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Self-sensing Soft Tactile Actuator for Fingertip Interface

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Abstract— **In this paper, we report a self-sensing soft tactile actuator based on Dielectric elastomer actuator (DEA) for wearable haptic interface. DEAs are one of electroactive polymer actuators, which are reported to have large area strain and fast response speed. A soft tactile actuator is constructed of a multi-layered DEA membrane layer, a passive membrane layer, and an inner circular pillar. The soft actuator was optimized by varying the geometry, and the force and displacement tests were conducted under a frequency range of 0 to 30 Hz. The selected actuator produces an output force up to 0.9 N, with a displacement of 1.43 mm. To provide accurate physical force feedback to the user, the actuator is integrated with a 1.1 mm thick film-type soft force sensor that enables feedback control. Under the pressure, touch layer contacts with the core, and the light inside the core scatters to the touch layer. A fabricated soft force sensor can measure the force in a range of 0 to 1.25 N under various frequency ranges. Our wearable prototype exhibits high output force of 0.9 N, as well as flexibility, conformity, and light-weight structure (3.2 g).**

I. INTRODUCTION

Owing to the technological advancement in recent decades, wearable devices have been integrated into our everyday lives. The plethora of visual and auditory information presented by these devices has seen their use rise in a broad range of fields. While considerable developments have been made in the visual and auditory domain, haptics provides an opportunity to provide users with richer and engaging experiences. This has seen its demand in a number of domains including consumer electronics, virtual reality, medical applications and gamming [1-2]. As haptics is the potential next big step in human-robot interaction, various researches have explored ways of providing tactile feedback. Currently, various haptic interfaces have explored tactile modalities such as pressure, force or vibration using a number of different actuators [3-5]. However, research on soft tactile displays need attention due to their inherent compliance, lightweight and wearability.

Dielectric elastomer actuators (DEAs) are promising soft actuators that have large area strain, fast response, high specific energy density, lightweight, low cost, and low power consumption [6]. Several researchers have proposed wearable tactile interfaces based on DEAs. Choi et al. developed an integrated tactile display device for a wearable application [7]. They used single-layered DE actuators and generated an output force of about 14 mN at an input voltage of 3.5 kV. In order to improve the output force performance, Mun et al. fabricated a multi-layered DE actuator and integrated it in a vibro-tactile wearable interface [8]. This soft actuator was designed to have a resonance frequency around 250 Hz, and produced a maximum output force of 255 mN at 4 kV of the input voltage. Carpi and colleagues presented a wearable vibro-tactile interface for fingertip interaction based on hydrostatically coupled DEA (HCDEA) structure [9-10]. The Fabricated multi-layered HCDEA was capable of generating an output force of 0.7 N at 4 kV input voltage. This work showed an improvement from the previous research. However, for the effective tactile interface, the larger output force is required. In addition, previously introduced haptic systems based on DEAs were open-loop controlled without using extra embedded sensors. However, the output force of wearable haptic systems can change depending on the interface that fits with the body [11]. For realistic tactile feedback, the feedback control is needed to provide accurate physical force feedback to the user.

In this paper, we present a self-sensing soft tactile actuator for the fingertip interface. Conical DEA configuration was used for the soft tactile actuator. The haptic devices based on conical DEA configuration were introduced from previous works [12]. However, the output force (44mN) of the previous devices were needed to be enhanced for an effective tactile interface [12]. In this work, we optimized the soft tactile actuator by controlling two design parameters to enhance both the output force and the displacement of the actuator. In addition, a film type force sensor is presented, to enable feedback control of a soft tactile actuator. By combining a soft tactile actuator with a soft force sensor, the integrated system is able to provide accurate physical force feedback to the user. The wearable haptic system is entirely soft, flexible, and lightweight (3.2 g).

II. FABRICATION

The soft tactile actuator was designed to provide the force feedback to the user's fingertip. The output force of the actuator can be controlled against the input voltage. The thin-film type sensor, which is located between the actuator and the fingertip, senses the interacting force between the actuator and the user. From the sensor data, it is able to control the force consistently and accurately. Due to the softness and flexibility of an actuator and a sensor, an integrated soft wearable system is designed to be flexible, soft, lightweight, and can be worn easily.

A. Soft Tactile Actuator

In this paper, a soft tactile actuator uses a concept of double cone DEA. A soft tactile actuator is composed of a DEA active membrane layer, a passive membrane layer, and an inner circular pillar that is bonded between two membranes. The actuator was designed such that it is able to protect the user from the electric shock by isolating the high voltage parts from the user-skin. Under no input voltage, a soft tactile

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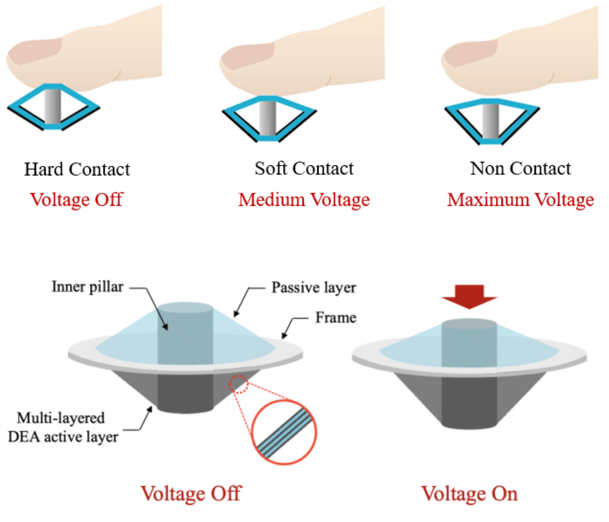


Figure 1. Illustrated operating principle of soft tactile actuator.

actuator is pressing the user's fingertip with a maximum force due to the restoring force of the polymer. When the input voltage increases, a soft tactile actuator moves downward, which leads to a decrease the interacting force. Under the maximum applied voltage, no contact occurred between the fingertip and the actuator which provide no force to the user. It is possible to control the contact force by varying the input voltage to the actuator, as illustrated in Fig. 1.

The deformation of DEA is determined from the electric field between the two electrodes of DEA [6]. When electric field is applied to the DEA, an electrostatic pressure, known as Maxwell stress, is induced to the both sides of DEA which leads the compression in thickness direction. The thickness strain s_z can be expressed as follows, [6]

$$s_z = -\frac{\varepsilon_0 \varepsilon_r}{Y}\left(\frac{V}{z}\right)^2 \qquad (1)$$

where V is the applied voltage, Y is the elastic modulus, ε is the relative permittivity, ε_0 is the permittivity of free space, and z is the thickness of the DE material. Because the DE is an incompressible material, the thickness compression leads the planar area expansion. The actuation of a soft tactile actuator depends on the force balance between two membrane layers. Upon applying a voltage to the DEA active membrane, the membrane expands in the planar direction that causes the inner circular pillar to move downward, as shown in Fig. 2.

For the prototype fabrication, both the passive membrane and the active membrane are formed using 3M VHB 4905 acrylic elastomer which was bi-axially pre-stretched to a ratio of 3. Among the various dielectric materials used, 3M VHB acrylic elastomer has benefits in generating large strain when used in DEAs under low frequency range (0-10 Hz) [6]. To maintain pre-strain of membranes, the pre-stretched mem-branes are bonded to an Overhead Projector (OHP) film frame of 100μm thickness with an outer diameter of 15mm, and an inner diameter of 12mm. The dielectric membranes were coated with carbon grease as the compliant electrode and

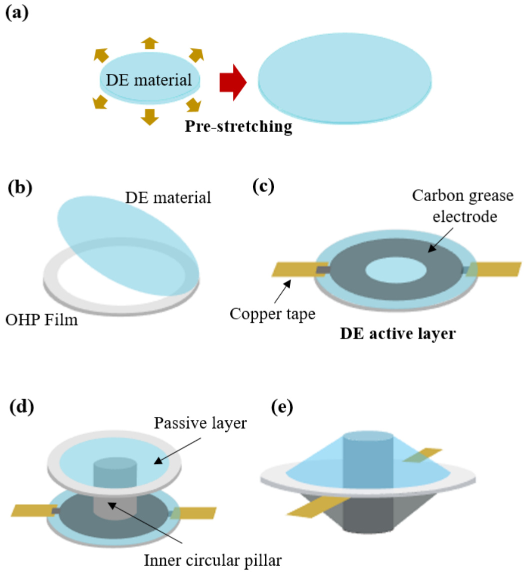


Figure 2. Illustration of the overall fabrication process of a soft tactile actuator: (a) pre-stretching DE materials, (b) attach pre-stretched DE matierla to OHP film frame, (c) coating with carbon grease electrode and attach copper tape. Repeat b-c process to make multi-layered DEA, (d) Place circular pillar between two layers, (e) Fabricated soft tactile actuator.

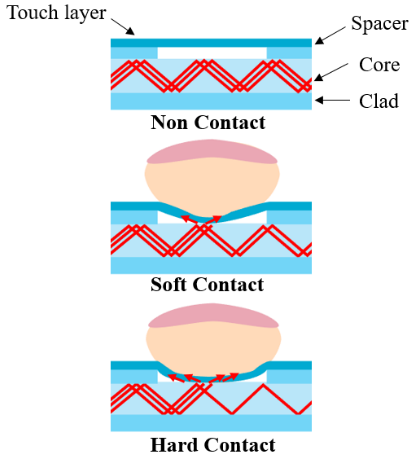


Figure 3. Illustrated operating principle of the soft force sensor.

stacked as a multi-layer structure to fabricate an active DEA membrane layer. We attached copper tapes on both electrode surfaces of the active DEA membrane layers for electrical connections. Finally, a 3D printed circular pillar was placed between two layers. Fig. 2 shows the overall fabrication process of the soft tactile actuator.

B. *Soft Force Sensor*

By controlling the input voltage, the interacting force between the user and a soft tactile actuator can be controlled. However, interacting force changes against the initial contact condition of the actuator with the user. For this reason, the feedback control is necessary to provide accurate physical force feedback to the user. To achieve the feedback necessary,

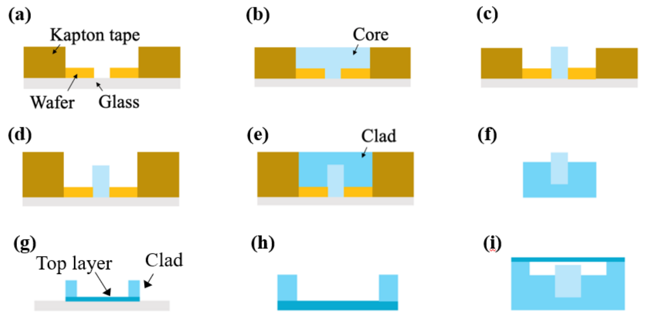


Figure 4. Fabrication process of a soft force sensor: (a) attatch kapton tape and wafer on the glass substrate, (b) place the optical fiber and pour core polymer, (c) after curing, blade the core, (d) add kapton tape, (e) pour clad polymer and cure at 150°C, (f) take off core and clad, (g) fabricate top layer (h) take off from the glass substrate, (i) bonding with the silicone adhesive.

TABLE I. REFRACTIVE INDEX INFORMATIONS OF THE MATERIALS

Parts	Refractive index
Core	1.418
Clad	1.389
Top layer	1.434

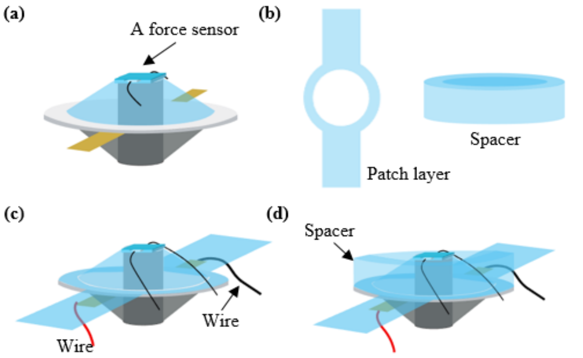


Figure 5. Fabrication process of a wearable interface prototype: (a) bonding the fabricated force sensor with the fabricated soft actuator using silicone adhesive, (b) make the patch layer and the spacer using VHB 4910, (c) attatch wires, (d) fabricated fingertip tactile inteface.

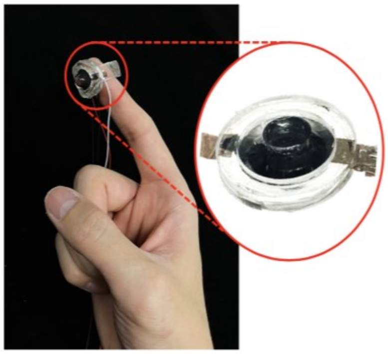


Figure 6. Overall desing of the prototype.

The thin-film force sensor was fabricated. The configuration of the soft force sensor is illustrated in Fig. 3. The force sensor is composed of a light source, photodetector, polymer waveguide, and a touch layer. The light from the light source pass through the polymer waveguide and photodetector detects the light intensity on the other side. As described in Fig. 3, under the pressure, the touch layer deforms and contact between the contact layer and the core induces the scattering of the light. The amount of scattered light changes under the contact force. By monitoring the light intensity from the photodetector, the contact force can be estimated.

In this paper, Dow Corning Sylgard 184 with a mixing ratio of 5:1 cured at 100 °C for 30 min was chosen as the core. To ensure adequate sidewall roughness, two 250 µm thick single crystal silicon wafers were placed 2 mm apart. The wafers were sprayed with Ease Release 200 from Mann Release Technologies, Inc. to facilitate the removal of the polymer from the wafers after curing. The mold of the core was made using Kapton tape having a thickness of 600 µm. Optical fibers (SH1001-1.0, Super Eska) were placed inside the mold before pouring and blade casting the core. The total length and width of the core were 8 mm and 2 mm respectively. A 750 µm thick clad was made by combining Sylgard 184 ratio 10:1 (polymer A) with Smooth-On Ecoflex GEL ratio 1:1 (polymer B). After mixing and degassing the polymers separately, they were mixed with a ratio of 1:1.5 (A: B), and cured at 65°C. Both the spacer and the top layer were blade casted with a thickness of 400 µm and 200 µm respectively. Clad material was used for the spacer while the top layer was Sylgard 184 (5:1) cured at 150 °C for 30 min. This ensured that the top layer had a higher refractive index than the core as light loss occurred into the top layer when it came in contact with the core. The spacer and top layer were assembled using silicone adhesive (Sil-poxy, Smooth-On Sil-poxy). The total thickness of the fabricated sensor was 1.1 mm. The fabrication process of the soft force sensor is illustrated in Fig. 4, and the measured refractive index of the core, clad, and top layers at 635 nm wavelength are summarized in Table I. The differences in the refractive index between the clad, core, and top layer were large enough to act as an effective polymer waveguides.

C. Design of a Wearable Interface

The wearable prototype interface comprised of the soft actuator, a patch, the soft force sensor and a spacer. As can be seen from Fig. 5, the fabricated force sensor is attached under the passive layer of the soft actuator using a silicon adhesive (Sil-Poxy, Smoot-On Co.). For the patch layer, 3M VHB 4910 film was chosen and bonded with the polyurethane tape of 20 µm thickness to remove its stickiness. The patch layer is attached to the fabricated actuator, and the electrical wires are connected to copper tapes. Finally, the spacer, made from stacked 3M VHB 4910 film, is attached to the actuator. Fig. 6 shows the overall design of the built prototype. The total weight of the fabricated prototype was 3.2 g.

III. EXPERIMENTS

A. Soft Tactile Actuator

For an effective wearable tactile interface application, the actuator is needed to exert enough force and displacement for a human. To find an optimal design that meets these criteria,

TABLE II. TEST SAMPLE PARAMETERS OF A SOFT TACTILE ACTUATOR.

Sample number		**Diameter of the pillar (mm)**		
		4	6	8
Height of the pillar (mm)	6	Sample 1	Sample 3	Sample 5
	8	Sample 2	Sample 4	Sample 6

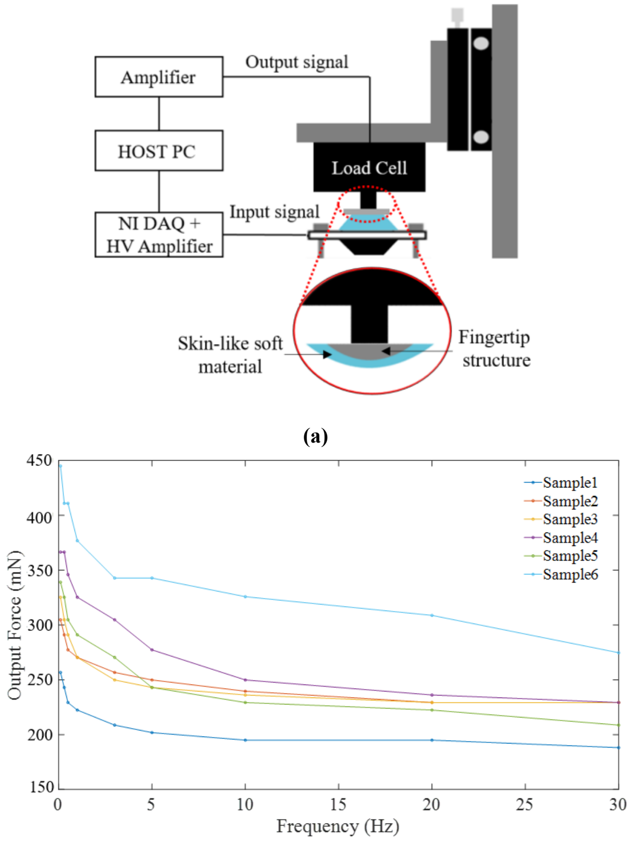


Figure 7. (a) Output force measurement experimental setup, (b) Measured output force of six samples

six samples were tested by controlling two variables, which were the diameter and height of the inner circular pillar. Detailed parameters of each sample are shown in Table II.

The performance of the soft tactile actuator can be evaluated by observing the output force and displacement characteristics. To measure the output force of an actuator, a high voltage amplifier (AMJ-4B10, Matsusada), a load cell (UMI-G500, DACELL), a load cell amplifier (DN-AM100, DACELL), a DAQ board (USB-6003, National Instruments), and a laptop were prepared. To ensure precise contact between the load cell and the actuator, the load cell was mounted on an aluminum bracket attached to a linear stage. Since this patch is to be worn on the user's fingertip, a skin-like soft material was attached on the tip of the load cell to simulate an actual wearing condition as shown in Fig. 7(a). The laptop was used to send voltage signals, ranging from 0.1 Hz to 30 Hz at 4 kV, to the actuator, and simultaneously collect resulting load cell data. Fig. 7(a) illustrated the output force measurement experimental setup, and the results are shown in Fig. 7(b). Force measurements of all samples were offset to the same initial condition of 0.01 N at 4 kV input voltage. As the results show, test samples exhibited similar resonance frequency properties at nearly 0.1 Hz. However, measured output force has a notable difference among the six samples. Results showed that increasing the diameter of the inner circular pillar increased the actuator output force.

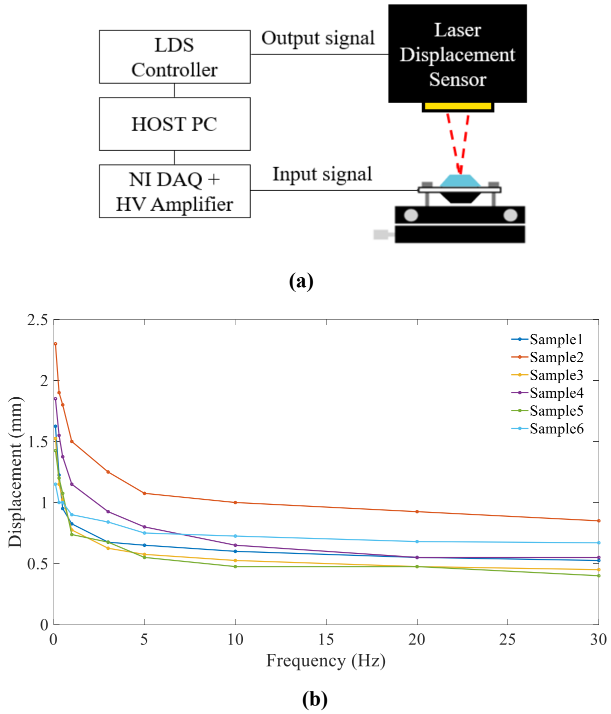
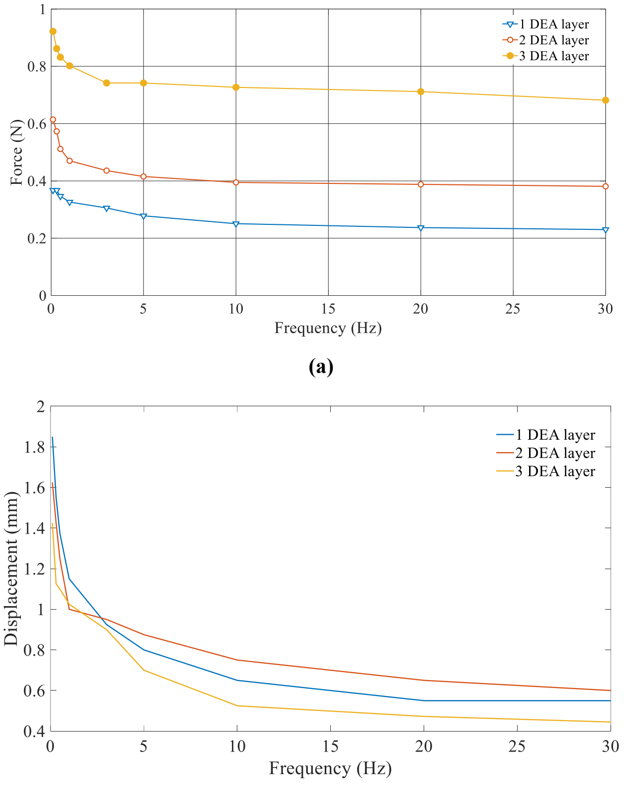


Figure 8. (a) Free displacement measurement exprimental setup, (b) Measured displacement of six samples.

The performance of the six actuator samples was further evaluated by observing its displacement characteristics. For the measurement, a laser displacement sensor (LK-500, Keyence) and its controller (LC-2100, Keyence), a high voltage amplifier, a DAQ board, and a laptop were prepared. The actuator's position was controlled to match the laser displacement sensor's laser scanning point to the actuator's center. The displacement measurement setup is shown in Fig. 8(a). The same frequency sweep program, as the output force test, was used to stimulate the actuator and collect resulting free displacement data. Results are plotted along with the frequency range and are shown in Fig. 8(b). Sample number two shows the maximum free displacement of 2.30 mm at 0.1 Hz. The resonance frequencies of all samples were observed around 0.1 Hz, which was the same as the resonance frequency of the output force measurement test. The results of the maximum output force the displacement test are summarized in Table III. Of prepared samples, sample number six exhibited the highest output force, whereas sample number two exhibited the highest displacement. However, for the effective tactile actuator, the actuator should have both a high output force and a displacement. For example, sample number six shows the highest output force among six samples but has small displacement. For the effective tactile actuator, sample number four was selected as a tactile actuator as it shows the high output force as well as the displacement among six

TABLE III. EXPERIMENT RESULT OF OUTPUT FORCE AND DISPLACMEENT TEST OF SIX SAMPLES.

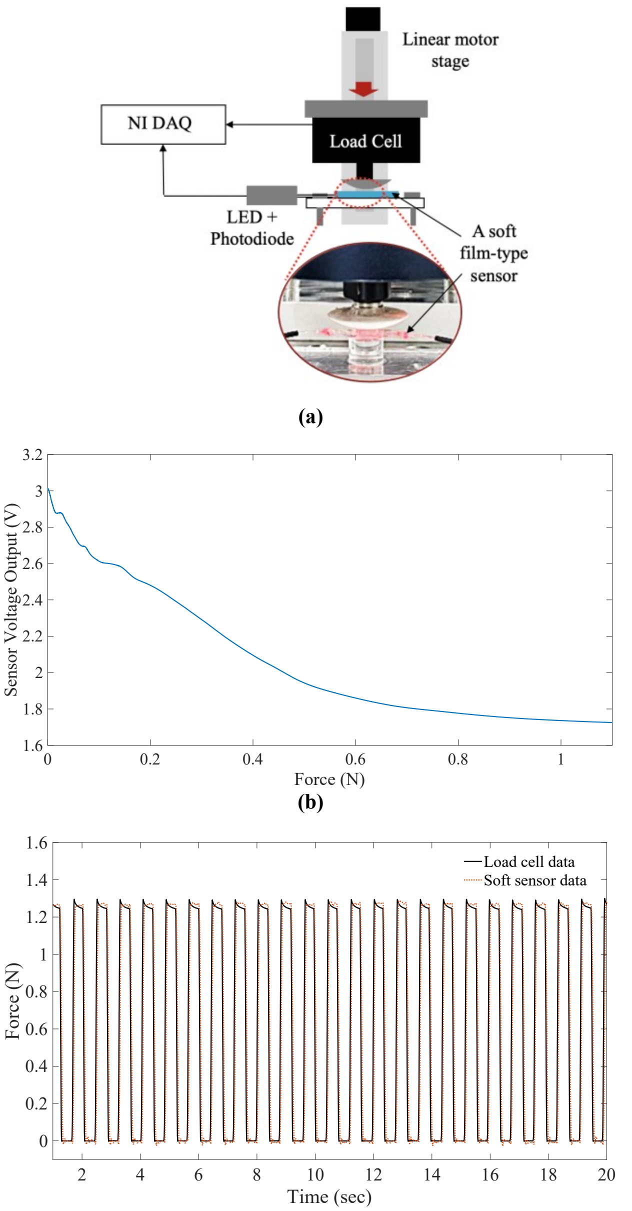
Sample number	Maximum output force (mN)	Maximum displacement (mm)
1	257.64	1.62
2	305.66	2.30
3	326.24	1.53
4	367.40	1.85
5	339.96	1.43
6	445.91	1.45



(a)

(b)

Figure 9. (a) Measured output force of samples with different number of DEA layers, (b) Measured dispalcement of samples with different number of DEA layers.



(a)

(b)

(c)

Figure 10. (a) Sensor expreimental setup, (b) Measured sensor data with applied input force, (c) Dynamic response of the soft force sensor at 1.25 Hz.

samples. The performance of the selected parameter, sample number four, was further evaluated by observing the output force and the displacement while increasing the number of DEA active layers from one to three. Fig. 9(a) shows the result of the output force measurement test and Fig. 9(b) shows the result of the free displacement test under different number of DEA active layers. The results indicate that the output force increases significantly when increasing the number of DEA layers. The maximum output force increased from 367.40 mN to 924.11 mN when the number of the DEA layers increased from one to three. However, the maximum displacement of the actuator only decreased from 1.85 mm to 1.43 mm. Based on these results, the soft tactile actuator was selected to use sample number four's parameter where the diameter of the inner pillar is 6 mm, and the height of the inner pillar was 8 mm with three active DEA layers.

B. Soft Force Sensor

To evaluate the performance of the fabricated soft force sensor, a linear servo motor stage (PK523HPMB, Suruga Seiki Co.), a motor controller (DS102, Suruga Seiki Co.), a load cell, a load cell amplifier, a DAQ board, and a laptop was prepared, as depicted in Fig. 10(a). A linear servo motor can produce a programmable input force based on the feedback control using the load cell data. In the test, two different input forces were applied to the sensor. First, the input force was increased linearly from 0 N to 1.2 N for 75 seconds. Fig. 10(b) shows the measured voltage output of the soft force sensor photodetector against to the input force ranging from 0 - 1.2 N.

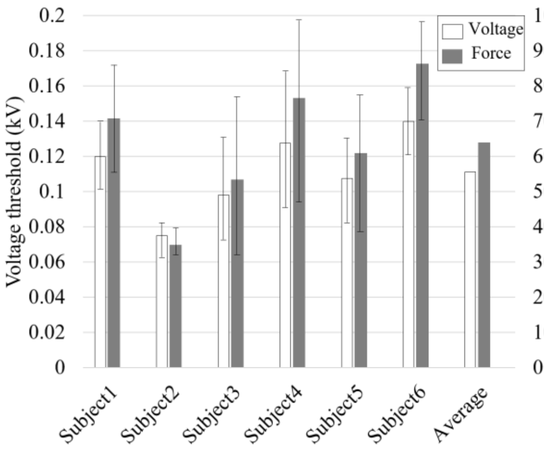


Figure 11. Measured tactile thresholds at 0.1 Hz.

Also, the square-wave driving input force ranging from 0 to 1.25 N at 1.25 Hz was applied to the sensor. The measured voltage output of the soft force sensor was converted to the force data, and was compared with the reference force data which can be measured from the load cell, as shown in Fig. 10(c). Results show the fabricated soft force sensor can monitor the force in a range of actuator's output force.

C. *User Test*

To verify the usability of the proposed fingertip tactile display, the user test was conducted to measure the perception thresholds of the actuator with six subjects. The age of six subjects was between 22 to 26 years. To measure the perception threshold of the indentation feedback, the following procedure was used. First, all subjects put their index fingertip on top of the soft tactile actuator. Then, the square wave input voltage with a different voltage level was applied at 0.1 Hz. The input voltage amplitude was increased from 0.01 kV with a constant step of 0.01 kV, until the participants perceive the difference in their tactile perception. The same experiments were repeated 5 times per each person. The graph in the Fig.11 shows the results of the tactile thresholds test of all subjects. The average voltage threshold of all subjects was 0.11 kV, which is corresponding to the force perception threshold of 64 mN. These indentation feedback thresholds are lower than the actuator's output force of 924.11mN, which has 14.5 times margins.

IV. CONCLUSION

In this research, a self-sensing soft actuator for fingertip interface was developed based on electro-active polymers. We chose a double cone DEA structure. Six actuator samples of different parameters were fabricated to optimize the design parameters. After carrying out two performance tests, the actuator sample with the most optimal properties was selected for use in a wearable interface. This sample was capable of producing 924.11 mN of output force at 0.1 Hz and 1.43 mm of free displacement at 0.1 Hz under 4 kV input voltage. This output force was 14.5 times higher than the measured perception thresholds based on the user test. A film-type soft force sensor of 1.1 mm thickness was also presented in this research. Under the pressure, the touch layer of a soft sensor makes contact with the core, which induces scattering of the light. The amount of scattered light varies under the contact force, and the interface force can be measured by monitoring the light intensity of the sensor. The fabricated soft force sensor was able to measure the force in a range of 0 to 1.25 N. The wearable prototype interface was fabricated by integrating a soft actuator, a soft force sensor, and a patch and spacer. The wearable prototype interface was able to provide accurate physical force feedback to the user from the feedback control. The wearable prototype interface is designed to have benefits in a soft, flexible, and light-weight structure (3.2 g).

In the future, a fabrication process of a soft pressure sensor will be done by adapting micro electro-mechanical systems (MEMS) technology. This will allow the sensor to increase the consistency, accuracy, and repeatability.

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