Influences of Structural Parameters and Materials on the Kinetic Characteristics of Pneumatic Networks Actuator

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Abstract: As one of the most popular actuators, design and manufacture the pneumatic networks bending actuator with good performance is the basis and key for the implement of the high-performance soft robots. However, at present, both the structural parameters and the materials were determined empirically, which would cause some inconvenient and confusion for the researchers and engineers. In this paper, the effects of both the geometrical parameters and the various material combinations on the performance of the pneumatic networks actuator were analyzed by the ABAQUS software or tested by the performance testing platform. Firstly, the ABAQUS software was adopted to analyze the influences of the structural parameters on the kinetic characteristics so as to obtain the optimal geometrical parameters. The pneumatic networks actuator with the optical geometrical parameters was then manufactured and its characteristic was tested on the performance testing platform. Finally, the influences of the different material combinations on the performances were analyzed. This work can provide some reference values for the geometrical parameters design and material selection of the pneumatic networks actuator.

Key words: Soft robots, Pneumatic networks actuator, Structural Parameters, Material Combinations

1 Introduction

Soft robots exhibit continuum body motion, large-scale deformation, and relatively high compliance compared to traditional rigid-bodied robots [1]. Such characteristics

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make this type of robots owning the abilities to mitigate uncertainty with passive compliance, perform highly dexterous tasks, and exhibit resiliency [2, 3]. And it is alternative to replace traditional hard rigid robots in biomedical applications where hard robots are unsuitable [4-10]. Soft robots involve simple design and control to generate desired movement and actuation, compared to hard robots that require complex and multicomponent mechanical structure. Research has showed that complex motion can be integrated into a simple and soft robot, to achieve actuation ranges from single degree-of-freedom motion to robot with multiple modes of gait.

One of the branches of soft robots is soft actuator, which is particularly preferable in exoskeleton application where high comfortability and safety level are required. The low inherent stiffness of soft actuator also makes it suitable for biomedical applications involving physical interaction with body parts, where the impedance is required to be sufficiently low and does not interfere with natural movement of the joints. Combined with appropriate design considerations such as desired range of motion, force and interfacing methods, soft actuator is able to fulfill specific tasks and applications that require compliant actuation.

As the actuating element of the soft robotics, design and manufacture the soft actuators with high compliance and reliability is the basis and key for the implement of the high-performance soft robots. At present, the normal drive methods of the soft actuators include pneumatic artificial muscles (PAM), pneumatic networks, shape memory alloy actuator (SMA), electro active polymer (EAP), cable actuators, fluidic elastomeric actuators (FEA) and so on [11-15]. Among these drive methods, the pneumatic networks actuators attract the most attentions because of their advantages of quick drive, easy control and measurement, light weight and pollution free, and are now widely investigated to apply in medical rehabilitation machineries for finger recovery, knee recovery, ankle rehabilitation, neck rehabilitation and so on[16-18]. However, most of the researches merely focus on the feasibility of the applications using the pneumatic networks, and both the material and structural parameters are normally selected empirically. For many applications, this empirical method will bring some inconveniences and confusion for the engineers and researchers. Therefore, build the model of the pneumatic networks actuator and investigate the influences of the structure or material parameters on the characteristics of the pneumatic networks actuator will surely provide some valuable references for the design of the pneumatic networks.

In this paper, the ABAQUS was firstly used to analyze the influences of the structural parameters on the kinetic characteristics of the pneumatic networks and obtain the optimal geometrical parameters, then the pneumatic networks with the optimal geometrical parameters were manufactured. Finally, a customized measurement platform was built up to test the kinetic characteristic of pneumatic networks manufactured with different material combinations in the extensible layer and the constraint layer. Both the agreement between the predicted results and the tested results and the influences of various material combinations on the kinetic characteristics were analyzed.

2 Simulation of pneumatic networks actuator by ABAQUS

2.1 Geometrical parameters of the pneumatic networks actuator

Fig. 1 showed the structural schematic of the pneumatic networks actuator. The pneumatic networks actuator mainly consisted of two parts, i.e. the extensible layer and the constraint layer. The extensible layer was constructed by several uniform pleats which were separated by even gaps. The constraint layer was constructed by three layers. From top to bottom, the layers were, in order, elastic layer whose material was the same with the extensible layer, the paper layer and another elastic layer whose material was a little stiffer than the extensible layer. In the driving process, when the air was pushed into the air chambers, the extensible layer would produce a large deformation while the constraint layer would produce only a little deformation because of the inextensibility of the paper layer. The difference on the deformation between the extensible layer and the bottom constraint layer then lead the actuator bend.

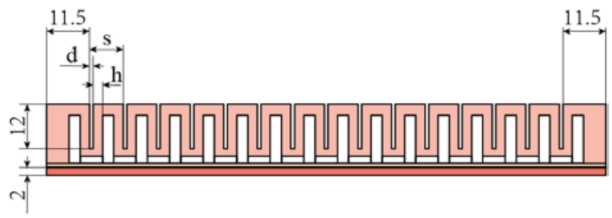

Fig.1. The structural schematic of the pneumatic networks actuator

In most applications, a quick and large bend was normally expected. As for a specific pneumatic networks, a bigger bending angle under a certain pressure indicates a easier bending characteristic, so pursing the biggest bending angle under a certain pressure should be the optimized aim for the geometrical and material parameters. Among the geometrical parameters of the pneumatic networks, the whole height and length of the actuator are normally determinated by the applied objects， the width of the internal channels should be as small as possible and was normally determined by the manufacture difficulty. In this paper, the internal channels width was set to 3mm, and the influences of both the pleat inside wall thickness and the gap

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between two adjacent pleats on the kinetic characteristic of the pneumatic networks actuator were analyzed detail.

2.2 The analysis method using ABAQUS

The flexible characteristic makes the pneumatic networks easy to deform largely while it also leads the motion and stress analysis very complex. In this paper, the ABAQUS software suite was used to analysis the theoretical characteristics of the pneumatic networks bending actuator. The main steps of the FEM analysis are as following:(1) Import parts and assign material properties to the parts; (2) Assemble parts and create a surface on inner cavity faces;(3) Apply pressure on inner cavity and set boundary conditions, then add contact interaction;(4) Create mesh and run job. By the FEM analysis, we can model the behaviors of the actuator at different pressures and also obtain the stress distribution at each pressure.

Fig. 2 shows the behaviors of 615-660 actuator at different pressures whose material above the paper layer is 615 and the material below the paper layer is 660. Each sub-graph demonstrates both the bending degree and the stress distribution of the actuator under a certain input pressure. Comparing the sub-graphs, it can be found that both the bending degree and the stress increase with the input pressures. For one single sub-graph, the stress on the constraint layer and the wall of the inner cavity are much bigger than the one on the outer layer and the end of the actuator. This is because that the outer layer and the end of the actuator have thicker materials.

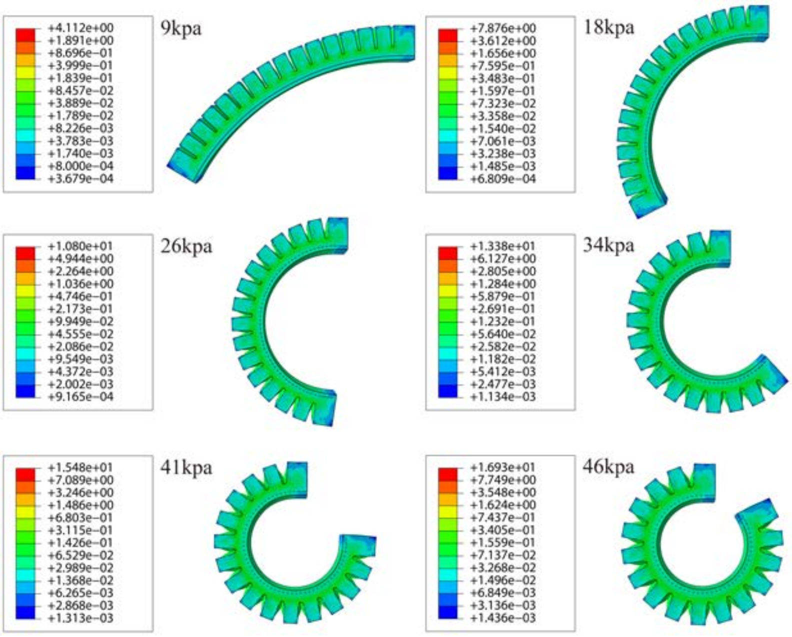


Fig. 2. The bending characteristics and stress distribution clouds at different input pressure for 615-660 actuator

Furthermore, the Radius of Curvature R and Max Stress S_{max} were extracted to indicate the states of the actuator at a special input pressure. The Radius of Curvature was defined as:

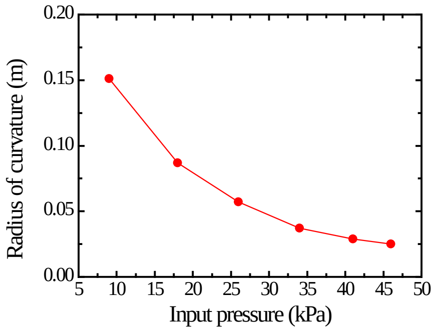
$$R = \frac{1}{k} \tag{1}$$

Where k is the curvature and can be expressed as:

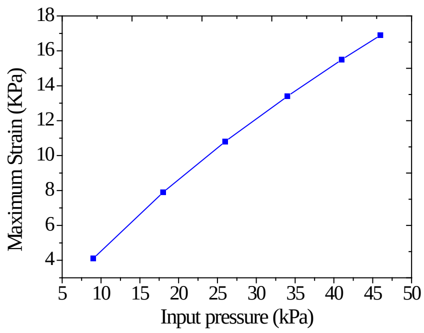
$$k = \frac{\Delta\varphi}{s} \tag{2}$$

Where $\Delta\varphi$ and s are the radian and the length of the arc of the bending actuator.

In this paper, the s was equal to the length of the constraint layer and was identical to 0.15m. The max stress of the actuator was equal to the maximum number of the color scale of each sub-graph. Fig.3 showed the theoretical radius of curvature and maximum stress of 615-660 actuator against the input pressure. From Fig.3.(a), it can be seen that the radius of curvature of the actuator decreased as the increase of the input pressure while the slope ratio of the curve became smaller gradually which indicates that it became more and more difficult to bend during the one bending process. From Fig. 3.(b), it can be seen that the maximum stress of the actuator nearly has a linear relationship with the input pressure. This characteristic would be very useful for the actuator design so that it can meet the ultimate stress requirement.



(a) the raduis of the curvature



(b) the maximum stress

Fig.3. The theoretical radius of curvature and maximum stress for 615-660 actuator.

2.3 The effects of structural parameters

In according to the previous discussion, the effects of the pleat inside wall thickness and the gap distance between the two adjacent pleats were discussed in this part so as to obtain the optimal geometrical parameters. Fig.4 showed the behaviors of 615-660 actuator under a pressure of 41kPa when the pleat inside wall thicknesses were 2.0mm, 2.5mm, 3.0mm respectively. From Fig.4, it can be seen that both the bending degree and the maximum stress increased as the descent of the pleat inside wall thickness which agreed with the expectations.

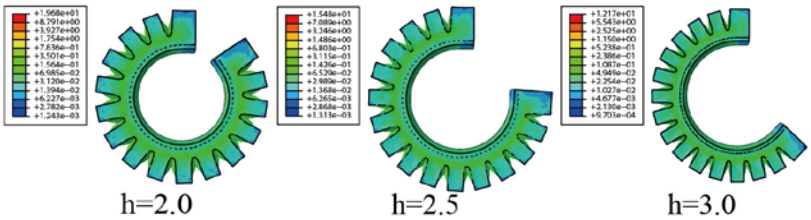


Fig.4. The effect of the different pleat inside wall thicknesses

Fig.5 showed the bending behaviors of 615-660 actuator under a pressure of 46kPa when the gaps were 0.5mm,1.0mm,1.5mm respectively. From Fig.5, it can be seen that both the bending degree and the maximum stress increased as the descent of the gap. This is because that a bigger gap would increase the interaction difficulty of the adjacent pleats and then decrease the bending degree.

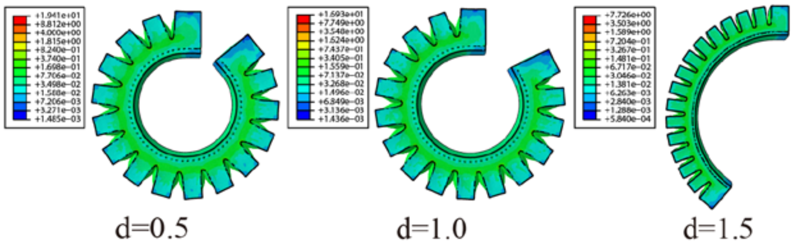


Fig.5. The effect of the different gaps

In conclusion, the smaller the pleat inside wall thickness and the gap, the easier the actuator could bend, and the bigger the maximum stress. While the small gap and thin pleat inside wall thickness would increase the manufacture difficulty greatly. From Fig.4 and Fig.5 we can found that the bending degree of the actuator only descreased a litte when the pleat inside wall thickness increased from 2mm to 2.5mm, and the similar case happened when the gap increased from 0.5mm to 1.0mm. Taking into both the manufacture difficulty and the bending characteristic of the actuator, the actuator with a pleat inside wall thickness of 2.5mm and a gap of 1mm was reviewed as the optimal one. Then the actuator with the optimal structural parameters was manufactured and the experimental bending characteristics were tested.

3 Fabrication of pneumatic networks bending actuator

Cho et al. review several manufacturing processes for soft biomimetic robots. The vast majority of soft elastomer robots rely on the processes of soft lithography and/or shape deposition manufacturing. Specifically, for soft elastomeric robots this fabrication process generally consists of two steps: (1) The beewax core which was the negative of the desired channel structure was firstly obtained via beewax core mold and the pedestal, as shown in Fig.6. (2) The extensible layer was casted by the combination of the out mold and the beewax core, and the constraint layer was casted by the mid mold, the paper and the top mold, as shown in Fig.7. In step (2), the paper located between the mid mold and top mold and was used to produce the inextensibility property required for actuation.

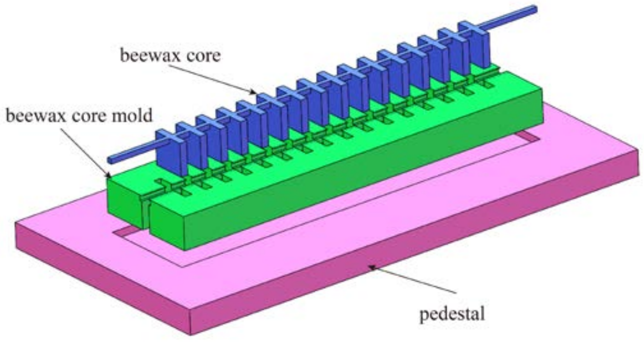


Fig. 6. Fabrication process for the beewax core.

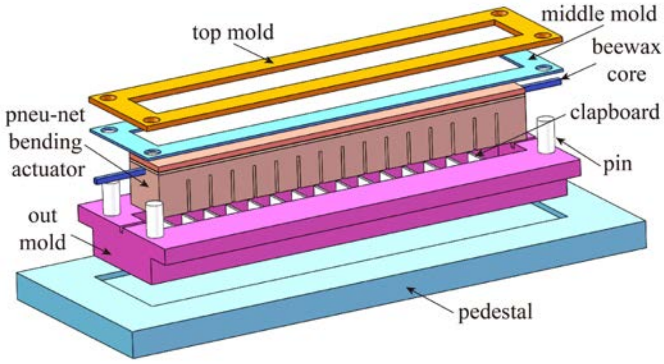


Fig. 7. Fabrication process for the pneumatic networks bending actuator

4 Experimental researches on the kinetic characteristic

4.1 Apparatus

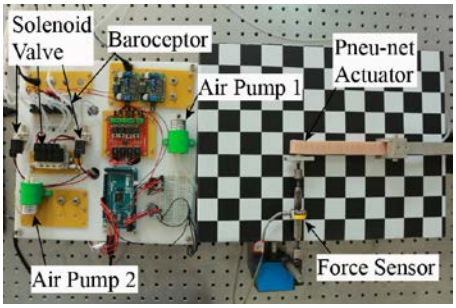


Fig. 8. Setup of Characterization Platform

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A customized platform for characterizing the soft bending actuator was built up, as shown in Fig. 8. The platform consisted mainly of a force sensor, a baroceptor, a NI signal acquisition system, two air pumps, a pneumatic networks actuator, two solenoid valves, a high definition camera, the clamps and the background plate. When air pump 1 works, the air passes through, in order, the solenoid valve, the baroceptor and finally arrives at the pneumatic networks actuator to drive the actuator bending forward, while when the air pump 2 works, a negative pressure is produced and finally drive the actuator bending backward. The force sensor was placed perpendicularly at the far end of the pneumatic networks actuator which is used to obtain the distal output force when the pneumatic networks actuator was pressured. The high definition camera was used to capture the bend status under different input pressures.

4.2 Experimental characteristics of the actuator

Fig.9 showed the pictures of the staged responses for the 615-660 bending actuator upon pressurization. Qualitatively, the bending actuator has a bigger deformation under a bigger input pressure which agreed with the theoretical expectations.

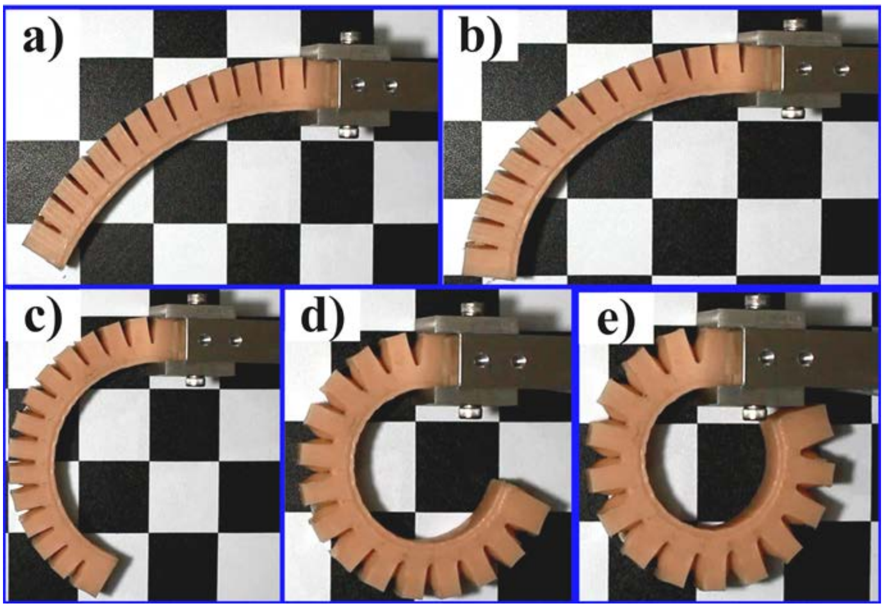

Fig.9. The pictures of the staged responses of the bending actuator upon pressurization

Quantitatively, the measured radius of curvature was compared with the theoretical ones. The radius of curvature of the bending actuator was analyzed using Image J image analysis software. Fig.10 shows the comparison between the measured radius of curvature and the theoretical ones under different input pressures. From Fig.10, it can be seen that the measured radius of curvature of the 615-660 bending actuator agreed well with the theoretical ones. From Fig.10, it can also be found that the measured results are a little bigger than the theoretical ones when the input pressure is below about 35KPa, this is because that the actuator was placed on the table and there would be some friction when the actuator bending. When the input pressure was small, the friction would not be neglected and would hinder the bending action while when analysis by the FEM, the friction was ignored so as to simplify.

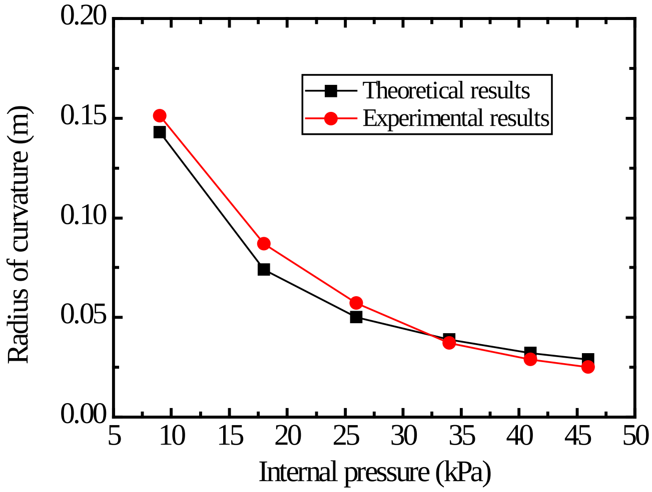

Fig.10. The comparison between the measured radius of curvature and the theoretical ones under different input pressures for 615-660 actuator

4.3 Effects of various material combinations

In the previous part of this paper, the effects of the geometrical parameters on the bending characteristics were analyzed via ABAQUS and the optimal geometrical parameters were obtained. Then the actuator with the optimal geometrical parameters was manufactured and also a customized platform was built up to characteristic this actuator. The comparison demonstrated that the predicted results agreed well with the tested ones. However, it should be noted that, except the geometrical parameters, the materials would also influence the characteristics of the bending actuator. As mentioned before, the pneumatic networks bending actuators were normally manufactured by the matching of two different soft materials, the extensible layer and the layer up the paper layer in the constraint layer were manufactured by a relatively softer material while the bottom layer of the constraint layer was manufactured by a relatively stiffer material. So as to investigate the influences of materials on the bending characteristics of the pneumatic networks actuator, a series of bending actuators were manufactured with various material combinations and then the bending characteristics were measured via the customized platform.

Fig.11 showed the bending curvature radius variation against the input pressures for the actuators with different material combinations. From Fig.11, it can be seen that the

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curvature radius of all the actuators decreased with the increase of the input pressure which agreed with the theory rule. Among the three combinations, comparing the characteristics of the 615-660 actuator and the 630-660 actuator, it can been found that the input pressure required for the 615-660 actuator to achieve the biggest bending status was much smaller than that required for the 630-660 actuator. This indicated that a softer extensible layer would make the bending much easier. Similarly, it can be found that a softer constraint layer can also make the bending easier by comparing the characteristics of 630-650 actuator and 630-660 actuator. However, the influence of the extensible layer material was much bigger than that of the constraint layer material. Therefore, in applications, the hardness of the extensible layer material should be paid most attention to so as to obtain a better bending characteristic.

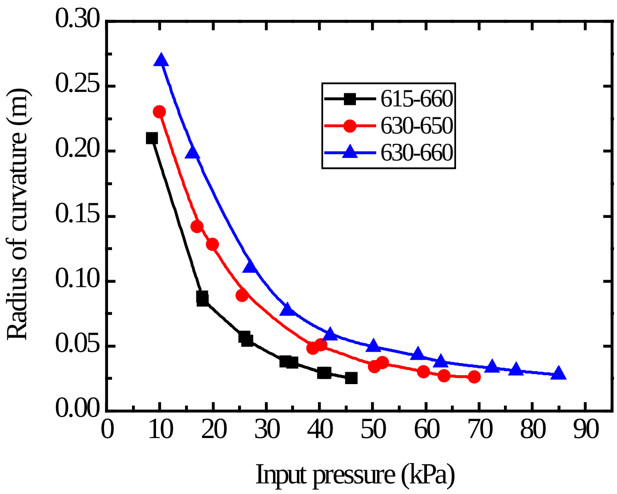

Fig. 11. The comparision of the bending actuators' curvature radius versus input pressures

Fig. 12 demonstrated the output force of the free end variation against the input pressure. From Fig.12, it can be seen that the output force of the actuator free end increased with the increase of the input pressure which agreed with the expectations. By comparing the output force of the 615-660 actuator and the 630-660 actuator under the same input pressure, it can be found that a softer extensible layer would lead a bigger output force. And it also can be found that, although much smaller than the influence of the extensible layer material, a stiffer constraint layer would help to increase the output fore of the actuator free end. Therefore, in practice, a softer material should be selected to manufacture the extensible layer while a stiffer material should be used to manufacture the constraint layer so as to obtain a bigger output force.

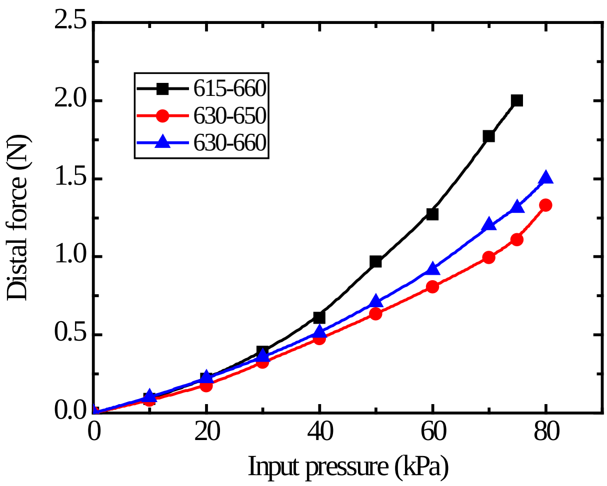

Fig. 12. Distal force Output – Input pressure relationship of bending actuators with different material combinations

5 Conclusions

As one of the most popular actuators, design and manufacture the pneumatic networks bending actuator with good performance is the basis and key for the implement of the high-performance soft robots. However, at present, both the structural parameters and the materials were determined empirically, which would cause some inconvenient and confusion for the researchers and engineers. In this paper, the effects of the geometrical parameters on the bending characteristic were investigated via ABAQUS and the effects of the various material combinations on the kinetic characteristics were tested by experiment. Some major conclusions can be obtained as following:

1. Among the geometrical parameters, the thinner the pleat inside wall thickness, the easier the actuator can bend, and a smaller gap also can make the bending easier. However, the optimal geometrical parameters should be determined by considering both the bending characteristics and the manufacture difficulty.

2. The pneumatic networks bending actuators manufactured with different material combinations have different bending characteristics. The material of the extensible layer has a great influence on the bending characteristics. The softer the extensible layer, the easier the actuator can bend. The constraint layer has a similar but much smaller influence on the bending characteristics of the actuator.

3. The actuator manufactured with a softer extensible layer can produce a larger free end output force. However, a stiffer constraint layer would help to increase slightly the free end output force.

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