have proposed different techniques to fabricate stretchable electrodes. The first reported devices involved electrodes that were hand-painted carbon grease. Since then, many methods have been proposed.\cite{9} Common stretchable electrodes for DEAs are based on conductive carbon grease\cite{14} because its conductivity can be preserved while sustaining a large strain. Carbon grease has long-term stability issues. A dry environment can stimulate the evaporation of the viscous matrix that binds carbon.\cite{9} This excessive evaporation of the viscous matrix in carbon grease may reduce the electrode flexibility. In some cases, the grease might diffuse into the elastomer, which can cause a short circuit or a swelling effect on the membrane.

Other common stretchable electrodes for DEAs are based on carbon particles because they lack stiff electrodes. However, handling a carbon particle is quite difficult. Recently, we proposed a new method to create stretchable electrodes based on a carbon nanotube (CNT) powder using a soft brush.\cite{10} This simple method can produce a relatively stable performance of DEA actuation.\cite{10} The use of CNT powder does not affect the stiffness of the elastomer membrane due to the looseness between the agglomerates.\cite{9} Similar to the previous electrode, there are several problems with this CNT powder. For example, the lifetime is limited because this powder has a high probability of detaching from the elastomer membrane. From the viewpoints of simplicity and rapid prototyping, painting CNT powder with a soft brush is relatively simple and can be performed in less than 5 min for single-layer DEAs. The latest research by Kajiwara et al. also confirmed that the use of CNT powder on an elastomer membrane can produce reliable DEA operation at a high frequency.\cite{20}

There are many advanced developments on fabrication method to enhance the quality of stretchable electrodes. One breakthrough method is a printed electrode, which was proposed by Poulin et al.\cite{21} However, setting up a printing method to optimize the results of stretchable electrodes is a time-consuming process. Another advanced method to fabricate stretchable electrodes is the Langmuir–Schaefer method (LS).\cite{22,23} The LS method can reliably fabricate low-voltage DEAs as it allows users to create an electrode film in the nanometer thickness range.\cite{23} The LS

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**Figure 1.** DEA structure and operation mode in the a) reference state and b) actuated state.
method is suitable for fabricating extremely thin PDMS membranes of around 1 μm,[23] which leads to low-voltage operations of DEAs. Researchers have also reported that the LS method can produce thin and reliable stretchable electrodes with excellent performance in low-voltage DEAs.[22,23] The LS method requires a long preparation process. For example, substrate preparation may take around 5 h.[23] This fabrication process also requires careful attention in every step as this method involves a liquid.

In this study, we established a simple, fast, and reliable fabrication process for DEA based on brushing technique. To examine the impact of the fabrication methods to the DEAs performance, we first investigate the relationship between the mechanical characteristics of Sylgard 184 and the mixing ratio between the elastomer base and its curing agent on a single-pull-to-failure tension test. The results contribute to the fundamental design information of DEAs. Second, we introduce simplified and reliable methods to fabricate DEAs using brushed CNTs as stretchable electrodes. In particular, we examine the electrical properties of the brushed CNT powder on various samples of PDMS. Then we perform an experiment on the static and dynamic characteristics of basic DEAs that use CNT powder as electrodes. The experiment focuses on finding the appropriate mixing ratio for PDMS to enhance the DEA performance. In this study, A–B in PDMS A–B represents the mixing ratio between the base polymer and the curing agent. Three different types of PDMS (Sylgard 184) samples (PDMS 10-1, PDMS 20-1, and PDMS 30-1) were prepared using the aforementioned methods. The samples were prepared via a simple molding and curing process to form sheets with dimensions of 145 mm × 135 mm × 2 mm. Then strips were fabricated using a precision dumbbell blade according to JIS K6251. For a single failure tensile test, we used Shimadzu AGS-X with a loading speed of 500 mm min⁻¹. The elongation and applied force during the test were recorded automatically. At least three measurement data were averaged.

Figure 2 describes the uniaxial engineering tensile test results for the three different PDMS samples prepared with different mixing ratios. In the small strain region (below 50%), the stress–strain curve (Figure 2) shows a linear behavior. However, the stress steeply increases in the large strain region above 100% strain for PDMS 10-1, 175% for PDMS 20-1 and PDMS 30-1. In addition, reducing the curing agent produces a softer material. From these results, we conclude that the mechanical properties of PDMS are controllable. In this research, for PDMS-based DEA, a softer PDMS with less curing agent is preferable to drive the DEAs in the lower actuation voltage. A softer PDMS also has a more stretchable structure and may produce higher actuation DEA performance (additional engineering cyclic tensile test is provided in Figure S1, Supporting Information).

3. Tackiness Evaluation of the PDMS Membrane

This section evaluates the stickiness of the PDMS sheet with various mixing ratios. There are several test methods to assess the
stickiness based on the force direction measured during the experiment with respect to the sample surface. These include normal adhesion tests (force and displacement measured parallel to the normal preload), shear tests (force and displacement measured perpendicular to the normal preload), peel tests (sample is peeled from the substrate at a defined angle).\(^\text{[24]}\)

In accordance with our research, we brushed multiwalled carbon nanotube (MWCNT) on the PDMS membrane. The brushing process did not involve pressing the brush on the elastomer membrane. Thus, the amount of MWCNT preserved on the elastomer membrane depends on the tackiness level of the PDMS surface. According to the American Society for Testing and Materials (ASTM D 6195 03), tackiness is the force required to separate an adherend and an adhesive at the interface shortly after they have been brought rapidly into contact under a light load with a short duration. To evaluate the tackiness level, ASTM D 6195 03 provides a detailed measurement procedure called the loop tack test. In the loop tack test, the PDMS membrane was cut into a 25 mm \(\times\) 175 mm specimen strip. Then the specimen was bent back upon itself to form a teardrop-shaped loop. The end of the loop was fastened together by masking tape before inserting it into the grips to prevent the contamination of the tensile tester grips. Next the loop was brought into contact with the pre-cleaned substrate (polished stainless steel SUS 430 that allows 25 mm \(\times\) 25 mm contact area) by lowering the loop until it covered the substrate surface (25 mm \(\times\) 25 mm contact area, Figure S2, Supporting Information shows the experimental setting for the loop tack test). The area in contact was inspected visually for any imperfections in the contact (e.g., wrinkles). Finally, the tensile test machine pulled the test sample at a speed of 300 mm min\(^{-1}\) until the PDMS membrane detached from the substrate surface, and the pulling force and displacement of the loop were recorded. Figure 3 shows the maximum tackiness of the PDMS membrane. As expected, increasing the curing agent (wt\%) reduces the tackiness of the PDMS. In the next section, we show the effect of the tackiness on the electrical properties of the MWCNT electrodes deposited on the PDMS surface.

4. Simple and Fast Fabrication of Stretchable Electrodes Using CNT Powder

A CNT powder can be easily patterned on the surface of a material. To define the shape of the CNT pattern on the PDMS membrane, we used a masking sheet, which was cut by a cutting plotter (Graphtec CE 6000-40). The shaping process of the masking sheet involved two steps. The first step designed the pattern using special software (e.g., Adobe Illustrator). The second step sent the design to the cutting plotter, which cut the design according to the design file. After the masking sheet was ready, we adhered it onto the surface of PDMS (Figure 4a) and brushed the CNT powder on to a thin layer of a prestretched membrane made of Sylgard 184 to make DEAs.

Figure 4 shows the overall method to fabricate stretchable electrodes. The CNT powder was a multiwalled carbon nanotube (MWCNT724769-25 G, Sigma-Aldrich). In the brushing method, the elastomer membrane was exposed to atmospheric pressure at room temperature. Then the multiple-brushing\(^\text{[10]}\) method created a stretchable electrode layer on a PDMS membrane. The brushing cycle can be neglected as the number of brushing times was constant in every elastomer sheet. To suppress the effect of the brushing direction, we kept the brushing direction of the MWCNT powder in the same direction.

The electromechanical properties of the stretchable MWCNT network brushed on the elastomer were examined using the four-probe method as it is recommended in a previous study.\(^\text{[25]}\) The mechanical and electrical coupling measurements were established to test the resistance–strain characteristics of the brushed MWCNT on the PDMS membrane. In principle, we prepared a long and thin rectangular strip of the elastomer with the MWCNT powder brushed on the elastomer.

Figure 5 shows the equipment arrangement for the electromechanical test. The length (\(L_0\)) was 50 mm. We used an aspect ratio (\(L_0/w\)) of 10:1 to ensure a homogenous current flow.\(^\text{[25]}\) The strips were measured by the four-probe method to avoid measuring the contact resistance. In the measurement, the sample was connected to a magnetic probe to ensure a uniform contact force in every test specimen. In the test system, the elastomer was pulled at a constant speed of 1 mm s\(^{-1}\) using Shimadzu AGS-X, and an LCR meter (IM3536) measured the resistance signal of the sample during the tensile test. All three sheet groups (PDMS 10-1, PDMS 20-1, and PDMS 30-1) were measured using the aforementioned method in a zero-strain condition (\(\epsilon = 0\)). Then we stretched the strips in the uniaxial direction until a strain of 0.3. We neglected the shrinkage in the width direction as it was insignificant compared with the extension of the PDMS.

Figure 6 shows the resistance of the brushed MWCNT for various mixing ratios of PDMS. Increasing the curing agent portion elevates the electrical resistance of the brushed MWCNT on the PDMS. The electrical resistance is influenced by the amount of powder attached to the surface of the elastomer. This elevated electrode resistance leads to the low conductivity performance of the stretchable electrodes. In addition, the resistance increases as the strain increases. This is attributed to the increased spacing among the nanoparticles making up the conductive network.\(^\text{[26]}\)

To investigate the surface condition of the elastomer membrane with the MWCNT powder in the initial state before stretching, we utilized field-emission scanning electron microscopy (FE-SEM) (JEOL JSM-7610F; JEOL). Figure 7 shows the surface morphology of the brush-painted MWCNT electrode on the various PDMS samples. Figure 7a–c show the color density. The MWCNT density increases as the elastomer’s sticky nature increases. The sticky nature is controlled by adjusting the mixing
ratio of the base polymer and the curing agent. The sticky nature of PDMS helps maintain the MWCNT powder on the elastomer surface. The brushing method also helps build a connection between the MWCNT network, improving the conductivity of the stretchable material.

All MWCNT electrodes are fairly transparent. Compared to the first- and second-brushed MWCNT electrodes (Figure 7a,b), the third electrode (Figure 7c) shows lower optical transmittances. Figure 7d–f show SEM images with different amounts of the MWCNT powder deposited on the surface of the PDMS with the same brushing cycle number. The MWCNT powder deposited on the surface of the elastomer membrane increases as the base polymer ratio in the mixture increases. Figure 7i shows more layers of MWCNT than the other MWCNT brushed on the elastomer membrane.

The mechanical integrity of the brush-painted MWCNT electrodes was evaluated by stretching the PDMS and subjecting the electrode to an electric current. Figure 8 shows the stretchable electrode when subjected to DC 5 V of the electric source while stretching. In the initial condition ($\varepsilon = 0$), the brightness of the light emitted by the light-emitting diode (LED) increases linearly with the density of the base polymer ratio. The brightness for a higher ratio of the base polymer is attributed to the better performance of the electrode conductivity.

Furthermore, to evaluate the effect of the cyclic tensile test on the surface morphology of brush-painted MWCNT on the PDMS, we prepared a rectangular-shaped test specimen similar to that tested in Figure 8. The specimen was 100 mm long and 10 mm wide. The specimen underwent a cyclic tensile test at a speed of 500 mm min$^{-1}$ and a maximum strain of 40% using Shimadzu AGS-X. Then the material was further investigated under FESEM JSM-7610 F (JEOL). Figure 9 shows that the PDMS surface has dense MWCNT. There is not a significant effect of the cyclic tensile test to the MWCNT deposited on the PDMS (Figure 7d–f and 9). As expected, the strong bond between MWCNT is maintained on the nanometer scale and PDMS 30-1 has more MWCNT attached to its surface because its tackiness level is higher than the other samples.

5. Fast and Simple Fabrication of Single-Layer DEAs

To further investigate the reliability of a stretchable electrode attached to the elastomer membrane, we applied this electrode on a single-layer DEA to understand its capability for sustaining high cycles. To prepare a thin PDMS layer, a
solution containing the base elastomer and the curing agent were blended with ratios of 10:1, 20:1, and 30:1. The mixing and curing process was similar to that used to fabricate a coupon test for the tensile test. We used a simple coating process on the acrylic plate to create a 0.5-mm-thick PDMS membrane. After fully curing, the PDMS membrane was peeled off of the acrylic plate. To prepare single-layer DEAs, we prestretched the membrane biaxially by 10%, 20%, or 30%. We then applied an acrylic frame to the prestretched membrane to maintain the prestretch condition (Figure S3, Supporting Information shows the detailed step-by-step process on the fabrication of single-layer DEAs).

Figure 4a shows the prestretched membrane attached to a blue acrylic frame. We attached the preholed masking sheet to shape the electrode. The hole size had a 20 mm diameter. To prevent the MWCNT from tarnishing another position, we designed a masking sheet that can cover the whole surface of the membrane using Adobe Illustrator. Then the masking sheet was cut according to the design by a cutting plotter (Graphtec CE 6000-40). Next, we poured a small amount of the MWCNT powder (Figure 4b) and brushed the powder on the entire surface (Figure 4c,d) until all of the layers were covered with MWCNT (Figure 4e). After brushing on both surfaces of the PDMS membrane, we removed the masking sheet and attached a copper wire on both surfaces of the electrodes.

Figure 6. Resistance change during a tensile test of the stretchable electrodes.

Figure 7. Surface morphology of brush-painted MWCNT on the elastomer membrane. Brushed MWCNT on the PDMS with a mixing ratio of a) 10-1, b) 20-1, and c) 30-1. d,g) SEM images of brushed MWCNT on PDMS 10-1. e,h) SEM images of brushed MWCNT on PDMS 20-1. f,i) SEM images of brushed MWCNT on PDMS 30-1.
6. Static Characteristics of DEAs

To demonstrate the performance of the DEAs prepared using the simple and fast fabrication method, we set up a single-layer DEA on a light board LED and used an HD camera to record DEA actuation. To understand the effect of stress softening on the DEA performance, we used a PDMS membrane with various mixing ratios (PDMS 10-1, PDMS 20-1, and PDMS 30-1). All sheets had an
initial thickness of 0.5 mm and were prestretched by 10%, 20%, or 30%. MWCNT was coated by the aforementioned brushing method on both surfaces with an overlapping circular region. This circular region was defined as the electroactive region.

Applying a voltage to both electrodes induces DEA actuation. As a result, the electroactive region expands against the passive region of the DEAs (Figure 10d). To calculate the area strain of the DEAs, the area expansion recorded by the HD camera was further analyzed by Image J. We calculated the area strain by determining the change in the electroactive areas through geometric relations.\(^{[16]}\)

Figure 10a–c show various actuation characteristics of DEAs due to the variation in the mixture ratio between the curing agent and base elastomer. As the curing agent ratio in the mixture increases, the actuation performance decreases. For all prestretched conditions, a device that uses PDMS 10-1 as the membrane does not show a significant increase in actuation compared with the others. Hence, stress hardening due to an excessive curing agent affects the DEA actuation performance. Because the PDMS 10-1 membrane has rigid characteristics, it requires a higher driving voltage to achieve a higher area strain. Furthermore, the surface characteristic of PDMS 10-1 is relatively less sticky than those of PDMS 20-1 and PDMS 30-1. The less sticky surface characteristics limit the ability of the membrane to preserve the MWCNT powder on its surface, lowering the electrode conductivity. In this case, a combination of a stiff membrane and a lower electrode conductivity can reduce the DEA actuation performance.

Devices that use PDMS 20-1 show almost the same actuation performance as PDMS 10-1 at a lower prestretched condition (10% prestretching). However, the performance is elevated as the prestretched condition increases (Figure 10b, c). In contrast, PDMS 30-1 shows the best performance. However, devices using this membrane exhibit a lower electrical breakdown field. Attributed to the DEA characteristic where PDMS is used as the elastomer membrane and MWCNT as the electrode, this finding shows that the stress-softening and surface characteristics affect the DEA area strain.

We also investigated the response time of DEAs upon applying a voltage. The response time of the actuator shown in Figure 11 was quantified as the time taken to reach 100% of the maximum area strain in the static test. Increasing curing agent (wt%) of the elastomer membrane realizes a faster DEA response time. This

![Figure 10. Area strain as a function of the electric field of various PDMS mixing ratio with the prestretching of a) 10%, b) 20%, and c) 30%. d) Photos of the actuators constructed from PDMS 30-1 and 30% prestretching.](image1)

![Figure 11. Response time of DEAs at various PDMS concentrations.](image2)
response corresponds to silicones, which have higher elastic properties, lower dissipative energies, and faster response times.[16,28,29]

Table 1 summarizes the work in this section. PDMS 30-1 has a lower electrical breakdown strength compared with PDMS 10-1 and PDMS 20-1 due to its lower mechanical strength. This lower mechanical strength combined with the increased dielectric permittivity increases the force produced by the applied voltage. The inability of PDMS 30-1 to hold the excessive force produced by the applied voltage induces a premature electrical breakdown. Hence, we conclude that the combination of the good conductivity produced by the MWCNT brushing method and the soft mechanical characteristics of PDMS 30-1 leads to the enhanced performance of single-layer DEAs.

Table 1. Single-layer DEA performance.

| No | Dielectric membrane | Prestretch | Dielectric permittivity at 1 kHz | Electrical breakdown strength (Eb) [static test] (kV mm⁻¹) | Area strain [%] |
|----|---------------------|------------|-------------------------------|-------------------------------------------------|----------------|
| 1  | PDMS 10-1           | 10%        | 3.26                          | 3.54 (at 60.24 kV mm⁻¹)                          | 3.26           |
|    |                     | 20%        | 3.68                          | (at 61.22 kV mm⁻¹)                               | 3.68           |
|    |                     | 30%        | 4.88                          | (at 62.77 kV mm⁻¹)                               | 4.88           |
| 2  | PDMS 20-1           | 10%        | 3.33                          | 55.78                                           | 4.31           |
|    |                     | 20%        | 58.21                         | 9.03                                            |                |
|    |                     | 30%        | 61.95                         | 12.5                                            |                |
| 3  | PDMS 30-1           | 10%        | 3.64                          | 30.39                                           | 13             |
|    |                     | 20%        | 37.24                         | 22                                              |                |
|    |                     | 30%        | 37.72                         | 25                                              |                |

7. Dynamic Characteristics of DEAs

The reliability of powder-based DEAs was investigated through an actuation performance test under a sine wave with an emphasis on device robustness under hundreds of cyclic tests. The previous section discussed the weakness of brushing methods in which the powder may detach from the elastomer surface due to the lack of a binding force. In this experiment, we tested the cyclic performance of the DEAs using a sine wave with a frequency of 4 Hz for 250 s. As the applied range includes positive and negative voltages, the transition period may be shortened between the peak voltage and zero. Hence, we expect the DEAs to achieve an actuation peak in every cycle.

Similar to the static test, the cyclic test used an HD camera with a recording speed of 30 frames per second to record the cyclic motion. The recorded motion was further analyzed by Image J software. Figure 12 shows the first 250 s cyclic area actuation strain of a device constructed from PDMS 10-1, PDMS 20-1, and PDMS 30-1 with 30% prestretching. Figure 12d summarizes the peak area actuation-strain performance from Figure 12a–c. The area actuation strain remains stable as the number of cycles increases. The stable actuation area is a satisfactory feature of the DEAs using the MWCNT powder as the electrodes. This result shows that the brushing method can fabricate DEAs that can endure a long actuation cycle. Corresponding to earlier research that the binding between the MWCNT powder and the elastomer surface may affect the DEA performance,[9] this research confirms that the binding force between the MWCNT powder and the elastomer membrane affects the stability of cyclic actuation. The DEA elastomer membrane in Figure 12c is stickier than the others (Figure 12a,b), and it exhibits a more stable actuation performance in every cycle.

Figure 12. Dynamic actuation performance of powder-based DEAs. a) PDMS 10-1 with 30% prestretching, b) PDMS 20-1 with 30% prestretching, and c) PDMS 30-1 with 30% prestretching. d) Summary of peak actuation of PDMS 10-1, PDMS 20-1, and PDMS 30-1 with 30% prestretching.
Samples of PDMS 20-1 (Figure 12b) and PDMS 30-1 (Figure 12c) drift from their equilibrium position by 0.4% and 2.9%, respectively, in the stable state. This behavior is attributed to the slower relaxation time compared to the cycle time (Figure S1, Supporting Information shows mechanical characteristics during cyclic tensile test). Similar behaviors have been observed in elastomers with a high viscoelasticity such as VHB polymers. PDMS 10-1 (Figure 12a) shows a relatively small drift compared with the other two samples as PDMS 10-1 shows a smaller area actuation strain.

8. Conclusion

Herein, a simple, fast, low-cost, and reliable method to fabricate DEAs is demonstrated. The DEAs fabrication strategies utilize a soft brush to directly pattern CNT powder on the elastomer membrane and tune the mechanical and surface-adhesiveness characteristics of a PDMS membrane. We found that altering the mixing ratio of the base elastomer and the curing agent helps to change the mechanical characteristics of PDMS. Reducing the curing agent in the mixing ratio results in materials with softer characteristics and stickier surface characteristics. By reducing the curing agent (from PDMS 10-1 to PDMS 30-1), we can improve the area actuation strain of the DEAs static performance for approximately 3–5 times higher at their maximum static actuation area strain (Table 1). We also found that reducing the curing agent in the mixing ratio realizes a DEAs that can be actuated in the lower electric field (for PDMS 30-1, 1% area actuation strain can be spotted around 10 kV mm\(^{-1}\) (Figure 10)). Furthermore, the stickier surface characteristic can strengthen the binding force between the MWCNT powder and the elastomer membrane. This strong binding force also strengthens the network connection between the MWCNT powder and helps to realize a better conductivity of electrodes, which allows the electricity to be transmitted uniformly over the electrodes network. This better electrode conductivity realizes the DEAs with a more stable dynamic actuation performance. Challenge for powder-based DEAs is increasing the frequency of the input voltage. We expect that the sticky surface and improved mechanical characteristics of the elastomer should help address this challenge and improve the performance in higher frequency operations. In the future works, we will apply our current fabrication methods to realize a high-performance PDMS DEAs speaker.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

Research data are not shared.

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