A DESIGN OF LONGITUDINALLY-DIVIDED BALLOON STRUCTURE IN PDMS PNEUMATIC BALLOON ACTUATOR BASED ON FEM SIMULATIONS

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ABSTRACT

Toward optimum design of micro devices using pneumatic balloon actuators (PBAs), we propose a design concept with longitudinally-divided balloon structure. We have performed FEM-based simulation and demonstrated its applicability to compute and characterize the bending motion of PBAs fabricated from PDMS (polydimethylsiloxane) material. In the present study, it is shown through the simulation that the bending characteristics can be significantly altered dependent on the number of balloon divisions. Moreover, it is experimentally indicated that, with the present design, the magnitude of the balloon inflation can be reduced so as to achieve a desired bending motion in more compact space than required with a single-balloon structure of the equivalent size of the balloon.

KEYWORDS

Pneumatic Balloon Actuator, PDMS, FEM, Bending Motion

1. INTRODUCTION

Recently, there has been increasing interest in biomedical application of flexible actuators with polymer-based materials [1, 2]. Pneumatic balloon actuators (PBAs) [3], fabricated by soft lithography techniques using PDMS (polydimethylsiloxane)-based materials [4], are attractive in terms of small, soft and safe (S^3) features [5]. Over the past decade, various types of functional structures have been designed and developed by benefitting attractive features of PDMS such as flexibility, elasticity, transparency and biocompatibility. High flexibility and elasticity, which can lead to large deformation through out-of-plane bending motions, are effectively used in various types of PBAs [5, 6]. In view of biomedical application, the further miniaturization of PBAs is considered to be one of the most challenging issues to be explored.

Although FEM simulations have been employed in various stages of the development of microactuators [7-12], simulation-based design of PBAs has not yet been reported. Thus, it is not clear whether the conventional FEM technique is effective for designing PBAs. For further advancement, it would be critically important to provide an efficient designing environment.

In the present study, the bending motion of PBAs, caused by the difference of the stress distribution of each membrane, is examined by FEM simulations. The specific objective of the present study is to propose a design concept with longitudinally-divided balloon structure and to examine its effectiveness for downsizing the existing micro devices using PBAs.

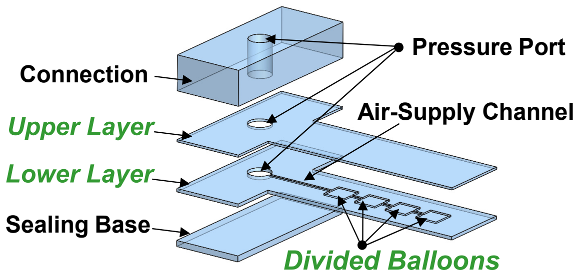

Figure 1: Configuration of the all-PDMS pneumatic balloon actuator.

Table 1: Different combinations of the membranes.

Combination	Upper Layer	Lower Layer
Case 1	PDMS-B, 95 µm	PDMS-A, 140 µm
Case 2	PDMS-A, 95 µm	PDMS-B, 140 µm
Case 3	PDMS-A, 95 µm	PDMS-A, 140 µm
Case 4	PDMS-B, 95 µm	PDMS-B, 140 µm

2. PRACTICAL DESIGN

Fabrication

The bending motions of typical PBAs are experimentally investigated. Figure 1 shows the multi-layered structure of all-PDMS pneumatic balloon actuator. The essential part consists of 2 layers of PDMS membranes with different thickness and physical properties. Typical examples of different combinations of upper and lower layers are listed in Table 1. PDMS-A refers to an 8:1 mixture of the base polymer and the curing agent (Sylgard 184, Dow Corning Inc.), while PDMS-B a 12:1 mixture. The present PBAs are fabricated using the soft lithography technique. Each device is fabricated by a PDMS mold process using the silicon mold and the oxygen plasma treatment for PDMS-to-PDMS bonding [3].

Experimental Observation

The static displacements at the tip of the devices according to the applied pressure are measured, as shown in Fig. 2. Downward motions are obtained in Cases 1, 3, and 4, and an upward motion in Case 2. It is noted that, when the upper layer becomes thinner than the present case, we can also obtain 'bidirectional' motion [3]. Conventionally, design parameters are determined mainly based on experimental observation as shown above. Thus, vast amounts of trial-and-error tuning tests are required to design and fabricate PBA devices with desired actuation mode for individual purposes. Therefore, it would be of invaluable benefit to establish a rational designing environment with numerical approach, which would

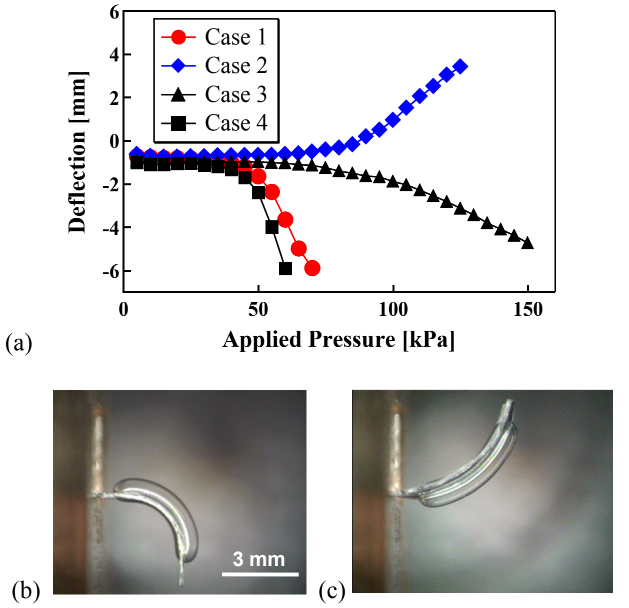

Figure 2: Experimental results: (a) deflection versus applied pressure, (b) downward motion in Case 1, (c) upward motion in Case 2.

significantly reduce the time and cost for the future development of PBA devices [2].

3. PBA WITH A SINGLE-BALLOON STRUCTURE

In the present study, we have performed FEM-based simulation to investigate its applicability to compute the bending motions of PBAs. Among the 4 cases shown in Tab. 1, Case 1 is considered in the following.

Bulge Test

Young's modulus and Poisson's ratio of PDMS membranes are estimated from a bulge test [13, 14]. PDMS membranes are bonded onto a Si substrate with a through hole of rectangular shapes of different dimensions. To prevent the membrane from peeling off the substrate, an aluminum jig is installed in the apparatus. The deflection along a line passing through the central point of the membrane is measured by a laser displacement sensor (LJ-G030, KEYENCE), changing the applied pressure, as shown in Fig. 3. By curve-fitting the data of the maximum deformation versus the applied pressure, Young's modulus of PDMS membranes is calculated as 4.5 MPa and 2.5 MPa for a PDMS-A and a PDMS-B, respectively. Poisson's ratio is estimated to be 0.48.

FEM Simulations & Experiments

Using the physical properties obtained from the bulge test, we have performed FEM simulations. In the present computation, COMSOL Multiphysics (Ver. 3.5) is employed. PDMS membranes are modelled as elastic membranes with hyperelasticity. We have adopted an incompressible Neo-Hookean material model as a constitutive equation for simulating the motion of PDMS

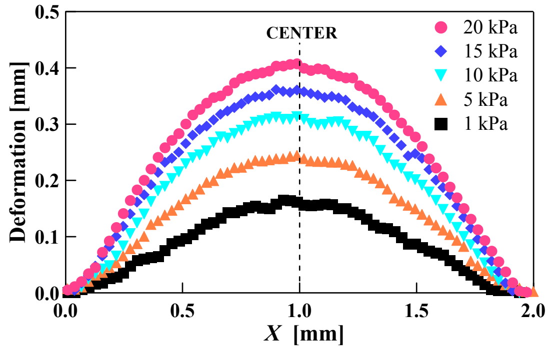

Figure 3: Experimental evaluation of the physical properties of PDMS membranes (deformation for different applied pressure with a 2 × 8 mm² hole and PDMS-A of 140 µm in thickness)

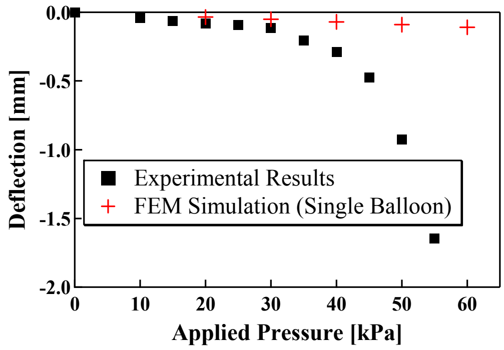

Figure 4: Comparison between FEM and experimental results of the PBA deflection.

materials with large deformation [9].

The PBA analysed in the present simulation consists of two PDMS layers with different thickness and physical properties. The upper layer of 95 µm in thickness is more flexible than the lower layer of 140 µm in thickness with the air channel and balloon cavity of 75 µm in thickness. The total length is 6.5 mm in each case, and the balloon size is 4 mm × 1 mm. With each model, the left end of the membrane is assumed to be clamped. The applied pressure is given as the boundary condition on all of the channel walls around the balloon cavity.

Figure 4 shows the comparison between FEM and experimental results of the deflection at the tip of the PBA (right free end) with a single-balloon structure. Here, the bending motion of a cantilever-type PBA, of which the material consists of the Case 1 configuration, is computed. For small applied pressure, the deflection increases in a linear way, and fairly good agreement is obtained. For large pressure with non-linear deformation, on the other hand, the difference between simulation and experiments becomes large due probably to the inability of the present FEM simulation to compute the large bending of the actual motions. Large strain is obtained around the edge regions of the balloon, and the principal strain exceeds 200% at the applied pressure of around 50 kPa.

It is indicated that the present simulation within the linearly-elastic region could be extended to practical designs of various PBA devices. It is also implied that, for analysis of larger bending motion with extremely-

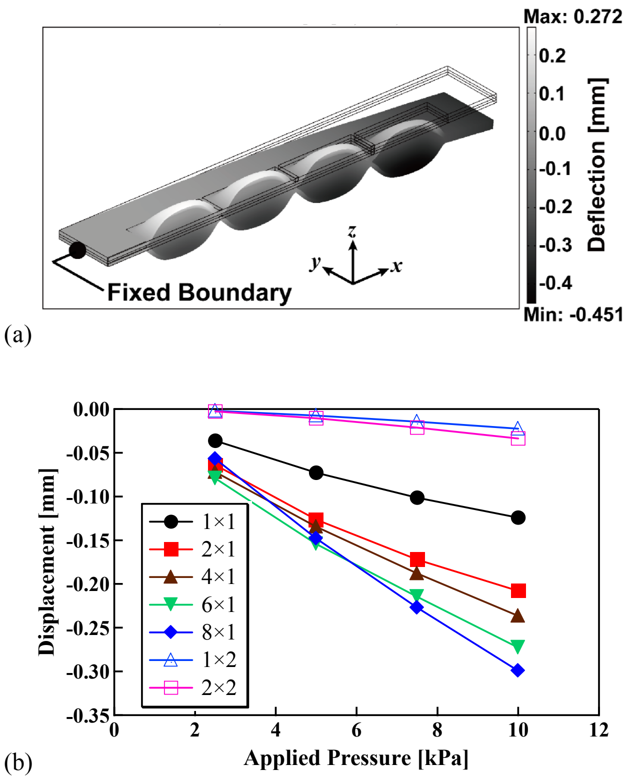

Figure 5: FEM results of the deflection of the PBAs with m × n division (m and n denote the number of divisions in the longitudinal and transverse directions, respectively): (a) Simulation for 4×1 PBA, (b) displacement vs. applied pressure.

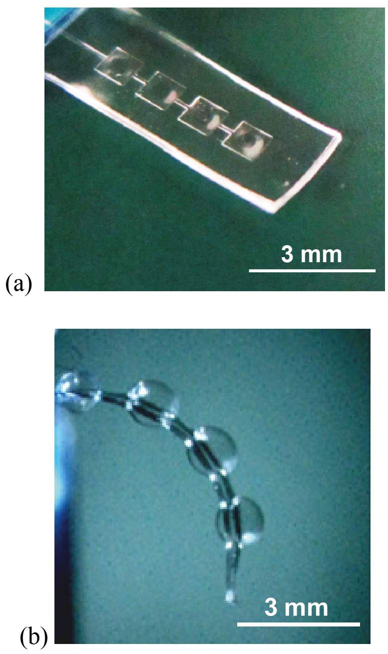

Figure 6: Experimental results for Case 1 with downward motion: (a) Bending of a PBA with single-balloon structure, (b) Bending with the present longitudinally-divided structure (m = 4, n = 1).

large strain, higher-order constitutive equation and/or more advanced numerical techniques such as a meshfree numerical method would be needed.

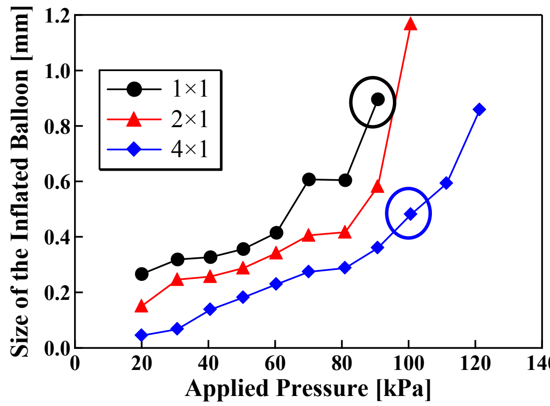

Figure 7: Experimental results of the size of the inflated balloons.

4. PBA WITH LONGITUDINALLY-DIVIDED BALLOON STRUCTURE

Present Strategy

For the miniaturization of PBAs, it is important to take into account the size of the inflated balloons when the pressurized PBA should be retracted within a limited space. One of the existing devices with such requirement satisfied is a cell-sheet transplantation tool [6], where the PBA is used for wrapping around a cell-sheet and retracting into a small pipe with a diameter of around 1-1.5 mm. Here, we propose a PBA design with longitudinally-divided balloon structure in order to obtain a desired bending motion with a reduced size of the inflated balloons.

FEM Simulations

Based on the simulation results of the PBA with a single-balloon structure, we have investigated the effect of the dividing pattern on the bending motion presumably within the linearly-elastic region. The numerical condition is the same as described in the previous section.

Figure 5 shows the FEM results of the deflection of PBAs with $m \times n$ division. Here, m and n denote the number of divisions in the longitudinal (x-) and transverse (y-) directions, respectively. The size of an undivided single balloon is 8 mm × 1 mm with a thickness of 65 μm, and the total area of the balloon is fixed for each division. As shown in Fig. 5a, which corresponds to 4 × 1 division, downward motions are obtained in all cases examined. As in the single-balloon structure, the PBA bending is caused by the difference of the stress distribution of each inflated membrane. As shown in Fig. 5b, at constant applied pressure, laterally-divided structures give negative effect on the deflection, while longitudinally-divided structures provide larger bending with increasing the number of divisions. It is considered that this tendency is obtained by the increase of the summation of bending moment with increasing the number of serially-connected balloons in the longitudinal direction, which would contribute to the larger deflection in a cooperative way.

Experimental evaluation

Figure 6 shows the bending motion of the present PBA with longitudinally-divided structure with (*m, n*) = (4, 1). In the present experiment, the size of the total balloon is 4 mm × 1 mm with the thickness kept the same as in the simulation. A fabricated device is shown in Fig. 6a. As simulated in Fig. 5a, a downward motion with effective cooperation of longitudinally-divided balloons is actually obtained as shown in Fig. 6b.

It is noted that the pressure response shown in Fig. 5b cannot be extrapolated in the large bending region at the larger applied pressure. The bending process is affected by the balloon division (not shown here). The required pressure for large bending (bending angle is 90 degree in Fig. 6b) is slightly increased. The bending characteristics including the response to the applied pressure are found to be significantly different from the single-balloon structure, and further characterization would be the focus of the future study.

Figure 7 shows the experimental results of the size of the inflated balloons, corresponding to the maximum deformation of the upper PDMS membrane. The bending angle of 90 degree is obtained at the applied pressure of around 90 kPa and 100 kPa for the single-balloon (1 × 1) and the divided-balloon (4 × 1) devices, respectively. With the divided-balloon structure, the size can be reduced by more than 40% according to the present results circled in Fig. 7. Thus, it can be expected that the proposed design strategy with longitudinally-divided balloon structure would be effective for the further miniaturization of PBA devices.

5. CONCLUSION

A design concept with longitudinally-divided balloon structure in pneumatic balloon actuators (PBAs) is proposed in order to realize further miniaturized PBA devices with optimized structure. We have performed FEM-based simulation and demonstrated its applicability to compute and characterize the bending motion of PBAs fabricated from PDMS (polydimethylsiloxane) material. In the present study, it is shown through the simulation that the bending characteristics can be significantly altered dependent on the number of balloon divisions. Moreover, it is experimentally indicated that, with the present design, the magnitude of the balloon inflation can be reduced so as to achieve a desired bending motion in more compact space than required with a single-balloon structure of the equivalent size of the balloon.

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