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PNEUMATICALLY DRIVEN COMPLIANT STRUCTURES BASED ON THE MULTI-ARC PRINCIPLE FOR THE USE IN ADAPTIVE SUPPORT DEVICES

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ABSTRACT

Adaptive support devices for bedded patients must allow a special relief for pressure reduction of compressed skin areas but also a suitable stimulation. Therefore, pneumatically driven compliant mechanisms offer great potential to influence the deformation behavior by geometrical design and/or material choice. This contribution deals with the FEM-based and experimental investigation and development of a compliant fluid actuator realizing a large stroke. Therefore, a multi-arched structure consisting of silicone is used. Moreover, the advantages of an additional position measurement based on electrically conductive foams, a mechanical adaptive patient contact and an adjustable stiffness of the flexible mechatronic system are described.

Index Terms - Fluid driven actuators, compliant mechanisms, silicone structures, multi-arc principle, support devices

1. INTRODUCTION

In addition to the movement with the help of persons or by using automatic multifunctional hospital beds [1], medical support devices of different complexity are used for the prevention and treatment of bedsores. Soft bedding, alternating pressure bedding and micro-stimulation are possible support methods. Crucial for the function of these support systems for pressure ulcer prevention is the avoidance of constant long-time compression of the skin and a dedicated stimulation of susceptible skin areas. Furthermore, reducing of shear forces, which are a crucial factor to intrigue the development of bedsores as well, is an important issue [2]. The used support system should realize both, an adequate stiffness (for supporting the patient) but also a specific compliance (for distributing and reducing the pressure to the skin). This can be achieved by adjustable stiffness using integrated sensor and actuator technologies, as shown in Figure 1.

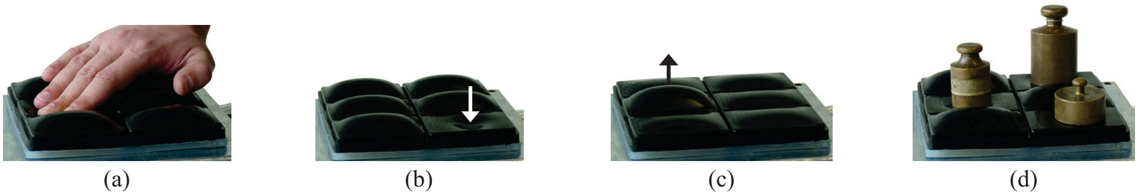

(a) (b) (c) (d)

Figure 1: *Active prevention treatments of an existing support device demonstrator [3] - (a) pressure detection, (b) dedicated soft bedding, (c) dedicated stimulation and (d) detection of pressure distribution*

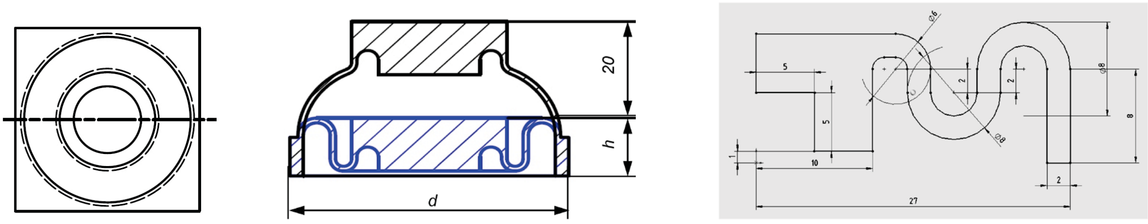
Due to their advantages, such as the ability to generate novel types of motion, the monolithic and simple construction and the intrinsic flexibility, compliant mechanisms are well-suited for medical applications (e.g. [4], [5]). In addition, the deformation behavior of particular fluid-driven compliant structures can be selectively influenced by geometric design and material properties. In case of realizing a translational motion for relieving and stimulating, compliant structures with statically stable and monotonous behavior are suitable [6].

Starting from an existing support device demonstrator (see Figure 1), which allows only a small range of motion, the realization of a new demonstrator with a large stroke is subject of this contribution.

2. MATERIAL AND METHOD

Based on an existing demonstration model made of silicone, in this work the design, the simulative adjustment as well as the development and testing of an improved adaptive support device is described. The goal of development is to design the used pressure-controlled compliant actuator elements for realizing a larger motion range of more than 20 mm regarding an initial low height of the complete support system.

Therefore the multi-arc principle is used, which is introduced by [7] and is inspired by snail tentacles. The rotationally symmetric structure with several arcs enables a translational motion caused by pressure de- or increase which can be used as a relieving and stimulating displacement, see Figure 2. Because of the deploy process high strains can be avoided, thus reducing fatigue.



(a) (b) (c)

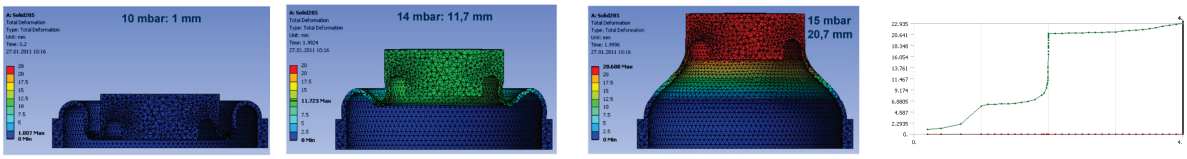
Figure 2: *Compliant actuator with a high stroke - (a) top view of the structure, (b) sectional view and (c) model with parameters*

The concept of the new two-part demonstrator to be developed is designed with nine actuator elements. The geometric shape of one of these rotational symmetric multi-arced actuator elements is designed and improved using FEM simulations regarding continuous and monotonic motion behavior. For the simulations, the upper actuator layer (stroke layer) was considered which is fixed to the frame at the bottom. A pressure is applied as boundary condition on the entire structure inside. All analyzed designs were of an overall diameter $d = 60$ mm and an initial height $h = 20$ mm. The required hyper-elastic material behavior of the used silicone material (Elastosil M4644, Co. Wacker), which has a Shore hardness of 40, is described by the phenomenological non-linear material model Ogden second order. After determining the test data with a uniaxial tension machine the characterizing material constants were fitted. The resulting and used constants are $\mu_1 = 0.0018$ MPa, $a_1 = 11.92$, $\mu_2 = 0.8295$ MPa, $a_2 = 0.978$ and $d_1 = d_2 = 0$ MPa^{-1}. The demonstration model has two parts, consisting of an upper and a lower silicone layer which are manufactured using a casting process of two components in combination with milled negative molds. Within the actuator elements electrically conductive foams are integrated to infer the current displacement position. To verify the simulation results the demonstrator is tested with an experimental setup.

3. RESULTS

3.1. Design and adjustment of a compliant multi-arced rotational symmetric actuator

The initial design of the compliant actuator leads to an unstable behavior with snap-trough effect under increasing internal pressure, see Figure 3.



(a) (b)

Figure 3: *Deformation behavior of the initial design - (a) FEM-results under increasing inner pressure and (b) pressure-displacement curve with snap-through characteristic*

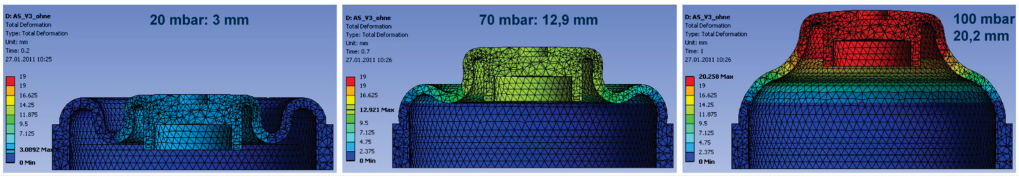


Figure 4: *Deformation behavior of the final design*

By the FEM-based adjustment of the geometry parameters, i.a. thickness and circular arcs respectively straight connecting segments, resulting a static monotonic deformation behavior. The simulation results of the final design are shown in Figure 4. Without patient load an internal pressure of 100 mbar results a displacement of the structure center of 20 mm for the designed geometry. The entire support system is designed, consisting of nine actuators with the overall dimensions of 165 mm x 165 mm x 20 mm.

3.2. Development and manufacturing of the separate silicone layers

For manufacturing the entire support demonstrator, the two molding techniques hot stamping (Figure 5) and casting were tested, while the transfer process of two components enables the best silicone layer quality. The parts of the molding tools were built by milling.

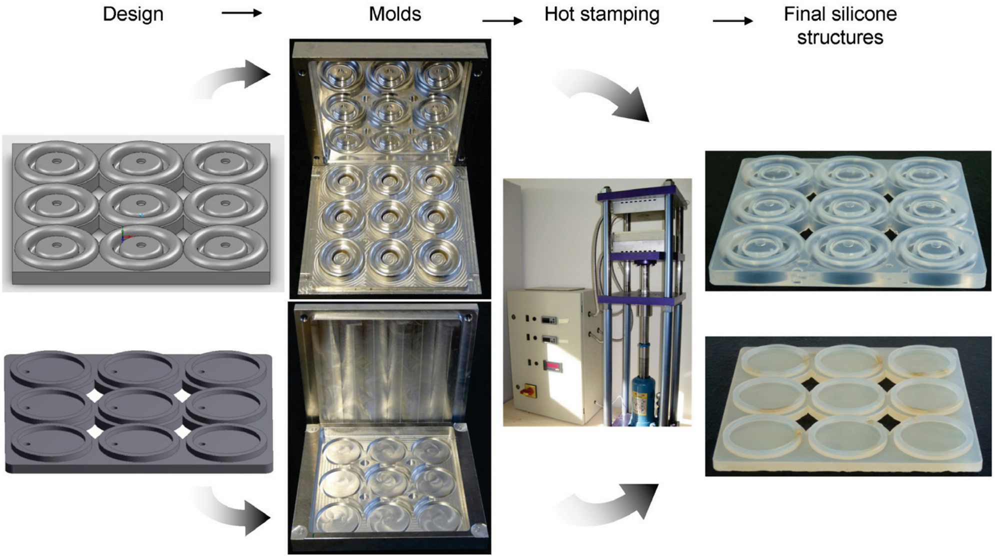
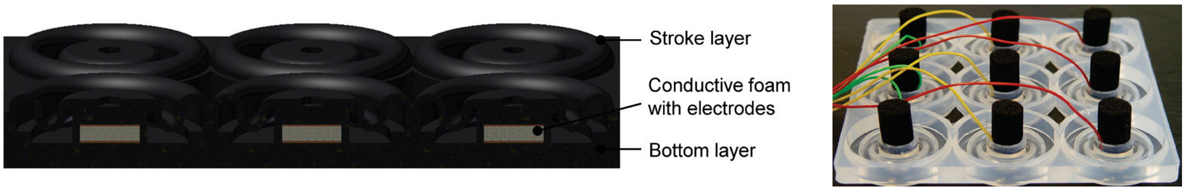


Figure 5: *Manufacturing of the silicone layers exemplified for the hot stamping molding technique*

3.3. Assembly of the demonstrator and integration of sensor technology

The manufactured silicone layers are bonded in the entire system. The stroke layer is designed, that the sensor technology can be integrated in the deformation-resistant center. Thereby the sensor material is moved with the center during the motion.

As sensor material electrically conductive foam with 25 mm thickness is used (Figure 6). Due to a change in resistance it can be used as an analogue stroke sensor in dependence of the elongation respectively compression. The used foam cylinders are positively and cohesively assembled in a pre-compressed state and contacted at the top and bottom sides with electrodes.



(a) (b)

Figure 6: *Assembly of the support system demonstrator with integrated sensor technology - (a) CAD-Modell and (b) manufactured stroke layer with the conductive foam blocks*

3.4. Test of the adaptive support demonstrator

Using a laser measuring system the comparison of simulated and measured results of the built up demonstrator shows a very good qualitative and a good quantitative correlation of the pressure (p)-displacement (v) curves as shown in figure 7.

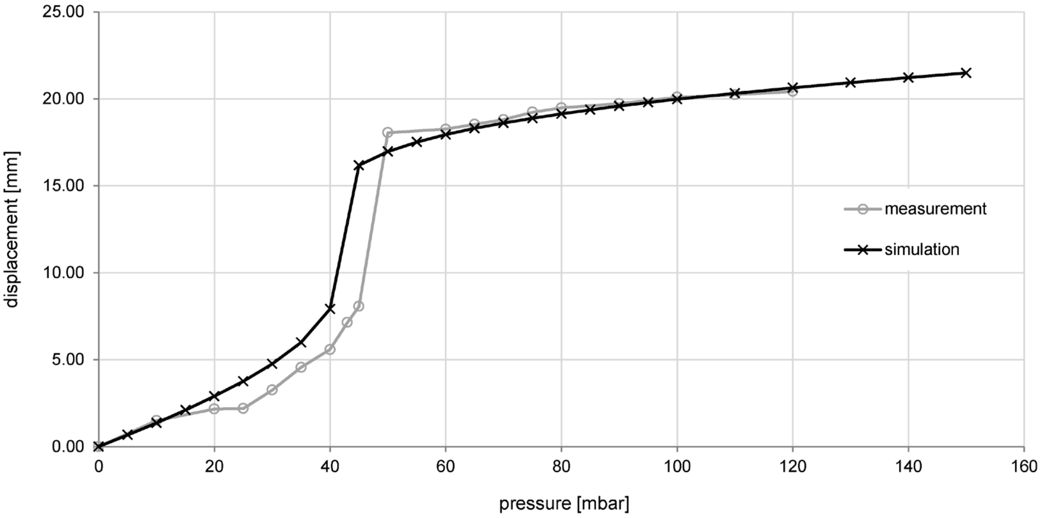


Figure 7: *Simulated and measured pressure-displacement-curves of one compliant actuator*

The comparison of the static deformation behavior of the FEM simulations with the real structure is shown for three pressure-displacement-states in Figure 8. It is obvious that this design results a slight snap-through behavior. However, this is only relevant for the case without patient load. In practical use the patient weight causes a load which stabilizes the extension motion.

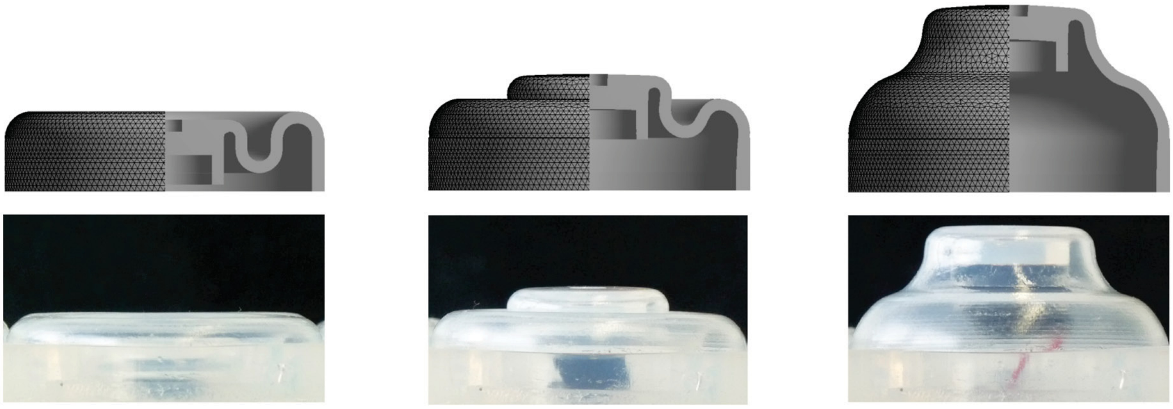

(a) (b) (c)

Figure 8: *Comparison of FEM-Simulations and the real structure under increasing pressure - (a) retracted state for p = 0 mbar, (b) intermediate state for p = 20 mbar and (c) extended state for p = 100 mbar*

Furthermore, the change of resistance of the conductive foam blocks was investigated in dependence of the stroke position, see Figure 9. The resulting curve shows a slightly non-linear correlation. This behavior can be used in principle for the detection of the current stroke position on the basis of a further calibration.

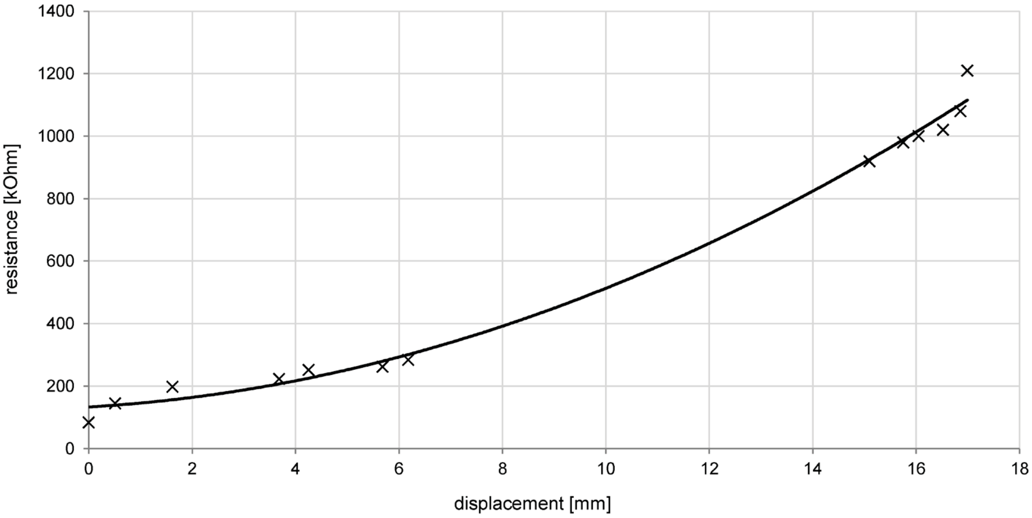


Figure 9: *Change of resistance of one conductive foam block as a function of stroke position*

4. DISCUSSION AND CONCLUSION

In this contribution, the design, the simulative adjustment as well as the development and testing of an adaptive support device for the prevention of bedsores is described.

The results show that the simulative design of pneumatically driven compliant structures consisting of silicone is possible and can be used effectively in goal-oriented design process. Furthermore the height of the support system can also be effectively reduced through the unfolding process of the used multi-arced structure.

The built prototype of the support device (Figure 10) allows an adaptive stiffness by adjusting the internal pressure. In addition, due to a lateral flexibility of each individual compliant actuator an adaptive deformation to the geometry of the patient is inherent in the structure.

Because of the used sensor material the detection of the current stroke position is possible due to the change in length which is a function of to the change in resistance. Thus, the integration of conductive foams allows a second measured value in addition to the value of the internal pressure in the air chamber. For the use in patient support devices a further investigation of some effects is necessary to calibrate the system. In particular, the assembling of the conductive foam blocks with the electrodes and the generation of reproducible measurement results are ongoing tasks of research. Furthermore, when measuring a short time delay of the resistance signal can be observed, which is less relevant for the mentioned application.

The further testing as well as simplification of the sensor technology, the possibility to determine the load direction and the implementation of reaction strategies are goals of further activities.

Figure 10: *Developed demonstrator of the support system*

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