Development of Silicone Outer Shell Type Pneumatic Soft Actuator

Yasuhiro HAYAKAWA¹, Keisuke KIDA¹, Yuma NAKANISHI¹, Hiroaki ICHII¹

¹ Department of Control Engineering Nara National College of Technology (22 Yata-cho, Yamato-Koriyama, Nara, 639-1080 Japan) hayakawa@ctrl.nara-k.ac.jp

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The pneumatic soft actuators have both passive flexibility of the casing and active flexibility through pressurizing and depressurizing. These features are expected to be human-friendly actuators because they enable the approach of using an original soft system by controlling the internal air pressure. The current pneumatic soft actuator has two technical points of interest; control method of driving direction and operating pressure level, requiring an actuator to match these points. In this study, a pneumatic soft actuator with a silicone rubber case, SCSRA (Sponge Core Soft Rubber Actuator) was proposed and developed to respond to the requirement. Thought some experimental results, it is cleared that SCSRA controlled the driving system by realizing a large stroke in the low-pressure region of 30kPa or less as well as peeling and adhering the silicone film.

Keywords: High Performance Insole, Pneumatic, Care Prevention, Walking, Soft Rubber Actuator

1. Introduction

There are many types of actuators used in today’s industrial, medical, and welfare fields, depending on their operating principles. Even for a simple piston-cylinder system, there are thermal, electric, and fluid types, and they are used in different ways depending on the application and operating object. Among them, pneumatic soft actuators are suitable for applications involving contact with flexible objects such as fruits and human bodies. These actuators, driven by air and mainly using rubber as casing, are referred to as “human-friendly actuators”.

This is because pneumatic soft actuators have “two flexibility features” that set them apart from other actuators. First, the flexibility of the case and the compressibility of the air allow the actuator to exhibit passive flexibility as an elastic body even when it is not pressurized. Secondly, the flexibility can be actively controlled by changing the shape and stiffness of the actuator by pressurizing inside of it. This feature makes it possible to realize a unique process in which an original soft system can be strengthened and utilized by control. Furthermore, the system does not require high current or high heat for operation, and even if the case is damaged, the operating energy is harmless air, resulting in minimal impact on the surrounding environment or the object being operated. Because of these features, systems using pneumatic soft actuators have been developed and realized in various fields beyond the existing applications in recent years.

There are two major technical points of interest in the pneumatic soft actuators that have been developed to date. The first is the pressure level to be used. For example, the PBA (Pneumatic Balloon Actuator) performing a bending motion requires an internal pressure of 70kPa for a 7 mm-motion stroke, and the twist actuator performing a twist motion, requires an internal pressure of 178kPa for a 70° motion. In the case of pneumatic soft actuators, which are often used in contact with flexible objects, there is a close relationship between the internal pressure and the safety of the operating energy, so from the viewpoint of the impact on the operating object and the surrounding environment, driving at even lower pressure is required. The second is the structure to control the driving direction. In order to generate deformation in a specific direction, the pneumatic rubber artificial muscle uses a sleeve woven with fibers, and the FMA (Flexible Micro Actuator), constrains the deformation direction by installing multiple air chambers. If the drive direction can be controlled with a simpler structure, it will be possible to reduce the cost and space of the actuator.

This study focuses on these improvements and aims to develop a pneumatic soft actuator, SCSRA (Sponge Core Soft Rubber Actuator), that satisfies the following three requirements.

(1) Low-pressure operation

A large internal pressure to motion stroke ratio can be achieved at lower pressure levels (small less than 30kPa) than conventional pneumatic soft actuators.

(2) Simple control method for driving direction

By keeping the pressure level low, the deformation direction can be constrained at low cost and with a simple structure.

(3) Both passive and active functions

It is equipped with both pressurized and non-pressurized functions by taking advantage of the “two-flexibility” characteristic of pneumatic soft actuators.

In this paper, the structure and fabrication method of the SCSRA were described first, and the functions of the SCSRA to satisfy three requirements mentioned above are explained. Next, the characterization experiments show that the specified functions could be achieved under both pressurized and unpressurized conditions, and the parameters affecting the characteristics are clarified.

2. SCSRA (Sponge Core Soft Rubber Actuator)

2.1 Structure and Features

The structure of SCSRA is shown in Figure 1. SCSRA is a pneumatic soft actuator consisting of a core foam sponge surrounded by a case made of silicone rubber and a polyurethane tube for inflow and outflow of air. The combination of three flexible materials and air pressure is suitable for applications involving contact with flexible objects, such as fruits and human bodies.

The difference from conventional pneumatic soft actuators is that...
the pressurized area is not just a cavity, but a gap between the continuous foam sponges. The presence of the sponge enables the actuator to maintain a certain level of rigidity even when the inside of the actuator is open to the atmosphere, and it also has the advantage that the same internal pressure can be obtained at a lower flow rate than when the inside of the case is simply pressurized.

Since the case is made of two-component Room Temperature Vulcanizing rubber, which is liquid before curing, any actuator shape and pressure area can be achieved by changing the shape of the sponge and mold. In addition, the sponge and silicone rubber may be adhered or separated during fabrication, so the functions described in the next section can be used.

2.2 Fabrication procedure

Figure 2 shows the fabrication procedure of the SCSRA. The procedure is roughly divided into (1) fabrication of the bottom surface, (2) processing and placement of the sponge, (3) fabrication of the side and top surfaces, and (4) installation of the tube. The bonding conditions between the silicone rubber and sponge may vary depending on the timing of the sponge placement. Specifically, in the case of adhesion, the sponge is placed before the silicone liquid on the bottom becoming elastic, and in the case of separation, the sponge is placed after the liquid becoming elastic.

For convenience, SCSRAs in which silicone rubber and sponge are adhered are referred to as “adhesive elements,” and SCSRAs in which silicone rubber and sponge are separated are referred to as “separated elements”.

2.3 Functions

The SCSRA has the following four functions, depending on whether the inside of the actuator is pressurized or unpressurized, and whether the sponge and silicone rubber are adhered or separated.

(1) Force-distribution function (Figure 3(a))

The passive function of the SCSRA is demonstrated by sealing the inside of the actuator with atmospheric pressure. The flexibility of the constituent materials themselves and the compressibility of the air disperse the force applied from the outside in multiple directions.

(2) Force-estimation function (Figure 3(b))

The passive function of SCSRA is demonstrated by sealing atmospheric pressure inside the actuator and connecting a pneumatic sensor to the tube. When an external force is applied to the SCSRA top surface, the pressure-receiving area and the indicated value of the air pressure sensor are substituted into Equation (1) to estimate the applied external force.

\[ P = \frac{F}{A} \]  

\( P \): Pressure [Pa]  
\( F \): Vertical force acting on a surface [N]  
\( A \): Force-activated area [m²]

(3) Rigidity-changing function (Figure 3(c))

The active function of SCSRA is demonstrated by fully adhering the sponge and silicone rubber, and pressurizing the inside of the actuator. Deformation of the silicone membrane under pressure is constrained by the sponge, which rapidly increases its stiffness in response to slight changes in shape.

(4) Shape-changing function (Figure 3(d))

The active function of SCSRA is demonstrated by separating the sponge and silicone rubber only on a specific surface and pressurizing the actuator. Since the silicone rubber other than the separating surface is constrained by the sponge, only the separating surface is deformed significantly under pressure. The driving direction can be controlled by changing the separation surface.

3. Characterization Experiments

3.1 Objective

In order to show that SCSRA satisfies the three requirements described in Chapter 1, characterization experiments were conducted. As explained in Section 2.2, there is a close relationship between the three requirements and the functions of SCSRA. Therefore, by showing that SCSRA can realize the four functions, the purpose of this study is considered to have been achieved.

The function (2), the external force estimation function, has been realized in the previous research in this laboratory, the high-performance shoes system for gait training6) (Figure 4). The SCSRA is used as an insole element and realizes the function of understanding the subject’s gait state through the foot pressure distribution.

In this study, the following functions are demonstrated through characteristic experiments: (1) external force dispersion function, (3) stiffness change function, and (4) shape change function.
3.2 Use of Devices

Table 1 shows the devices were used for the characteristic experiments.

3.3 Experimental Devices

Figure 5 shows the experimental apparatus used in the characterization experiments. The system is divided into two parts: one is to control the internal pressure of the SCSRA, and the other is to measure the displacement caused by pressurization or load application using a laser displacement meter. The final output value is obtained by converting the analog output of the laser displacement meter to a digital value using an A/D converter. The internal pressure of the actuator is controlled by the electro-pneumatic regulator, and the output of the air pressure sensor is obtained as a voltage value.

![Fig. 3 Functions of SCSRA](image)

**Fig. 3 Functions of SCSRA**

![Fig. 4 Insole Elements of High-performance Shoes](image)

**Fig. 4 Insole Elements of High-performance Shoes**

3.4 SCSRA for the Experiments

The parameters affecting the properties of SCSRA are shown in Figure 6, and the physical properties of the sponge and silicone rubber used in SCSRA are shown in Table 2 and Table 3. In this study, the SCSRA with the parameters shown in Table 4 is used as the reference SCSRA, and we examined how the overall characteristics changed when each parameter is changed.

4. Expansion Characteristics Experiment

4.1 Experimental method

The following procedures are used for the experiment.

1. Using the experimental setup shown in Figure 5, the internal pressure of the reference SCSRA is set to 0, 5, and 10 kPa.

2. The relationship between the internal pressure and the amount of expansion is obtained by measuring the top of the expansion shape (the point at which the amount of expansion is maximum) using a laser displacement meter.

![Table 1 List of Equipment Used for Experiment](image)

**Table 1 List of Equipment Used for Experiment**

<table>
<thead>
<tr>
<th>Device Name</th>
<th>Manufacturer</th>
<th>Model Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC Stabilized Power Supply</td>
<td>Gwinstek</td>
<td>GPS-3030D</td>
</tr>
<tr>
<td>METRONIX 512C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control Circuit</td>
<td>Arduino</td>
<td>UNO R3</td>
</tr>
<tr>
<td>AD Converter</td>
<td>ELMOS</td>
<td>RAI-16</td>
</tr>
<tr>
<td>Laser Displacement Meter</td>
<td>FASTUS</td>
<td>CD22-35V</td>
</tr>
<tr>
<td>Micro Pump</td>
<td>Parker</td>
<td>CTS</td>
</tr>
<tr>
<td>Pressure Sensor</td>
<td>Fujikura</td>
<td>AG213-200KG</td>
</tr>
<tr>
<td>3-Port Spool Valve</td>
<td>SMC</td>
<td>S070C-RDC-32</td>
</tr>
</tbody>
</table>

V1~V3: Supplied by a DC stabilized power supply.
V4~V6: Supplied from each pin of the Arduino, the control circuit.
V7: Supplied from the USB port of the PC.
From the standard SCSRA, only the bonding condition of the top surface is changed, and the same procedure is performed for the SCSRA in which the silicone film and sponge has completely adhered.

4.2 Results and Discussion

The relationship between the actuator internal pressure $p$ and the amount of expansion for the two types of SCSRA is shown in Figure 7. The results can be summarized as follows.

1. The expansion characteristics of SCSRA followed a quadratic curve:
   The correlation coefficients for the quadratic curve approximations were above 0.9 for both the separated and adhered elements, indicating a very strong positive correlation. This is thought to be largely due to rubber elasticity, which is a key property of silicone rubber. From the characteristic curve, it can be seen that the increasing rate of the expansion decreased with raising internal pressure, especially for the reference SCSRA.

2. The characteristics of separated and adhered elements could be clearly distinguished:
   The property curves show that there is a clear difference between the properties of the separated and adhered elements. The first-order coefficient, which is the most important term in the approximation equation, shows a difference of about 24.9 times, and the expansion amount at an internal pressure of 15 kPa shows a difference of about 38.2 times, indicating that the rigidly- and shape-changing functions of SCSRA could be switched depending on the adhesion conditions of the silicone film.

3. The separate elements had a high internal pressure-to-operating stroke ratio:
   Focusing on the reference SCSRA in the expansion characteristic curve, an expansion of approximately 26.0 mm was achieved at an internal pressure of 15 kPa. This indicates that the SCSRA had a shape-changing function. Although it is difficult to compare simply with the bending and twisting motions in the previous studies described in Chapter 1, the internal pressures used were 4.6 and 11.9 times those of the SCSRA, respectively, and the motion stroke was equal to or less than that of the SCSRA. This indicates that the SCSRA achieved higher internal pressure and motion stroke than conventional pneumatic soft actuators.

5. Spring Stiffness Characteristics Experiment

5.1 Experimental method

The following procedures are used for the experiment.

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Table 2 Main Property of Sponge

<table>
<thead>
<tr>
<th>Sponge</th>
<th>Stiff Urethane Sponge EMO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density [kg/m$^3$]</td>
<td>50 ± 5</td>
</tr>
<tr>
<td>Hardness [N]</td>
<td>12.75 ± 0.05</td>
</tr>
</tbody>
</table>

Table 3 Main Property of Silicone

<table>
<thead>
<tr>
<th>Silicone</th>
<th>KE-1316</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hardness [Durometer A]</td>
<td>23</td>
</tr>
<tr>
<td>Viscosity [Pa·s]</td>
<td>35</td>
</tr>
<tr>
<td>Tensile Strength [MPa]</td>
<td>6.5</td>
</tr>
<tr>
<td>Elongation at Break [%]</td>
<td>700</td>
</tr>
<tr>
<td>Tear Strength [kN/m]</td>
<td>33</td>
</tr>
<tr>
<td>Line Shrinkage Ratio [%]</td>
<td>0.1</td>
</tr>
<tr>
<td>Density [g/cm$^3$]</td>
<td>1.13</td>
</tr>
</tbody>
</table>

Table 4 Parameters of Reference Actuator

<table>
<thead>
<tr>
<th>External Shape [mm]</th>
<th>50×50×9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wall Film Thickness [mm]</td>
<td>4</td>
</tr>
<tr>
<td>Upper and Lower Film Thickness [mm]</td>
<td>2</td>
</tr>
<tr>
<td>Internal Pressure $P$ [kPa]</td>
<td>0</td>
</tr>
<tr>
<td>Adhesive conditions on the Top Surface</td>
<td>Separated</td>
</tr>
</tbody>
</table>

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(1) Using the experimental setup shown in Figure 5, the internal pressure $p$ of the reference SCSRA is set to 10, 20, and 30 kPa.

(2) A load of 100, 200, 300, 400, 500, 1000, and 2,000 g is applied to the SCSRA top surface, and the amount of sinking is measured by a laser displacement meter to obtain the spring stiffness characteristics.

The stresses in Figs. 8, 9, and 10 are obtained from p.2 Equation (1), where $A = 25 \times 10^{-4}$ [m$^2$].

(3) The internal pressure of the reference SCSRA is set to 0 kPa, and the wall thickness $a$ (Figure 6) is changed to 2, 4, and 6 mm, respectively, and the same measurements are made using the procedure (1)~(2).

(4) The internal pressure of the reference SCSRA is set to 0 kPa, and the upper and lower film thicknesses, $b$, are changed to 2 and 4 mm, respectively, and the same measurements are made using the procedure (1)~(2).

5.2 Results and Discussion

Figure 8 shows the stress-strain curves under different internal pressure “$p$” from the reference SCSRA. Note that only 100, 200, 300, 400, and 500 g loads are applied to the data because excessive stress under pressure may cause the actuator to break. The results are as follows.

(1) The spring stiffness characteristics of SCSRA followed an exponential function:

In common with each “$p$”, the correlation coefficient for the exponential function approximation exceeded 0.9, indicating a very strong positive correlation. This characteristic, in which the required stress increased with raising displacement, was extremely similar to the characteristics of air and rubber materials during compression, suggesting that silicone rubber and compressed air formed the spring stiffness characteristics.

It is thought that changing the stiffness of the internal sponge or silicone rubber itself would also change the spring stiffness characteristics, but this is not considered in this experiment.

(2) The spring stiffness increased with raising internal pressure:

As the “$p$” increases, the stress required to generate a certain amount of displacement also increases, indicating an increase in spring stiffness. It can be said that the SCSRA realized the rigidly-changing function with the results of extended characterization experiments.

When the initial internal pressure was applied, small deformation was observed as shown in Table 5. Since the deformation was less than 3% of the total SCSRA thickness of 9 mm, it was not considered to be a problem in the experiment.

The stress-strain curves for wall film thickness “$a$” (Figure 6) different from the reference SCSRA are shown in Figure 9. The results show that as “$a$” increases, the stiffness of the entire SCSRA decreases. This may be due to the fact that the stiffness of the silicone rubber used in the experiment is less than that of the sponge. In addition, even if the interior of the SCSRA is measured at atmospheric pressure, the characteristics follow an exponential function as in the case of pressurization. This indicates that the SCSRA has the capability to distribute external force due to the passive flexibility of silicone rubber, sponge, and air under non-pressurized conditions.

Figure 10 shows that the stress-strain curves for the reference SCSRA and upper and lower film thicknesses “$b$” (Figure 6). The results show that as “$b$” increases, the stiffness of the entire SCSRA decreases. This can be attributed to the decrease in the spring stiffness according to the series connection equation (Figure 11) because the increase of the top and bottom film thicknesses corresponds to the addition of a silicone film in series with the reference SCSRA.

6. Conclusions

In this study, a pneumatic soft actuator, SCSRA, with a sponge core and a silicone rubber case was developed. First, three
requirements for SCSRA were defined based on advantages and problems of the previous studies, and then the requirements were specified by passive and active functions. Then, we showed that the SCSRA can realize these functions through characterization experiments.

7. Acknowledgments

We would like to express my sincere gratitude to Associate Professor Pak Keunyoung for her English guidance during her busy schedule in conducting this research. We would also like to thank SMC Corporation for providing some of the experimental equipment. Finally, we would like to express my utmost gratitude to all the students who supported my research, both inside and outside the laboratory.

References