

STIFF-FLOP Surgical Manipulator: mechanical design and experimental characterization of the single module

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Abstract— This paper presents the concept design, the fabrication and the experimental characterization of a unit of a modular manipulator for minimal access surgery. Traditional surgical manipulators are usually based on metallic steerable needles, tendon driven mechanisms or articulated motorized links. In this work the main idea is to combine flexible fluidic actuators enabling omnidirectional bending and elongation capability and the granular jamming phenomenon to implement a selective stiffness changing. The proposed manipulator is based on a series of identical modules, each one consisting of a silicone tube with pneumatic chambers for allowing 3D motion and one central channel for the implementation of the granular jamming phenomenon for stiffening. The silicone is covered by a novel bellows-shaped braided structure maximizing the bending still limiting lateral expansion. In this paper one single module is tested in terms of bending range, elongation capability, generated forces and stiffness changing.

I. INTRODUCTION

Minimally Invasive Surgery (MIS) has become the gold standard in the majority of abdominal operations, although some fundamental limitations – immediately observed after the introduction of this technique less than 30 years ago [1] – are still present and are far to be really approached despite emerging robotic solutions.

The reason why traditional laparoscopic operations need up to 4 or 5 trocar accesses depends on the limited dexterity, flexibility, maneuverability of the available tools. In addition especially in the case of laparo-endoscopic single-site surgery (LESS) [2] and natural orifice transluminal endoscopic surgery (NOTES), rigid or semi-rigid tools may lead to significant clashing of instrumentation and increase the complexity of the procedures [3]. Flexible endoscopes can be used for NOTES or LESS; indeed thanks to their high flexibility, they may allow to reach the surgical target while being inserted remotely or by a natural orifice. However endoscopes may lack stability that rigid tools normally provide [4].

Novel surgical instrumentation is being developed in order to provide higher dexterity and flexibility to the

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surgeon [5]. Such systems are designed to be highly flexible and are actuated by motors moving rods [6], gears [7] or a combination of cables and rods [8]. Due to the rigid mechanical properties of the structure, stiffness control can be challenging.

Yet biological “manipulators”, such as the octopus arm and the elephant trunk, can manipulate objects while controlling the stiffness of selected body parts and being inherently compliant when interacting with objects [9]. For this reason they have been considered as inspiration source for soft robotic arms and manipulators. Even if not directly applied to the medical field, there exist several valuable examples of “Continuum Robots” which usually have a large number of redundant DOF, are typically flexible and deformable (soft-bodied). The elephant trunk developed at Clemson University [10] is one out of many examples of lightweight continuum devices with many degrees of freedom actuated by cables and passive spring elements. Another possibility is to use pneumatic actuators to obtain remote deformations as in the case of the OCTARM continuum robot [11] or the elephant trunk proposed by FESTO group [12]. Their rigid nature imposes limitations in their usability in the medical field. Solutions with no rigid structures usually count on hybrid systems: the redundant manipulator by Kinetic Science Inc. [13] and the Air-Octor [14] combine pneumatic bellows and tendon actuation for controlled bending and extension. A different approach based on Shape Memory Alloys and tendons connected to a braided sheath [15] [16] has been attempted in the OCTOPUS project where an octopus-like robotic arm shows high softness and dexterity thanks to the materials and smart actuation mechanism adopted. Another very recent robotic tentacle is presented in [17] where a network of pneumatic chambers is embedded and distributed along a silicone structure, thus enabling large amplitude actuation in the soft elastomer by pressurizing and inflating them. This last class of soft manipulators represents the most

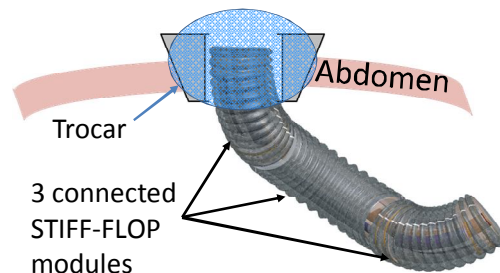


Figure 1. CAD drawing of the overall architecture of the STIFF-FLOP manipulator.

attractive solution for medical applications, but none of the mentioned systems answer to the un-met MIS requirements. Flexibility and softness come generally with limited force; while high forces are tough to be achieved without any rigid supports.

A variable stiffness robot takes advantage of the best of rigid and soft robotics. Based on the mentioned limitations of traditional mechanical designs, a different approach has been pursued for the STIFF-FLOP manipulator [18], taking inspiration from the manipulation capabilities of the octopus arm. The manipulator is designed to present elongation, squeezing and large flexibility in bending, but also contemporary showing stiffness changing capabilities.

In the current paper, the mechanical concept design of the entire manipulator is described in Section II, while Section III and IV illustrate the design and fabrication of a single manipulator module, respectively. Preliminary tests as proof of concept and assessment of performances are described in Section V and widely discussed in Section VI.

II. MANIPULATOR SPECIFICATIONS

The flexible manipulator has been designed to meet specific requirements extracted by medical literature and by in vivo biomechanical tests of internal organs. It should show squeezing capabilities to be able to pass through a traditional trocar port for single access surgery; high dexterity is required, thus active capability to bend in any direction and elongation are fundamental main features; an active, flexible and articulated manipulator would allow turning around organs in the thoracic and abdominal cavities, independently on the entrance point; a sufficient force should be achieved at relevant points along the arm to allow the displacement of organs during arm motion and important surgical operations, including organ retraction. For this reason a selective and tunable stiffness is also required, thus allowing to smoothly adapt to soft organs geometries as well as to become rigid for retraction actions.

In order to meet the above mentioned requirements, as general principle, a modular approach has been followed by developing soft actuated units (modules) selectively operated by the user and (whenever necessary) able to singularly bend in any direction, elongate and change stiffness. The STIFF-FLOP robotic manipulator concept is illustrated in Figure 1, in the specific embodiment with three identical elongation/bending/stiffening modules.

III. DESIGN OF THE SINGLE MODULE

As introduced in the previous section, the modules have identical size and capability and each one is able to perform independently omnidirectional bending, elongation and stiffening. This is possible thanks to two different actuation systems integrated in each module: flexible fluidic actuators combined with a chamber exploiting the granular jamming mechanism. The main component of the manipulator module is an elastomeric cylinder (silicone Ecoflex™ 0050 - Smooth-on Inc.). This material guarantees the right level

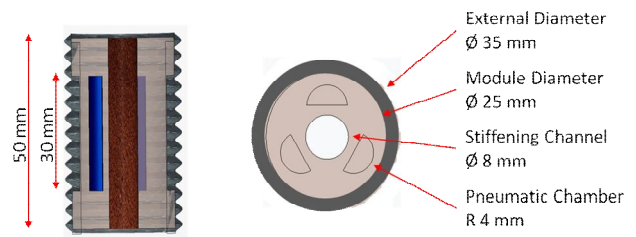


Figure 2. From left to right, sketch of the longitudinal and transversal cross section design of the module with the semi-cylindrical fluidic chambers and the central stiffening channel.

of softness when deformed passively and it is suitable to host internal chambers that can be used to modulate the characteristics and the behavior of the module. The cylindrical elastomer hosts three equally spaced chambers which are embedded in radial arrangement (the fluidic actuators) and another one centrally placed (for the granular jamming) as shown in Figure 2. Externally the module is provided with a braided bellow-like structure.

A. Active motion

Flexible fluidic actuators have been already successfully used as active motion system enabling elongation and bending of soft structures [19]. The use of such technology is eased by the wide available literature in terms of modelization [20] and application cases [21].

Optimal geometries for this specific system are under investigation, but previous works comparing several cross section designs for similar applications [22] concluded that the key factor is to find a trade-off between the thickness of the separation wall among the chambers and their diameter. Moreover in this case an additional criterion is the maximization of the internal available space to host the stiffening chamber.

A well-known drawback on the use of soft material chambers inflated by pressurized fluids is the very low mechanical efficiency respect to the desired movement associated with the bending and elongation capabilities. This is due to the fact that the inflated chambers tend to expand in every direction, like balloons. In Figure 3 the effect of 0.32 bar pressure on one chamber is shown and it is evident that the outwards expansion is dominant with respect to the bending of the module and it reaches an unacceptable high risk of explosion.

On the contrary, in order to produce a more pronounced bending effect with minimal lateral expansion, the radial expansion of the chamber should be minimized inducing a

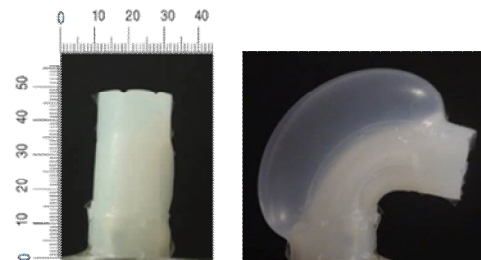


Figure 3. Effect of 0.32 bar pressure on a single silicone (Ecoflex 0050) chamber.

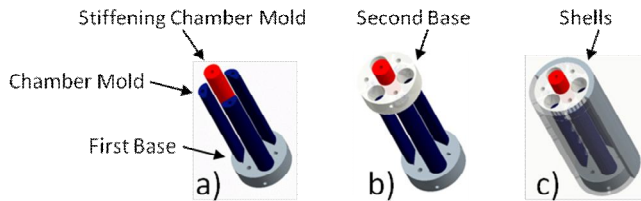


Figure 4. Assembling the mold for the silicone cylinder hosting the three fluidic chambers and the central stiffening channel.

maximal longitudinal deformation. Since the elastomeric materials are considered isotropic, there are no preferential directions of expansion; however, adding other structures (fillers or external constrains) would force the elongation or the bending, limiting the diameter expansion and changing the overall module behavior.

Previous attempts to limit this lateral expansion demonstrated that circular fibers arranged all around the structure can serve the scope [23], but as the chamber deforms the coils start to separate leaving weaker areas on the external surface which could likely cause abrupt and dangerous lateral expansions. This risk is specially high if the elastomeric material is very soft and the achievable curvature is high. On the other hand, harder elastomers or a huge number of stiff circular fibers could compromise the performances of the manipulator or require a more powerful fluidic source.

Based on the above considerations, the main idea is to couple the silicone cylinder and its internal chambers with a braided structure (i.e. a sheath). Braided structures (like those used in the McKibben actuators) are highly flexible and can temporarily follow bending and elongation movements providing a radial constraint to the excessive expansion especially if thermally formed to remain in a bellows-like shape.

The braided sheath is placed externally respect to the chambers and it is fixed at the distal ends of the cylinder. When the chambers are inflated to bend (or to elongate) the braided sheath contains and limits the radial expansion thus maximizing the longitudinal effect of the deformation.

B. Stiffness variation

For stiffness modulation, a granular jamming solution is used. The effectiveness of this strategy on soft robots has been already demonstrated in [24] and [25]. One of the most interesting features of this technology is that it keeps a high deformability in the unjammed state and undergoes to a drastic stiffness increase in the jammed condition. In our application coffee powder was used as granular material and latex as containing membrane. Jamming is induced by increasing density in the flexible membrane due to the applied vacuum. By controlling the vacuum level the stiffness can be tuned.

IV. MODULE FABRICATION

The fabrication of the elastomeric cylinder hosting actuating chambers is performed in multiple stage by

molding silicone in an aluminum mold. As shown in Figure 4a the three chambers mold (shown in blue) and the stiffening chamber mold (in red) are fixed to a base by screws. Alignment grooves on the base allow correct positioning and orientation of the fluidic chambers. A second base is fixed on top (Figure 4b) and the fluidic chambers are fixed on it again using screws. Finally, two semi-cylindrical shells close the mold (Figure 4c) and silicone is cast inside. After complete curing the two bases are removed and silicone is again cast to create a 10 mm silicone layer on the top closing the chambers. On one of the two sides three screws (one for each fluidic chamber) are left screwed in the fluidic chambers mold in order to keep a free channel for lodging the tubing for the fluidic actuation. When polymer reaches a complete curing, the chambers are removed from the channels left by the screws.

With a separate procedure an off-the-shelf flexible braided sheath (RS Components) with a maximum reachable inner diameter of 33 mm is processed in order to create circular folds along the structure (Figure 5). An aluminum bar was inserted inside as a support and the sheath was compressed from the top in order to induce the formation of the bellows. The repeatability of the process is guaranteed by the structure itself, which allows the formation of the folds only in particular positions along the sheath during the compression. Moreover, the final shape is always visually observed. Such shape was thermally fixed by heating the sheath at 400°C with a heat gun for a few minutes. The sheath is then fixed at the two bases of the elastomeric module with silicone and the central cylinder is finally removed to free the central channel.

V. EXPERIMENTAL ASSESSMENT OF MODULE PERFORMANCES

In Figure 6 a scheme of the components used for the active motion and stiffness modulation is reported. The active motion of the STIFF-FLOP module was performed by controlling the pressure in each fluidic chamber independently. Three pressure regulator valves (series K8P, E.V.P. systems) enable the modulation of the air pressure inflated in each chamber. A compressor (Compact 106, Fiac Air-Compressors) was used for pneumatic supply.

Vacuum for stiffness modulation was obtained by using a vacuum pump (LB.4, D.V.P. vacuum technology). A 5 μm filter (MC104-D10, E.V.P. systems) was used to prevent particles to enter into the pump. A vacuum reducer with

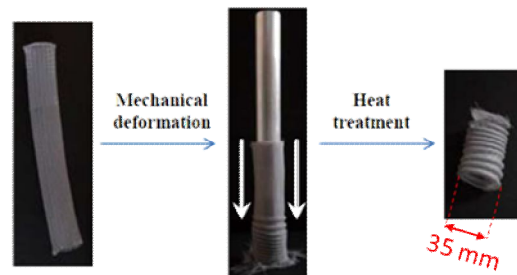


Figure 5. Fabrication procedure of the braided structure in bellows-like configuration.

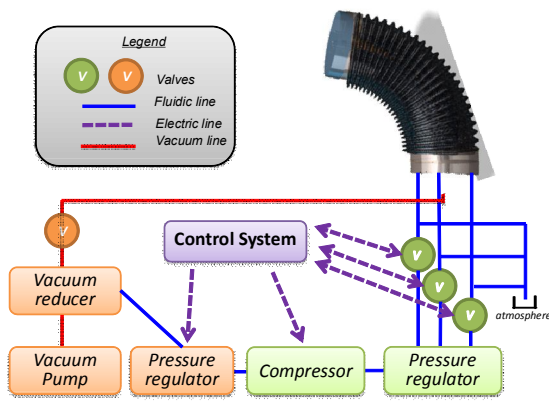


Figure 6. Components involved in the activation of the manipulator module.

pneumatic regulation (110130, E.V.P. systems) was used in combination with a pressure regulator valve (series K8P, E.V.P. systems) powered by the compressor in order to control the vacuum level in the stiffening chamber.

The output pressure of the four pressure regulator valves is measured with four analog outputs (voltage) by using an acquisition board (USB NI6363 DAQmx). A LabView interface was set up for controlling input pressures to the module both via joystick (SAITEK P580 Blue Rumble Pad) or directly setting the target pressure value for each chamber and the target vacuum level for the stiffening chamber.

For characterizing the bending and elongation performances of the STIFF-FLOP module the fluidic chambers have been actuated singularly, in pairs and all at the same time. In case of single fluidic chamber activation, pressures ranging from 0 to 0.65 bar with a step of 0.05 bar were imposed. At each step an image of the module was taken in the same working conditions and elaborated in MatLab for determining the bending angle. The same procedure was carried out activating two chambers at the same time at the same pressure. In the case of three fluidic chambers activation, elongation is obtained and by applying the same pressures as for the bending tests the length variation was measured.

The captured images have been analyzed with an algorithm custom made that calculates the bending angle from the module curvature. The elongation has been evaluated with the same simplified algorithm that takes in account the length of the module at the different steps.

The force developed by the STIFF-FLOP module was measured by positioning an ATI Mini45 load cell on the top of the module and actuating one fluidic chamber with a pressure ranging from 0 to 0.8 bar. The same test was performed actuating three fluidic chambers at the same time from 0 to 0.8 bar.

With the aim of measuring the stiffening capabilities, different displacements were imposed at the tip of the module at different configurations of the STIFF-FLOP module by using a 6 DOF industrial robot (RV-6SL, Mitsubishi). Four conditions were tested: a) base condition

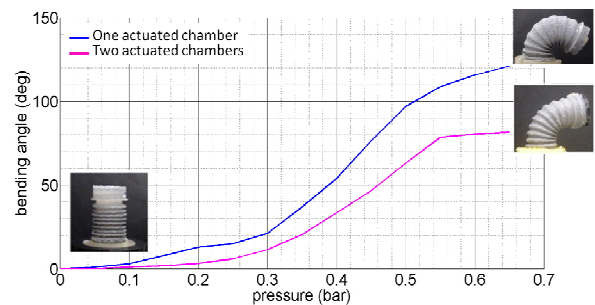


Figure 7. Bending capability of the single module under the action of increasing pressure: upper line refers to single chamber activation; lower line refers to two chambers activation.

(no actuation of the fluidic chambers); b) 90 deg bending condition, lateral displacement of 16.5 mm along the x-direction; c) 90 deg bending condition, lateral displacement of 16.5 mm along the z-direction; d) 90 deg bending condition displacement of 8 mm on the upper base (x-direction). The tests were carried out both without activating the stiffening chamber (atmospheric pressure) and at the 0.1 bar vacuum pressure (maximum possible vacuum pressure). Each test was repeated three times. Forces necessary for the above displacements were recorded using the already mentioned load cell.

VI. RESULTS AND DISCUSSION

The experimental tests described in the previous section led to a complete description of the module performances in terms of bending and elongation capability, achievable forces, stiffening variation range and passive squeezing capability. All the results are reported in the following and summarized in Table I.

A. Bending

Tests on omnidirectional bending capability demonstrated the possibility to reach a bending angle of 120 deg when a single chamber is inflated and 80 deg when two chambers are simultaneously used. The plot in Figure 7 shows the relation between the pressure applied to the chambers and the respective achievable angle. The graph shows a first part (up to 0.3 bar) where the increase of the pressure produces a slow increase of the bending angle.

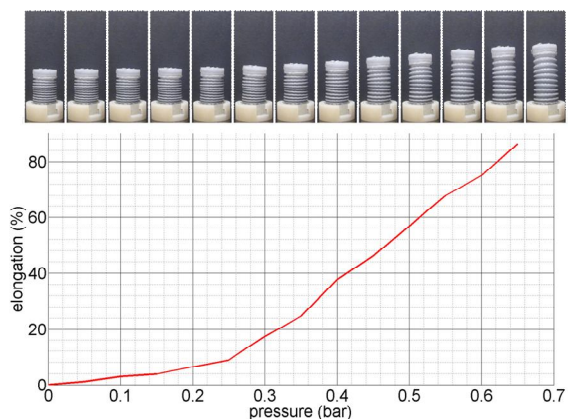


Figure 8. Elongation capability of the module under the action of increasing pressure applied simultaneously to all the chambers (values on x-axis refer to the pressure of every single chamber).

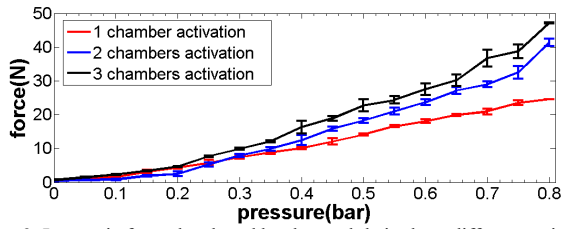


Figure 9. Isometric force developed by the module in three different activation conditions.

This is due to the expansion of the chamber which at those pressures is free to expand in any direction. When the pressure reaches 0.3 bar the interaction between the chamber and the braided sheath starts to limit the radial expansion thus leading to a considerable improve in bending (higher slope in the graph in Figure 7). On the other hand, when the pressure exceeds 0.55 bar the bending capability does not increase at the same rate and seems to reach a saturation level. At this point the portion of the braided sheath located externally along the bending plane reached its maximum elongation capability due to the folds stretching and thus starts limiting the achievable angle (also visible in the upper inset of Figure 7). When the two chambers are actuated simultaneously a similar behavior is shown, but the saturation occurs at lower angles because of the double activation which the braided sheath has to contain.

B. Elongation

Elongation has been modulated by activating the three chambers simultaneously: with an activation pressure of 0.65 bar in each chamber, starting from an initial length of 50 mm, a final value of 83.3 mm is achievable, corresponding to an elongation of 86.3%. In Figure 8 the relation between pressure and module length is reported and it shows that the overall behavior follows the same trend as

in the bending movement, except for the absence of the saturation effect: in this case the folds of the external braided sheath never reach a completely stretched configuration.

C. Force

As described in the previous section, the force that the module is able to produce has been assessed in two different conditions. The results show that one single chamber is able to generate 24.6 N increasing almost linearly respect to the input pressure (Figure 9). In the case of two and three chambers activated the force reaches 41.4 N and 47.1 N respectively which perfectly meet the requirements identified for the specific application.

D. Stiffening

The activation of the central chamber demonstrated the possibility to change and to modulate the stiffening of the module. The first test carried out on the module at base condition (shown in Figure 10a and explained in Section V) shows a consistent increase of the module stiffness when the stiffening chamber is vacuumed (36%). In the second test with the 90 deg bending condition, the stiffening demonstrated to be less performing since the internal channel is deformed and its cross section is reduced (Figure 10b, c and d). In y-direction the maximum stiffness increase is equal to 19.6%, in x-direction it is 12.4% and in z-direction it is 17.2%. It worth noting that for low imposed displacements the plots in Figure 10a, b and c show a very similar trend that results from the compression of the external silicone part of the module. After a few millimeters of displacement the resistant force contribution of the central stiffening chamber starts to predominate and the force needed to deform the module increases with a higher slope. In the last plot of the same figure this phenomenon is

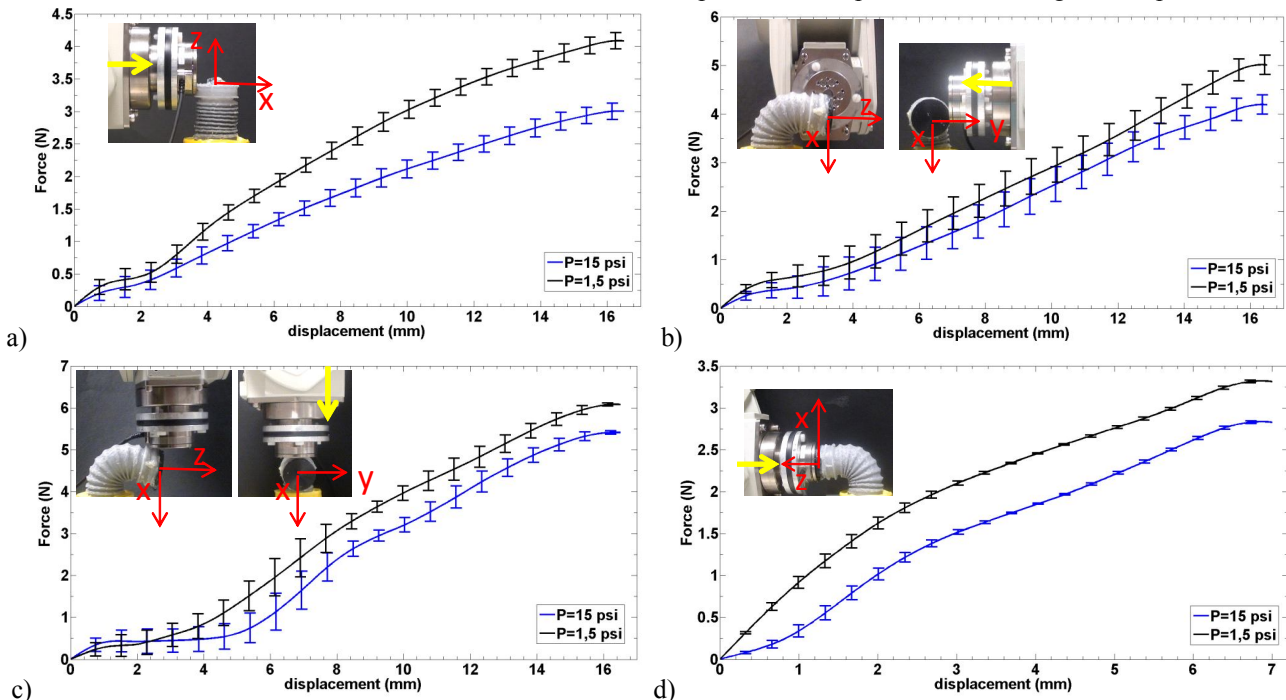


Figure 10. Stiffening variation tests: the module has been tested in base condition (a) and at 90 deg bending position along y (b), x (c) and z direction.

not present since the displacement is applied directly to the stiffening channel.

These results underlined that it is not possible to generate a complete shape locking of the module, but a remarkable increase of the stiffness. This is a necessary capability for addressing the surgical task aim to stabilize the robot during the operation and to comply with the surgical environment. In the current version of the module, coffee is used as granular material since it has been already successfully used in literature. Different materials can be considered in order to better comply with the requirements of medical instrumentations as in [26].

An additional property of the module, also related to stiffening, is squeezability. When in passive state, the module can be highly deformed and squeezed (a rough estimation is about 40% of its original diameter) without affecting its functionalities. This feature could be also employed to avoid the risk of damaging both the manipulator and the organs and to fit with different trocar diameters (see Figure 1).

TABLE I. ACTIVE PERFORMANCES OF THE MODULE

Max bending angle (one chamber @0.65 bar)	120 deg
Max bending angle (two chambers @0.65 bar)	80 deg
Max elongation (@0.65 bar)	86.3%
Max force (one chamber @0.65 bar)	24.6 N
Max force (three chambers @0.65 bar)	41.4 N
Max stiffness variation (@base condition)	36%

VII. CONCLUSION

In this paper the concept design of a new modular manipulator for minimal access surgery has been presented. The manipulator combines omnidirectional bending, elongation capability and selective stiffness changing. Proof of concept and experimental results conducted on one module have been reported demonstrating that even with a not optimized geometry for length, chambers shape and materials, the proposed structure reaches promising values respect to the specifications derived from surgeons needs. Future work will aim at optimizing the fluidic chambers and external sheath and at developing an integrated manipulator with at least three modules.

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