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A SOFT TENTACLE_ROBOT FOR MINIMALLY INVASIVE SURGERY

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Abstract. This paper considers a tentacle-robot composed of soft materials designed to provide similar motion capabilities as the octopus tentacle, in order to reach the surgical target in biological structures. The manipulator is composed of two or three identical tentacles, which can be controlled independently. The tentacles can bear multi-directional bending and the stiffening capabilities, like an octopus tentacle. The performances in terms of workspace, stiffening capabilities and generating forces are numerical simulated. A major importance is given to constitutive laws of soft materials. The constitutive models for soft materials are continuum-based models with more-realistic details for behavior of nonlinear elastic materials.

Key words: soft robotics, tentacle-robot, constitutive law for silicon.

1. INTRODUCTION

The term *soft robotics* describes the soft and organic embodiments with biologically-inspired sensors and strategies combined with safe, intuitive and more sensitive interaction [1].

Natural robots, such as elephant trunks, octopus arms, squid tentacles and snakes have been widely investigated for achieving improvements of performance of traditional devices, in terms of locomotion or grasping [2, 3]. The use of soft robotics in surgery can lead to novel instrumentation able to overcome limitations of current systems [4]. Similarly to biological manipulators, a soft tool could perform a compliant interaction with tissues; in addition, by exploiting a variable stiffness mechanism, it could actively interact with surrounding structures.

Traditional surgical procedures imply the use of multiple specialized instruments such as graspers, retractors, vision system, dissectors etc. to carry out a single procedure. Also, the organ retraction is typically needed for shifting or lifting organs in order to generate the necessary space for reaching the target organ [5, 6]. Retraction tasks can be also investigated if the tentacle-robot is used. As an example, Fig. 1 illustrates schematic examples of surgical tasks performed by a tentacle-robot. The yellow line indicates the stiffening of the manipulator portion, red indicates the organ and green the surgical target. By becoming stiffer, the tentacle-robot accomplishes the retraction task, which traditionally requires the insertion of additional instruments.

The multidirectional bending, elongation and stiffening are achieved by the elastomeric materials. The flexible fluidic actuators (FFA) are exploited in the last decade for the bending and elongation of the soft module, while a granular-jamming-based stiffening mechanism is used for stiffness variation [7 -9].

The actuator is composed of elastomeric material (Silicone 0050, Ecoflex, Smooth on Inc., Shore Hardness 00–50, 100% linearized Tensile Modulus 83 kPa).

This material was selected due to its high flexibility, low hysteresis, and easy molding.

In addition, FFAs can provide high forces and do not require electrical connections and external energy

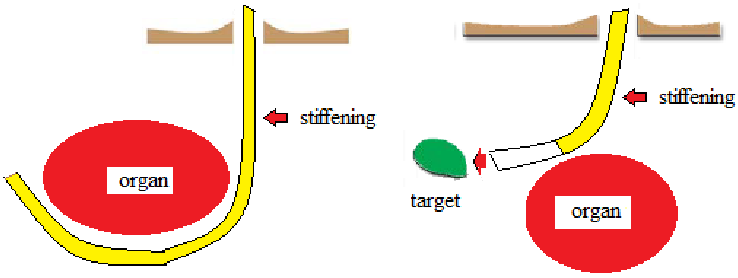

Fig. 1. a) Organ retraction by grabbing and lifting up of the organ. b) Fitting in tiny spaces, shifting down of an organ with the base portion and reaching the surgical target.

Three human-robot interaction distinguishes the human acting on robot where the user guides the motion of the robot, the human and robot working together and the robot acting on human.

In the first case, the robot guides the motion of the human user, e.g. a co-robot lifting and handling of elderly patients or a wearable robot as a substitute for motor deficiency. In the second case, the user guides the motion of the robot, e.g. human user teaching a co-robot a new task by programming by demonstration and wearable robots allowing the user to move freely, and in the last case, both robot and human guide their own motions, e.g. for the cooperative handling of objects with co-robots or the rehabilitation of reduced muscular functions.

The soft material modeling requires second order constitutive models (i.e. Eringen, Mooney-Rivlin, Ogden, Yeoh model etc.), which essentially are based on experiment data in order to simulate the behavior of nonlinear elastic materials [10,11]. However, there is currently no theoretical solutions for kinematic or dynamic modelling problems of soft structures with complex boundary conditions [12].

2. A CONSTITUVE MODEL FOR SILICON

In order to obtain the constitutive equations for silicon 0050, the nonlocal balance laws for mass, momentum, moment of momentum and energy are used [10, 11]

$$\rho_{,t} + \mathrm{div}(\rho\tilde{\mathbf{v}}) = \hat{\rho}\,, \tag{1}$$

$$\mathrm{div}\,\mathbf{t}_k + \rho(\mathbf{f} - \dot{\tilde{\mathbf{v}}}) = \hat{\rho}\tilde{\mathbf{v}} - \rho\hat{\mathbf{f}}\,, \tag{2}$$

$$\mathbf{i}_k \times \mathbf{t}_k - \rho(\mathbf{x}\times\hat{\mathbf{f}} - \hat{\mathbf{l}}) = 0\,, \tag{3}$$

$$-\rho\dot{\varepsilon} + \mathbf{t}_k\cdot\tilde{\mathbf{v}}_{,k} + \nabla\cdot\mathbf{q} + \rho h - \hat{\rho}(\varepsilon - \frac{1}{2}\tilde{v}\cdot\tilde{v}) - \rho\hat{\mathbf{f}}\cdot\tilde{\mathbf{v}} + \rho\hat{h} = 0, \tag{4}$$

$$\int_V \hat{\rho}\,\mathrm{d}v = 0\,,\quad \int_V \rho\hat{\mathbf{f}}\,\mathrm{d}v = 0\,,\quad \int_V \rho\hat{\mathbf{l}}\,\mathrm{d}v = 0\,,\quad \int_V \rho\hat{h}\,\mathrm{d}v = 0\,, \tag{5}$$

where a superposed dot a material time derivative. Here, ρ is the mass density, $\mathbf{t}_k = \mathbf{t}_{kl}\iota_l$ the stress tensor, $\mathbf{i}_k$ the Cartesian unit vectors, ε the internal energy density, $\mathbf{q}$ the heat flow vector, h heat source per unit mass, $\hat{\rho}$ the mass residual, $\hat{\mathbf{f}}$ the body force residual, $\hat{\mathbf{l}}$ the body couple residual, $\hat{h}$ the energy residual, all residuals being the nonlocal production of these quantities per unit mass due to the rest of the body.

The second law of thermodynamics is obtained from the master balance laws of the nonlocal theory

$$\rho\dot{\eta} - \nabla\cdot\mathbf{q} - \frac{\rho h}{\theta} - \rho\hat{b} + \hat{\rho}\eta \geq 0 \quad \text{in } V-\sigma , \tag{6}$$

where η is the entropy density, θ is the absolute temperature and $\hat{b}$ is entropy residual subject to

$$\int_V \rho\hat{b}\,\mathrm{d}v = 0 , \tag{7}$$

For the linear theory of nonlocal elastic materials, whose natural state is free of nonlocal effects, the nonlocal body force vanishes, i.e.

$$\hat{f}_k = 0 .$$

So, the constitutive equations of the nonlocal linear homogeneous and isotropic elastic solids and residuals do not violate the global entropy inequality (6) and (7) if and only if they are of the form

$$t_{kl} = \lambda e_{rr}\delta_{kl} + 2\mu e_{kl} + \int_{V-\sigma} (\lambda_1' e_{rr}'\delta_{kl} + 2\mu_1' e_{kl}')\mathrm{d}v' , \tag{8}$$

$$\Sigma = \Sigma_0 + \frac{1}{2}\lambda(e_{kk})^2 + \mu e_{kl}d_{kl} + \int_{V-\sigma} (\frac{1}{2}\lambda_1' e_{kk} e_{ll}' + \mu_1' e_{kl} e_{kl}')\mathrm{d}v' ,\ \hat{\rho} = 0 ,\ \hat{f}_k = 0 , \tag{9}$$

where λ, μ are the classical Lamé elastic constants, and λ' and μ' are the nonlocal Lamé elastic functions which depend on $|\mathbf{x}' - \mathbf{x}|$, Σ is a functional over all argument functions of $\mathbf{x}'$ covering the entire body, defined by

$$\rho_0\psi = \Sigma(\mathbf{x}', \mathbf{x}'_{,k}) ,$$

with

$$\psi = \varepsilon - \theta\eta$$

the free energy functional, Σ_0 refers to the value in the natural state, and ρ_0 the density in the natural state, δ_{kl} is the Kronecher delta, e_{kl} is the strain tensor of the linear theory

$$e_{kl} = \frac{1}{2}(u_{k,l} + u_{l,k}) , \tag{10}$$

where u_k are the components of the displacement vector.

A prime placed on quantities indicates that they depend on $\mathbf{x}'$ and $t' \leq t$, where $\mathbf{x}'$ is any other point in the body and t' any time at or prior to present time t The conditions $\hat{\rho} = 0$, $\hat{f}_k = 0$ means that we don't have the mass and body force nonlocal production in the body.

The *nonlocal Lamé elastic functions* $\lambda'(|\mathbf{x}' - \mathbf{x}|)$ and $\mu'(|\mathbf{x}' - \mathbf{x}|)$ are influence functions, which are positive decreasing functions of $|\mathbf{x}' - \mathbf{x}|$. Another form of (8) and (9) is obtained by incorporating λ and μ into λ' and μ'

$$t_{kl} = \int_{V-\sigma} [\lambda'(|\mathbf{x}'-\mathbf{x}|)e'_{rr}(\mathbf{x}')\delta_{kl} + 2\mu'(|\mathbf{x}'-\mathbf{x}|)e'_{kl}(\mathbf{x}')]\mathrm{d}v'(\mathbf{x}'), \quad (11)$$

$$\Sigma = \Sigma_0 + \int_{V-\sigma} [\frac{1}{2}\lambda'(|\mathbf{x}'-\mathbf{x}|)e_{kk}(\mathbf{x})e'_{ll}(\mathbf{x}') + \mu'(|\mathbf{x}'-\mathbf{x}|)e_{kl}(\mathbf{x})e'_{kl}(\mathbf{x}')]\mathrm{d}v'(\mathbf{x}'). \quad (12)$$

The Lamé constants for the silicon can be taken as

$$\lambda'(|\mathbf{x}'-\mathbf{x}|) = \alpha(|\mathbf{x}'-\mathbf{x}|)\lambda \ , \ \mu(|\mathbf{x}'-\mathbf{x}|) = \alpha(|\mathbf{x}'-\mathbf{x}|)\mu \ , \quad (13)$$

where λ and μ are the Lamé constants for the nonlocal case, and $\alpha(|\mathbf{x}'-\mathbf{x}|)$ is the nonlocal kernel function which measures the effect of the strain at $\mathbf{x}'$ on the stress at $\mathbf{x}$. Eringen (2002) has showed that

$$t_{kl} = \int_V \alpha(|\mathbf{x}'-\mathbf{x}|)\sigma_{kl}(\mathbf{x}')\mathrm{d}v'(\mathbf{x}'), \quad (14)$$

where $\sigma_{kl}(\mathbf{x}')$ are the local stress fields. For the kernel function we consider the Artan representation [11]

$$\alpha(|\mathbf{x}'-\mathbf{x}|) = \begin{cases} B\left\{1-\frac{|\mathbf{x}'-\mathbf{x}|}{d}\right\}, & |\mathbf{x}'-\mathbf{x}|<d, \\ 0, & |\mathbf{x}'-\mathbf{x}|>d, \end{cases} \quad (15)$$

where $B=1/d$, with d a reference distance. For our problem $d=4\times10^{-2}\,\mathrm{cm}$.

The constants B and d are determined from the experimental measurements of the the average of five cycles of loading/unloading of the silicone performed with an Instron 5900 Testing System silicon (Ecoflex, Smooth on Inc.) [13]. The maximum measured variability was ± 3.4 kPa and the hysteresis was 0.05 J. Data were fitted using a third-order polynomial function.

The nonlocal constitutive law for silicon 0050 is presented in Fig. 2.

We see that the silicone sample supports 200% deformation.

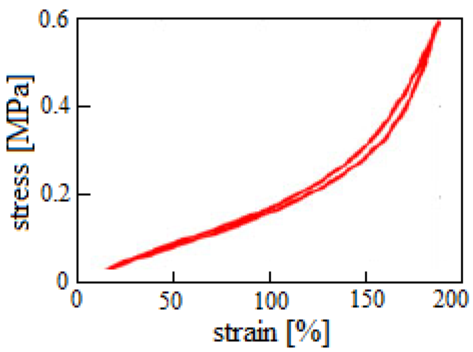

Fig. 2. Stress–strain nonlocal law of silicone 0050.

3. DESIGN THE MOTION OF A SILICON CYLINDER FOR ELONGATION, BENDING AND STIFFENING

Let us consider a cylinder made from silicon 0050 containing three fludic chambers in radial arrangement (Fig.3). Multidirectional bending and elongation of the silicone cylinder can be achieved by combining the inflation (a biaxial extension method) of the three chambers.

In order to understand the inflation of silicone 0050, Figs.4 and 5 show as a rectangle inflates with a given stretched length. The points A, B, C become after inflation a, b, c. The stretch ratio is $\lambda = l_s / l_0$.

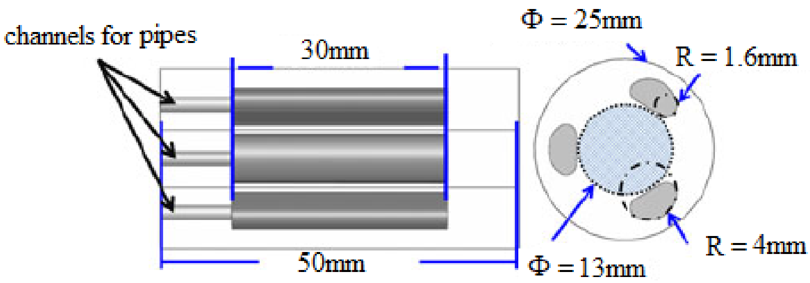

Fig.3. Dimensions of the silicone cylinder.

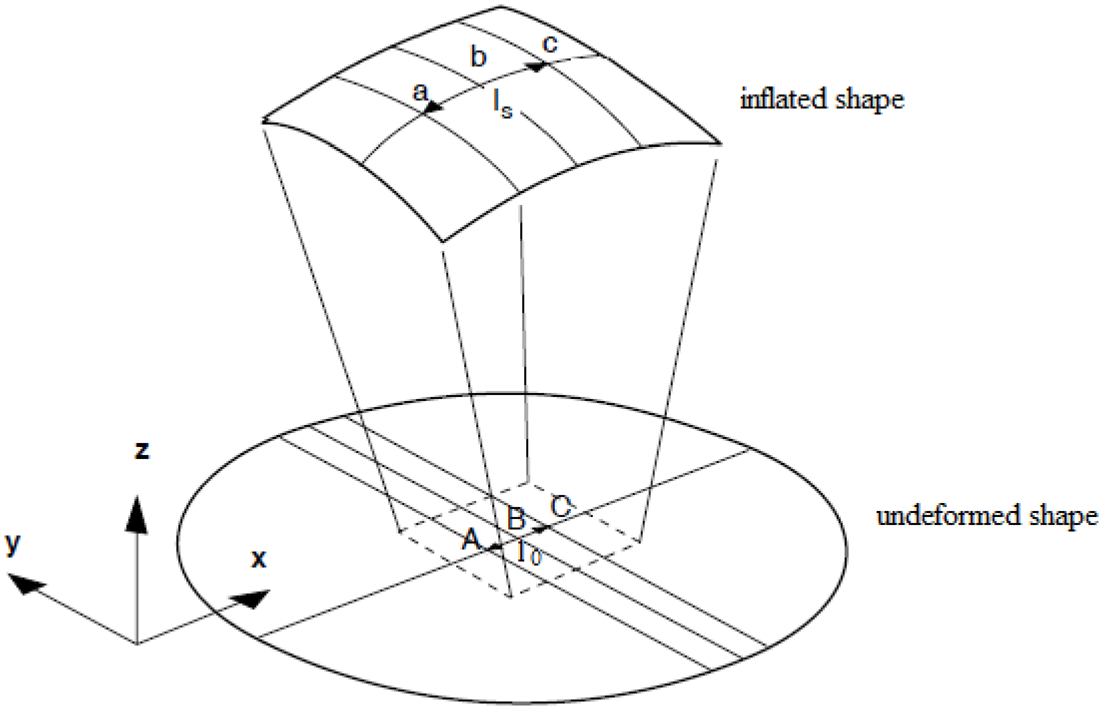

Fig.4. Inflated shape of a rectangle.

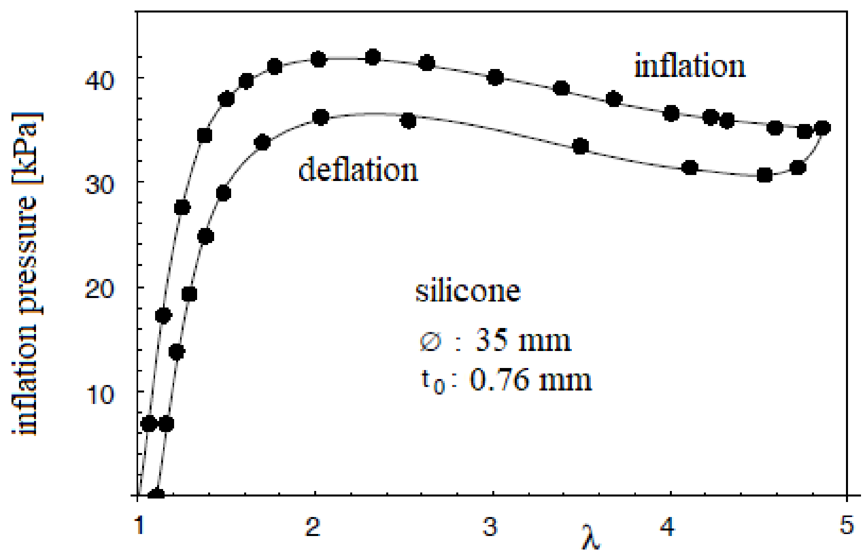

Fig.5. Inflation pressure vs. stretch ratio for silicone 0050.

Actuating a single chamber leads to bending in one direction, actuating two chambers with the same pressure will generate bending in the plane in between the two chambers, and, finally, inflation of all the chambers together with the same pressure will lead to elongation of the cylinder along its main axis.

The stiffening ability needs to obey the motion of the tentacle module in terms of the elongation and bending.

Another ability to be taken into considerations is the tuning the robot compliance while interacting with biological structures. This aspect is very important in medical instrumentation. In addition, the ability to stiffen part of their body can lead to better compensation for environmental disturbances, thus potentially increasing stability and accuracy [14-18].

The describing of a module behavior was simulated using the cnoidal method [19].

The force and pressure solutions by actuating one, two and three fluidic chambers of the module are expressed as superposition of cnoidal functions

$$F = \sum_{l=1}^{n} f_l \mathrm{cn}^2(m_l), \quad p = \sum_{l=1}^{n} p_l \mathrm{cn}^2(m_l), \tag{16}$$

where $0 \le m_k \le 1, n$ is the order of particular solutions, and f_l and p_l are parameters determined from the least-squares optimization technique of agreement between theoretical and experimental data available in Ranzani [7]

$$\Upsilon = \sum_{l=1}^{N} \left[f_i^e - f_i^c \right]^2 + \sum_{l=1}^{N} \left[p_i^e - p_i^c \right]^2, \tag{17}$$

where f_i^e, p_i^e are the measured i pressure and force, f_i^c, p_i^c are the corresponding model prediction, and N number ot the experimental data. This problem was solved by a genetic algorithm for $n = 5$ and $N = 216$.

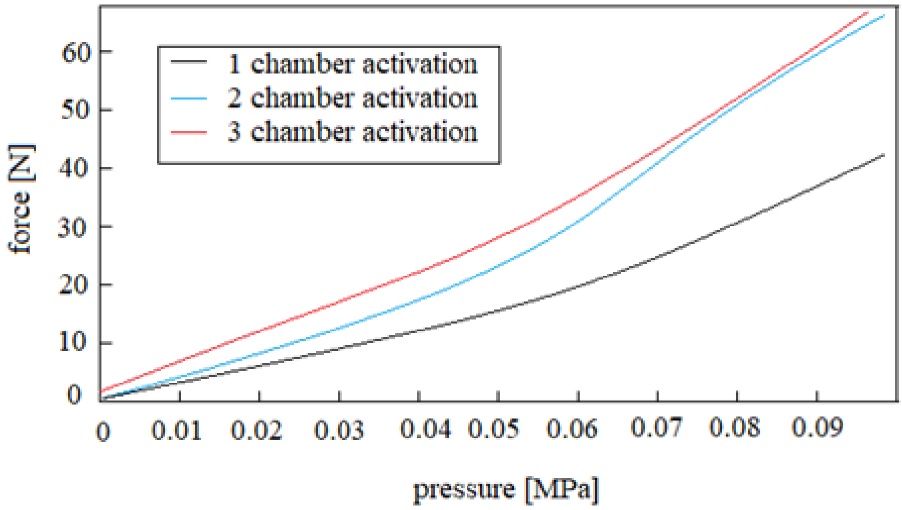

Fig.6. Computed force-pressure relatioship, by actuating one, two, and three fluidic chambers of silicon module.

The relationship force-pressure, by actuating one, two, and three fluidic chambers of silicon module is presented in Fig. 6. One single chamber is able to generate 24.6 N increasing almost linearly in relation to the input pressure. By activating two and three chambers, the force reaches 41.4 and 47.1 N, respectively.

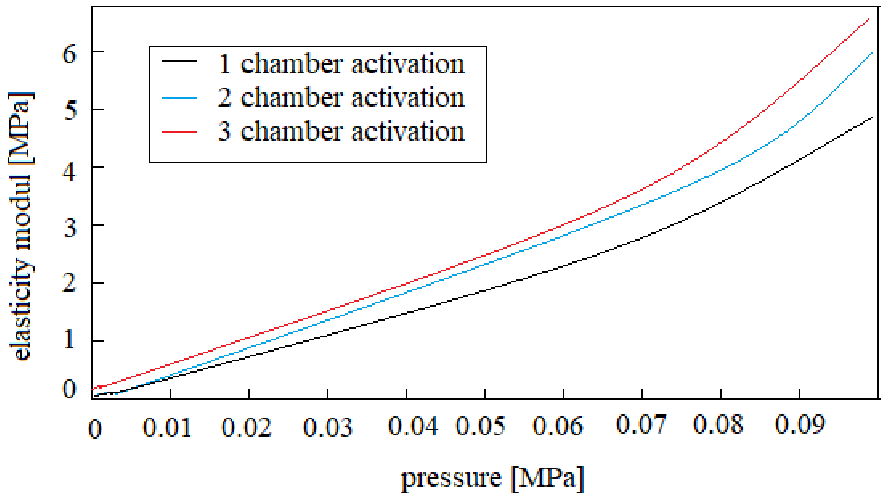

Fig.7. Variation of the elasticity modulus with respect to pressure, by actuating one, two, and three fluidic chambers of silicon module.

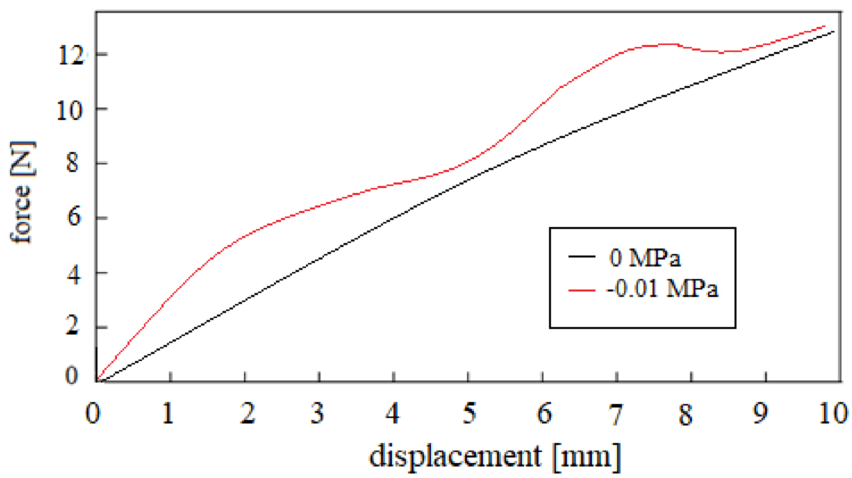

Fig.8. Lateral displacement with no chamber inflation.

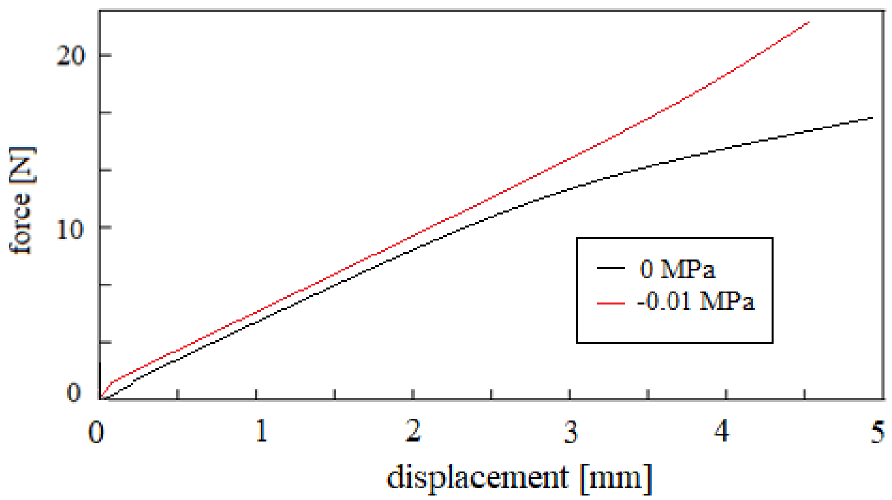

Fig.9. Axial displacement with no chamber inflation.

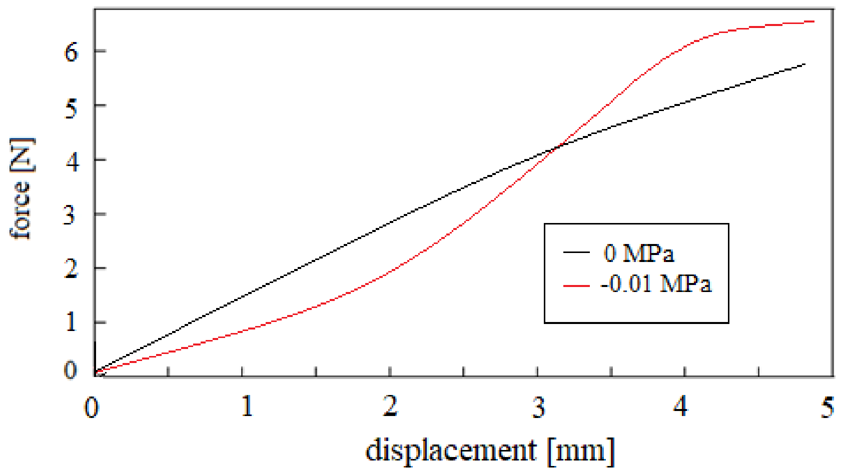

Fig.10. Axial displacement, single-chamber inflation of 0.04 MPa.

The variation of elasticity modulus with respect to pressure, by actuating one, two, and three fluidic chambers of silicon module is shown in Fig.7.

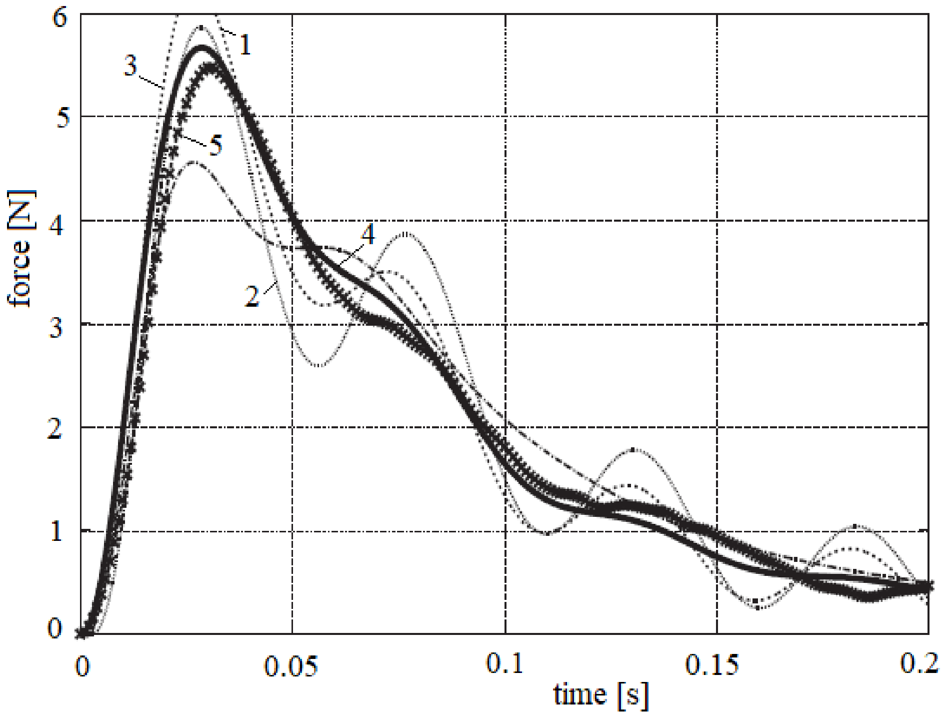

Fig. 11. Force-time relationship in the bending of the silicon cylinder by actuating one (number 1), two (number 2), and three fluidic chambers (number 3) and intermediate two combinations of the three chambers (numbers 4 and 5).

The lateral displacement with no chamber inflation is presented in Fig.8. The axial displacement with no chamber inflation is presented in Fig. 9, while the axial displacement, single-chamber inflation of 0.04 MPa, in Fig.10.

The plots in the last three figures show that the force required to deflect, in the case of lateral tests, or to compress, in the case of axial tests, increases significantly when the stiffening system is activated (−0.01 MPa pressure).

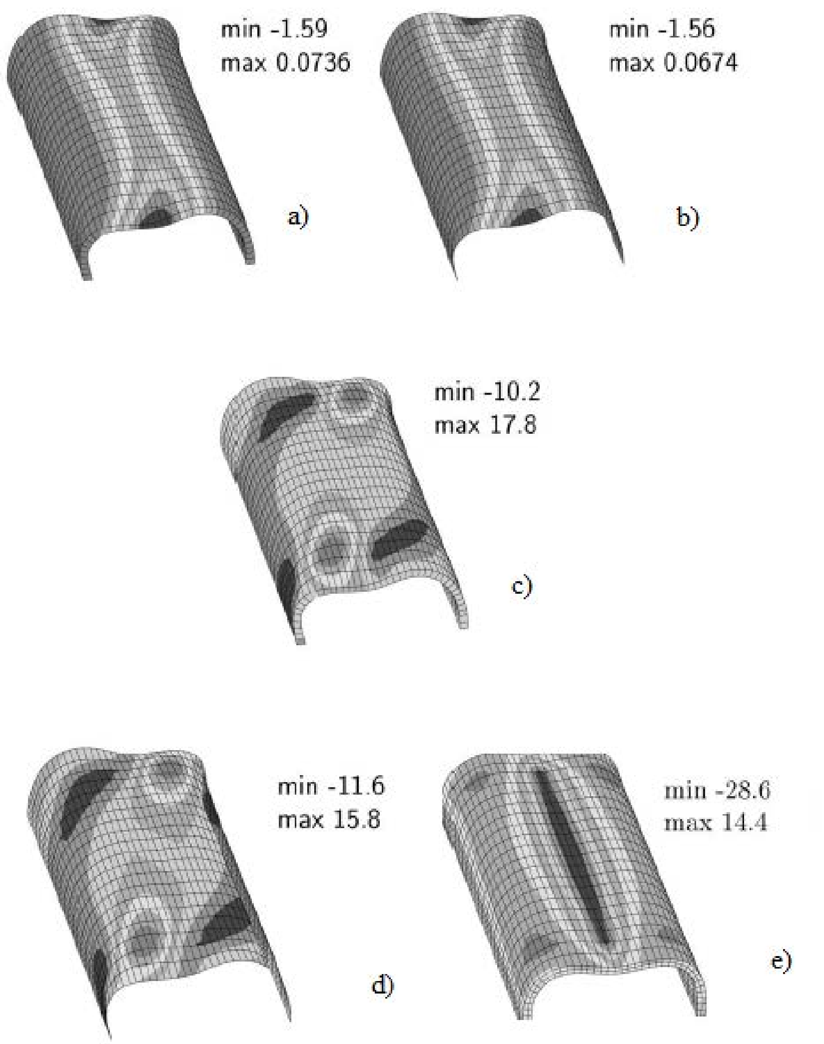

Fig.12. The axial displacement [mm] with a) one actuated fluidic chamber, b) two actuated fluidic chamber, c) three actuated fluidic chambers and d),e) intermediate two combinations of the three chambers.

The force-time relationship in the bending of the silicon cylinder by actuating one (number 1), two (number 2), three fluidic chambers (number 3) and intermediate two combinations of the three chambers (numbers 4 and 5) is presented in Fig. 11. The last two cases give different intermediate module configurations.

The axial displacements [mm] for one actuated fluidic chamber (Fig.12a), two actuated fluidic chamber (Fig.12b), three actuated fluidic chambers (Fig.12c) and intermediate two combinations of the three chambers (Fig.12d,e) are presented for a 3D discretization with shell elements for a half silicone cylinder. The displacements are point symmetric.

4. CONCLUSIONS

The *soft robotics* describes the soft embodiments with biologically-inspired electronics, sensors, and drive technology, effectively linked with one another. Soft robotics is a growing field generating innovative concepts and novel systems. The soft robots can be used as a third helping hand, in the medical field. Inspired by the elasticity of human muscles, elastic soft robots are designed with the possibility of imitating humans or animals motion.

The aim of this paper is to outline a framework for the research byconsidering a tentacle-robot composed of soft materials designed to provide similar motion capabilities as the octopus tentacle, in order to reach the surgical target in biological structures.

The manipulator is composed of two or three identical tentacles, which can be controlled independently. The tentacles can bear multi-directional bending and the stiffening capabilities, like an octopus tentacle. The performances in terms of workspace, stiffening capabilities and generating forces are numerical simulated.

Soft robot are complex systems, because of intricateness and couplings between components (actuators, sensors, structure) and the complex mechanical behaviour (non-linearity in large deformation, viscoelasticity). In addition, the complex geometries (free-form, foam-like structure) must be taken into consideration. In order to deal with this complexity, simulation must be used to support human intuition, to develop novel control strategies and design ideas.

Multi-physics simulations combining different fields such as mechanical deformation and electrical field are of particular importance for soft actuators and sensors. Powerful and predictive simulation tools rely on good models.

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