TECHNICAL UNIVERSITY OF CLUJ-NAPOCA

ACTA TECHNICA NAPOCENSIS

Series: Applied Mathematics, Mechanics, and Engineering
Vol. 67, Issue II, June, 2024

EXPERIMENTAL RESEARCH OF A MULTI-SEGMENT SOFT ACTUATOR

Dan-Mihai RUSU, Silviu-Dan MÂNDRU

Abstract: *In the present work, we have experimentally addressed the influence of the inner cavity wall thickness on the characteristics of motion's amplitude and force developed by pneumatically actuated multi-segment soft actuators. These are used for various soft robotics applications, such as rehabilitation/assistance or prehension. This parameter was varied on a series of 4 multi-segment actuators starting from a wall thickness of 1 mm up to 2.5 mm. The multi-segment soft actuators were manufactured based on a rigorous methodology through moulding technology using DragonSkin 20 bicomponent silicone rubber with shore hardness of 20 A in 3D printed moulds - CraftBot Plus from polylactic acid (PLA) material. The output force developed by each actuator variant as a function of the applied input pressure was monitored using Chatillon DFE 2.5kN dynamometer. Also, to determine the kinematic behaviour of the actuator, the actuators were pressurized at a pressure of 50 kPa and the amplitude of motion of the segments was experimentally monitored.*
Key words: *Soft robots, pneumatic actuator, multisegment, range of motion, force, rehabilitation.*

1. INTRODUCTION

Soft actuators, as part of the field of soft robotics, are an essential component for the development of applications in this field. The field of soft robotics, as a relatively new subfield of robotics, has experienced significant scientific development due to the advances it has over robots made of rigid materials [1]. Biomimicry, biocompatibility, high flexibility of movement, simplicity of construction, and relatively unpretentious manufacturing methods make soft robots provide safe human-robot interaction as well as high locomotion capability with inspiration from the living world. These characteristics of soft robots make them widely used in medical and life-inspired locomotion applications [2].

Based on the above considerations, a large part of the applications in the medical field addresses wearable devices intended for rehabilitation and assistance, especially of the upper limbs. This happens due to the lower forces/moments required in actuation. Within this category, many papers address the realisation of wearable devices intended for the rehabilitation/assistance of human hands. In the literature, there is a wide variety of such wearable systems based on different types of soft actuators. The most commonly used are pneumatic actuators, shape memory alloys, and dielectric elastomers [3]. However, out of these three categories of soft actuators, pneumatic actuators have received additional attention and are used extensively for hand phalanx actuation. A variety of soft pneumatic actuator configurations have been proposed in the literature and a few of these actuator types are presented below. Panagiotis Polygerinos et al. used pneumatically actuated inner PneuNets channel actuators with 1 mm wall thickness for their hand rehabilitation glove. Three different lengths of actuators were used and the thumb was omitted. At 43 kPa pressurization, the maximum force of 1.21 N was obtained [4]. A variant using the same type of actuator but controlled using EMG signals is found in [5]. Mahmoud H. Mohamed et al. used fiber-reinforced soft actuators to assist the patient in daily activities. They analyzed the bending angle using bending sensors integrated into the 5 actuators. At a pressure of 80 kPa, a range of motion of 150 degrees was developed [6]. Heung KHL. et al. proposed a glove for daily activities that integrates bidirectional

Received: 30.04.24; **Similaritie**s: 29.05.24: **Reviewed**: 30.05./10.06.24: **Accepted**:26.06.24.

pneumatic soft actuators with bending and extension capability. Capabilities related to the control of object grip force as a function of inlet pressure and bending angle have been analyzed [7].

All of the wearable device designs shown above use soft actuators made of elastomeric materials that have a uniform and continuous bend along their length. This can cause discomfort and ultimately unworn wearables due to the relative movements that occur between the actuator and the fingers due to the different kinematics of the actuator with the fingers. The fingers consist of three joints (fingers 2-5) and two (finger 1) respectively, and these joints are connected by rigid bony segments, which is why the kinematics of the fingers differ from that of the actuator. The solution to provide high comfort through kinematics similar to that of human fingers is to design multi-segment soft actuators. In these actuators, the bending moment is applied to the joint area only, so that the constraining forces in the segments are eliminated and the kinematics and range of motion are like that of fingers. A number of papers have been identified in the literature that address the use of multi-segment soft actuators. Panagiotis Polygerinos et al. addressed the development of a wearable device for the rehabilitation of hands having a finger-like range of motion using fiber-reinforced soft actuators. Using the configuration of motion-limiting fibers, finger-like trajectories were achieved [8]. Jiangbei Wang et al. developed a wearable device that is based on actuators with multisegment inner channels. Several different bending chambers were used to have a bending range as similar as possible to that of fingers [9]. Also, Keqin Sun et al. developed a soft prehensor based on multisegment soft actuators with fiber reinforcement on semi-rigid segments. In the paper, the influence of factors related to the number of chambers, bottom layer thickness, as well as segment length were analyzed [10].

All these articles deal with the design, modelling, and testing of multi-segment soft actuators in various applications, mainly considering the number of chambers per joint, the lengths of the semi-rigid segments, and the thickness of the bottom layer on the actuator kinematics. In this paper, the authors aim to identify the influence of the wall thickness of the inner bending chambers on the range of motion, as well as on the resulting force of multi-segment PneuNets soft actuators.

2. DESIGN OF THE PNEUNETS MULTI-SEGMENT ACTUATOR

The tests were performed on a multi-segment actuator with a total length of 135 mm, a proximal width of 20 mm, a distal width of 15 mm, and a total height of 14 mm. The geometry together with the structural elements of the multi-segment actuator are shown in Figure 1.

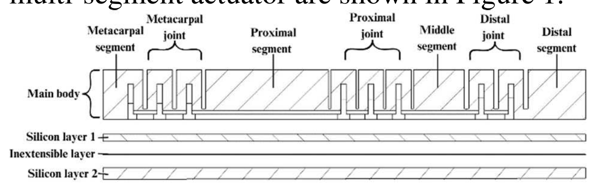

Fig. 1. Actuator structure in longitudinal section.

The actuator consists of three joints and 4 rigid segments. Also, its main component element is the main body which has provided the joints and rigid segments together with the channels and inner chambers. Silicone layers 1 and 2 are used to seal the base of the actuator and the inextensible layer is used to prevent axial deformation of the actuator. The inextensible layer is made of paper with a density of 80 g/m^2. It has been designed to have characteristics as similar as possible to human fingers, both in terms of structure, material, and range of motion. Its dimensions are selected based on average anthropometric values. From the point of view of the dimensional characteristics of the joint elements together with the internal cavities, a detail of the constructional parameters of the joint is shown in Figure 2.

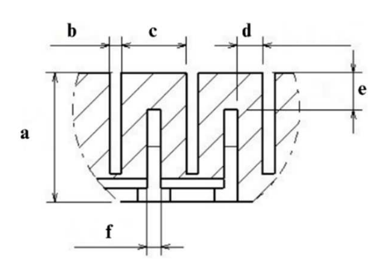

Fig. 2. Geometric design parameters of multi-segment pneumatic actuators.

At the joint, the bending moment is created by deforming the side walls of the inner cavities until they come into contact and angularly deform the entire structure in proportion to the value of the input pressure. Of the 6 geometrical parameters, the parameter that was varied in the present work was the parameter d - wall thickness. The wall thickness was varied, starting from thicknesses of 1, 1.5, 2, 2.5 mm, and for each thickness variation, the range of motion and force characteristics were analyzed.

3. DEVELOPMENT OF THE MULTI-SEGMENT ACTUATOR

In the field of soft robots, there are two main technologies for their production: 3D printing and casting. The two are often used together, with 3D printing being used to make moulds [1]. In this case, too, these two technologies were used together, with 3D printing being used for rapid prototyping of casting moulds.

The actuators were made of a two-component silicone rubber from the company SmoothOn, namely the DragonSkin 20 material variant with Shore A hardness of 20 A translucent color. The elongation at break of the material is 620% and the tensile strength is 3,972 N/mm^2 [11]. It is mixed in equal quantities and allowed to cure for 4 hours at room temperature, it is composed of a base and a catalyst. Each part of the silicone was weighed accurately with a precision scale and mixed at a time of about 3 min for homogenization.

Due to the mixing in the material, a series of air bubbles are produced, which once in the material can lead to errors in its behaviour or even premature degradation. In order to prevent this, a rigorous casting technology has been followed to ensure that the actuator has a homogeneous material structure. To remove air bubbles, a vacuum plant was used, in which the silicone mixture was left for about 2 minutes to remove all air bubbles and keep the material homogeneous.

The design of the 4 moulds (two for the main body; one for the inextensible layer 1 and one for the inextensible layer 2), was done in the three-dimensional modelling program Catia V5R20 and then made by 3D printing using CraftBot Plus from PLA (polylactic acid) material. For the main body, a number of 4 lower units (one for each dimension) and one upper unit, that was positioned over the lower one at the time of casting, were made. The moulded units are shown in Figure 3 below.

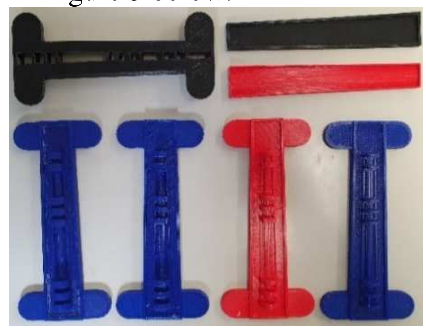

Fig. 3. Actuator casting moulds.

Once the silicone material was prepared and the mould assembled, the actual moulding of the material into the moulds was done. The whole moulding process is shown in Figure 4 below, which is based on the structure of the [12].

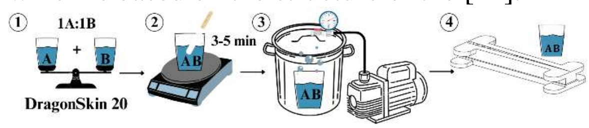

Fig. 4. Actuator casting steps.

After the actual casting in the moulds, the material was left to cure for about 4 hours to harden completely. After curing, the main body of the actuator was removed from the mould together with its first two layers. Once cured and removed from the die, the 4 die components were bonded together using the same silicone, with the inextensible paper layer sandwiched between the two layers. The final version of the 4 multi-segment actuators with different wall thickness - d is shown in Figure 5 below.

Fig. 5. Final version of the 4 actuators with different wall thicknesses.

4. EXPERIMENTAL TESTS ON RANGE OF MOTION AND OUTPUT FORCE

In terms of the range of motion and the force developed by the soft actuator, these are two fundamental characteristics in the development of applications in this field. One of the most widely used methods to determine these characteristics is by carrying out appropriate experimental methods that facilitate their determination. Analytical methods are also less used due to the non-linearity of the material and its hyperelasticity. Regarding the choice of wall thickness, the most commonly used thicknesses in different applications have been chosen from the literature.

4.1 Experimental tests on the range of motion of multisegment actuators

With the range of motion of the multi-segment actuator, we want to determine its behaviour at different actuating pressures at the three joints. An air compressor with a pressure regulator was used as equipment to pressurize the actuator and an ABPDANV150PGAA5 pressure sensor was used to monitor the pressurization levels [13]. This has a pressure range of 0 - 1000 kPa powered at 5 V DC and relates to an ATmega328 microcontroller. The actuator supply pressure was determined experimentally, it was initially set at 100 kPa, but due to the large deformations suffered by the actuators, especially those with wall thickness of 1 and 1.5 mm, their supply pressure was set at the value of 50 kPa under free conditions. Figure 6 shows the high deformations of the multi-segment actuator with a wall thickness of 1.5 mm at a pressure of 100 kPa.

Fig. 6. 1.5 mm wall thickness multi-segment actuator pressurized to 100 kPa.

In various applications, such as wearables or prehension devices, a range of motion of high amplitude joints is unusable. Determining the range of motion involved using a camera to capture the final geometry of the actuators at a pressure of 50 kPa. After capturing the geometry of each actuator, based on the photo captures, the semi-rigid segments and the three joints positioned in the centre of the joint were traced and positioned. This was done in an editing program. The range of motion for each actuator with different thicknesses is shown below.

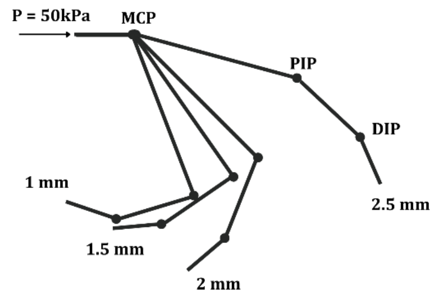

Fig. 7. Range of movement of 4 actuators 1, 1.5, 2, and 2.5 mm thick.

It can be seen from Figure 7, that there is a different range of motion of the 4 actuators, which is why the thickness of the walls influences quite a lot the range of motion of the multi-segment actuators. This is related to the higher elastic resistance that a thicker wall has, which is why more pressure is needed to deform the wall until two adjacent walls come into contact.

4.2 Experimental tests on the output force of multi-segment actuators

To determine the force characteristics of the 4 actuators, an experimental stand was used, which is shown schematically in Figure 8.

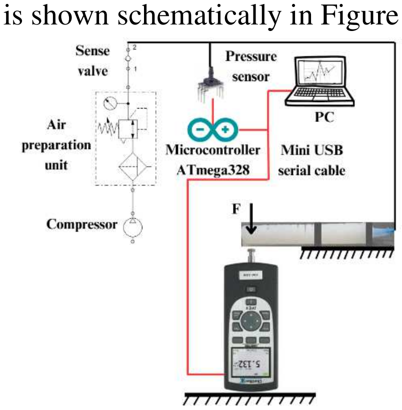

Fig. 8. Experimental stand on the determination of force-related characteristics.

A compressor with a pressure regulator was used in the stand to supply air to the actuators. The pressure was monitored using the pressure sensor, which transmitted data to the computer via the microcontroller. Force was captured using a Chatillon DFE 2.5 kN force gauge, with data from this being captured to the computer via a mini-USB cable. One segment of the actuator was positioned on a rigid support from the proximal end to the proximal joint (PIP), and the other segment was positioned at the center of the shaft axis of the dynamometer. The actuators were gradually pressurized from the pressure regulator to the pressure of interest, and the pressure as well as the force developed by them were monitored. The position of both the Chatillon dynamometer and the actuator are fixed with no relative movement between the two, and the actuator was positioned centrally on the circular measuring stand which is connected to the dynamometer shaft by a threaded assembly.

The test results for each actuator with different wall thicknesses are shown in Figure 9. All 4 actuators were pressurised to 50 kPa pressure. This pressure was chosen in order not to reach very high deformations or even destruction of actuators with wall thickness of 1 mm or 1.5 mm which cannot withstand such high pressures.

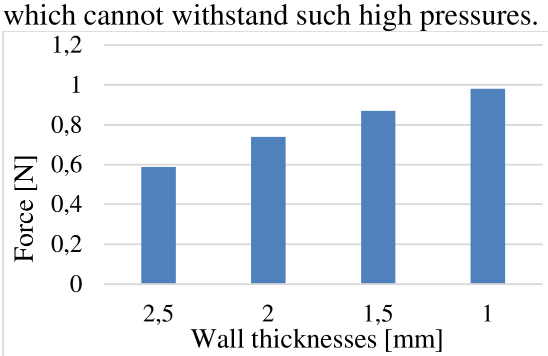

Fig. 9. Force values obtained for the 4 actuators.

The actuator with the highest force developed was the 1 mm wall thickness actuator, which developed a force of 0.98 N, followed by the 1.5 mm wall thickness actuator with a force of 0.87 N and the 2 mm wall thickness actuator with a force of 0.74 N. In the case of the 2.5 mm wall thickness actuator, the force developed was 0.59 N. An approximately linear dependence is observed therefore using the tools in excel the linear regression equation was determined:

$$F = 0.13x + 0.47 \quad (1)$$

In medical or prehension applications, choosing too small a thickness can lead to limitations in force capabilities. Also, an increase in wall thickness can lead to an increase in output force, but the range of input pressures also increases, ultimately leading to additional stress in the actuator.

7. CONCLUSION

In this article, two important characteristics of the PneuNets multi-segment actuators have been analysed: the range of motion and the force developed by them. The two characteristics were analysed using experimental methods, as they are essential characteristics for determining the behaviour of these actuators. Changing the parameters related to the wall thickness leads to a modification of the actuator behaviour through different ranges of motion and important variations related to the force at identical input pressures. The selection of these parameters will be made according to the specific application required.

8. REFERENCES

[1] Rusu, D.-M.; Mândru, S.-D.; Biriș, C.-M.; Petrașcu, O.-L.; Morariu, F.; Ianosi-Andreeva-Dimitrova, A. *Soft Robotics: A Systematic Review and Bibliometric Analysis,* Micromachines 2023, 14, 359. https://doi.org/10.3390/mi14020359.

[2] Rus, D., Tolley, M. *Design, fabrication and control of soft robots,* Nature 521, 467–475 (2015). https://doi.org/10.1038/nature14543.

[3] Pan, M.; Yuan, C.; Liang, X.; Dong, T.; Liu, T.; Zhang, J.; Zou, J.; Yang, H.; Bowen, C. *Soft Actuators and Robotic Devices for Rehabilitation and Assistance.* Adv. Intell. Syst. 2021, Vol. 4.

[4] Polygerinos, P., Lyne, S., Zheng Wang, Nicolini, L. F., Mosadegh, B., Whitesides, G. M., & Walsh, C. J. *Towards a soft pneumatic glove for hand rehabilitation.* IEEE/RSJ International Conference on Intelligent Robots and Systems 2013, doi:10.1109/iros.2013.6696549.

[5] Biriş, C.-M.; Racz, S.-G.; Gîrjob, C.-E.; Grovu, R.-D.; Rusu, D.-M. *A Wearable Device for Upper Limb Rehabilitation and Assistance Based on Fluid Actuators and Myoelectric Control*, *Appl. Sci.* 2023, *13*, 10181, https://doi.org/10.3390/app131810181.

[6] Mohamed MH, Wagdy SH, Atalla MA, Rehan Youssef A, Maged SA. *A proposed soft pneumatic actuator control based on angle estimation from data-driven model,* Proc Inst Mech Eng H. 2020 Jun;234(6):612-625. doi: 10.1177/0954411920911277.

[7] Heung KHL, Li H, Wong TWL and Ng SSM, *Assistive robotic hand with bi-directional soft actuator for hand impaired patients*, *Front. Bioeng, Biotechnol*2023. 11:1188996. doi: 10.3389/fbioe.2023.1188996.

[8] Panagiotis Polygerinos, Zheng Wang, Kevin C. Galloway, Robert J. Wood, Conor J. Walsh, *Soft robotic glove for combined assistance and at-home rehabilitation*, Robotics and Autonomous Systems, Volume 73, 2015,135-143, ISSN 0921-8890, https://doi.org/10.1016/j.robot.2014.08.014.

[9] J. Wang, Y. Fei and W. Pang, *Design, Modeling, and Testing of a Soft Pneumatic Glove With Segmented PneuNets Bending Actuators*, IEEE/ASME Transactions on Mechatronics, vol. 24, no. 3, pp. 990-1001, June 2019, doi: 10.1109/TMECH.2019.2911992.

[10] Keqin Sun, Yongding Tian, *Numerical investigation of a bioinspired multi-segment soft pneumatic actuator for grasping applications*, Materials Today Communications, Volume 31, 2022,103449, ISSN 2352-4928, https://doi.org/10.1016/j.mtcomm.2022.103449.

[11] SmoothOn, DragonSkin 20, https://www.smooth-on.com/products/dragon-skin-20/, (Accessed 08.03.2024).

[12] Rusu, D.M.; Petraşcu, O.L.; Pascu, A.M.; Mândru, S.D. *The Influence of Industrial Environmental Factors on Soft Robot Materials,* Materials 2023, *16*, 2948, https://doi.org/10.3390/ma16082948.

[13] Pressure Sensor, Honywell, (Accesed: 08.03.2024,https://www.tme.eu/ro/details/abpdanv015pgsa3/senzori-de-presiune/honeywell/?brutto=1&currency=RON&gad_source=1&gclid=CjwKCAiAi6uvBhADEiwAWiyRdtUpdZeUyEt3VAw6Ga-QyOWwXZH2IWBsgaN9iGnsLGxHGfHeL3v2PhoCGFoQAvD_BwE)

Cercetarea experimentală a unui actuator soft de tip multisegment

În cadrul lucrării de față s-a abordat într-o manieră experimentală influența grosimii pereților cavităților interioare asupra caracteristicilor ce țin de amplitudinea de mișcare și forță dezvoltată de către actuatori soft de tip multisegment acționați pneumatic destinați diferitelor aplicații din domeniul roboticii soft, cum sunt cele de reabilitare/asistare sau prehensare. Acest parametru a fost variat pe o serie de 4 actuatori multisegment pornind de la grosimea peretelui de 1 mm până la 2.5 mm. Actuatorii soft multisegment au fost realizați pe baza unei metodologii riguroase prin tehnologia de turnare utilizând cauciuc silicon bicomponent DragonSkin 20 cu duritatea shore de 20A în matrițe realizate pe imprimanta 3D – CraftBot Plus din materialul acid polilactic (PLA). Forța de ieșire dezvoltată de fiecare variantă a actuatorului în funcție de presiunea de intrare aplicată a fost monitorizată utilizând dinamometru Chatillon DFE 2.5kN. De asemenea, pentru a determina comportamentul cinematic al actuatorului s-au presurizat actuatorii la presiunea de 50 kPa, fiind monitorizată experimental amplitudinea de mișcare a segmentelor.

Dan-Mihai RUSU, Ph.D. student, Technical University of Cluj-Napoca, Department of Mechatronics and Machine Dynamics, 103-105 Bd. Muncii Cluj-Napoca, Dan.Rusu@mdm.utcluj.ro, Phone: +40757670339.

Silviu-Dan MÂNDRU, Professor, Technical University, Cluj-Napoca, Department of Mechatronics and Machine Dynamics, 103-105 Bd. Muncii Cluj-Napoca, Dan.Mandru@mdm.utcluj.ro, Phone: +40264401645.