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A modular soft manipulator with variable stiffness

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***Abstract*— This paper presents the design of a single module composing a modular soft variable stiffness manipulator for minimal access surgery. The module exploits flexible fluidic actuation for obtaining multi directional bending and elongation capabilities. A novel flexible crimped braided sheath is introduced in order to increase the performances of the flexible actuator. Granular jamming based stiffening mechanism is used to tune the stiffness of the module. The fabrication of the module is described and the performances in terms of bending, elongation and stiffening are reported.**

Keywords— Surgical manipulator; soft manipulator; variable stiffness; minimally invasive surgery; flexible fluidic actuator; granular jamming; crimped braided structure

I. INTRODUCTION

Among the innovative tools for Minimally Invasive Surgery (MIS) [1] flexible tools represent a promising solution to overcome the limitations of current instrumentation [2]. Flexible endoscopes can be used for endoluminal and transluminal surgery since they allow reaching the surgical target from a remote insertion trocar or a natural orifice. However endoscopes may lack stability that rigid tools normally provide [3] and the achievable dexterity is still limited to the distal end.

Continuum manipulators consent to fully control their shape taking advantage of robotic technology, enabling the surgeon to perform challenging tasks not only in endoscopy but even in surgery, in a minimally invasive way [2]. Such systems are able to pass through obstructed and tortuous passages to reach the surgical target. Due to their unique features they have been proposed for different body districts like abdomen [4], heart [5], throat [6] and brain [7]. The aforementioned systems are mainly externally actuated and generally have an underactuated structure with a compliant backbone [8], which often results in low stiffness at the end effector. The lack of possibility to control the stiffness of the structure may limit the performances and the possible tasks achievable by such highly dexterous structures as shown in [8]. Various stiffening mechanisms for medical instruments have been developed in literature and have been extensively reviewed in [3]. For continuum like structures different rigidity control strategies have been applied such as phase change polymers [9], interlocking fibers [10], granular [12] or layer jamming [13] and systems based on cable tensioning [14]. Most of them can provide an on/off behavior with the exception of cable tensioning that by the way may suffer of backlashes and requires powerful actuators located in a proximal position. Layer and granular jamming seem promising technologies since they can provide tunable stiffness and still can be integrated in continuum like structures.

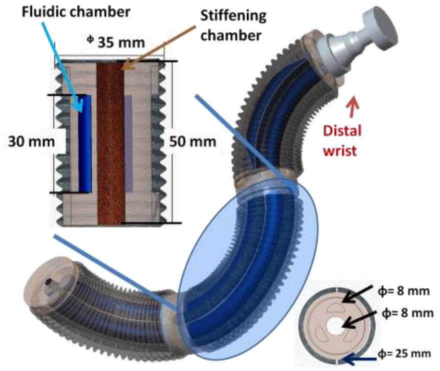

Fig. 1. Achitecture of the STIFF-FLOP arm and dimensions of a single module. On the left inset section of the single module, on the right inset cross section of the module.

Biological manipulators, such as the octopus arm and the elephant trunk, are considered an interesting source of inspiration, because they can manipulate objects while controlling the stiffness of selected body parts and being inherently compliant when interacting with objects [15]. Several soft manipulators were developed trying to emulate the capability that biological manipulators [16][17][18] have in manipulating objects while controlling their stiffness [15]. Soft robots present distributed deformation with theoretically an infinite number of degrees of freedom (DoF) and generate little resistance to compressive forces and thus easily conform to obstacles. In addition, they can squeeze through openings smaller than their nominal dimensions [19]. In this paper a variable stiffness soft manipulator for MIS is presented. Due to its soft structure it is able to elongate, squeeze and reach high bending angles. A stiffness mechanism based on granular jamming was integrated in the manipulator in order to be able to control its stiffness.

II. ARCHITECTURE OF THE MANIPULATOR AND DESIGN OF A SINGLE MODULE

The envisaged architecture is shown in Fig. 1. The manipulator will be composed of multiple modules, e.g. three modules, each of them capable of bending in all directions, elongating and stiffening independently. On the tip, a wrist will provide

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the necessary dexterity for orienting a surgical tool. The wrist is under development and will not be described in this paper.

In this paper the design and characterization of one single module is presented. The module of the manipulator is basically composed of a silicone cylinder. Inside this cylinder there are three equally spaced semi-cylindrical chambers in radial arrangement (the fluidic actuators) and another one centrally placed (for the stiffening mechanism) as shown in Fig.1.

A. Actuation system

Flexible fluidic actuators technology was exploited for moving the module. The use of such technology is facilitated by the available literature in terms of modeling [21][22] and application cases [23]. Optimal geometries for this specific system are under investigation, previous works comparing several cross section designs [24] concluded that the key factor is to find a trade-off between the thickness of the separation wall among the chambers and their diameter.

The dimensions of the module and the embedded chambers are reported in Fig. 1. The inflation of one chamber causes a small bending coupled with an outward expansion in the radial direction (Fig. 2). In order to constrain the lateral deformation maximizing the bending, a crimped braided sheath (like those used in McKibben actuators) is used around the module (Fig. 2, right). The sheath is fixed at the ends of the module and due to the crimped structure it allows high deformations of the module without affecting its flexibility. Since three chambers are embedded in the module bending in all directions is possible, actuating them both singularly or in combination. Elongation can be obtained by inflating all the three chambers at the same time with the same pressure.

B. Stiffening system

For stiffness modulation, a granular jamming solution is used. The effectiveness of this strategy on soft robots has been already demonstrated in [20], [25], [12], [26]. One of the main advantages of this technology is that it is highly deformable 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. The stiffening chamber is placed in the central cannel of the module (Fig. 1).


Figure 2. Effect of 0.32 bar pressure on a single fluidic chamber.

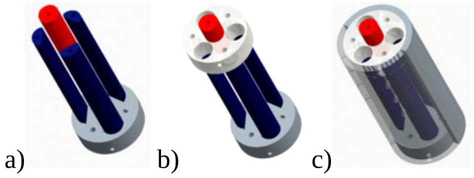

Figure 3. Assembling of the mold for the silicone cylinder hosting the three fluidic chambers and the central stiffening channel.

III. FABRICATION

The flexible fluidic actuator is fabricated by pouring silicone (Ecoflex™ 0050 – Smooth on Inc.) in an aluminum mold. As shown in Fig. 3a, the three chambers mold and the stiffening chamber mold are fixed to a base by screws and aligned on the top with alignment grooves (Fig. 3b). Two semi-cylindrical shells close the mold (Fig. 3c) and silicone is cast inside. After complete curing the two bases are removed and silicone is again cast to create a layer on top for closing the chambers. On one side three screws are left screwed in the fluidic chambers mold in order to keep a free channel for leaving space to insert the pipes.

The external crimped sheath is realized starting from an off-the-shelf flexible braided sheath (RS Components) with a maximum reachable inner diameter of 33 mm. The sheath is fitted in an aluminum cylinder 20 mm in diameter and compressed until the development of the crimped structure. The obtained 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.

The stiffening chamber is fabricated by filling 5 g of coffee powder in a latex membrane. It is then inserted in the central channel of the flexible fluidic actuator and fixed on top of it using silicone glue.

IV. EXPERIMENTAL CHARACTERIZATION OF A SINGLE MODULE

Pressurizing the three embedded fluidic chambers, bending in all directions and elongation can be obtained. Three pressure regulator valves (series K8P, E.V.P. systems) enable the modulation of the air pressure in each chamber. Pneumatic supply is provided by a compressor (Compact 106, Fiac Air-Compressors). Vacuum for stiffness modulation is generated by 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 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 in the fluidic chambers and the vacuum level in the stiffening chamber.

Bending and elongation performances of the module were characterized by inflating the fluidic chambers singularly, in pairs and all at the same time. The applied pressures ranged from 0 to 0.65 bar, with a step of 0.05 bar, and each test was repeated three times. At each step the bending angle was estimated from a static picture elaborated in MatLab. In the case of three fluidic chambers activation, elongation is obtained and the length variation was measured.

The force developed by the single module was measured by fixing a load cell (ATI Mini45) on the top of the module and actuating one fluidic chamber with a pressure ranging from 0 to 0.8 bar in isometric conditions (inset of Fig. 6). The same test was performed actuating two and three fluidic chambers.

The rigidity variation, due to the vacuuming of the stiffening chamber, was measured by imposing different displacements at the tip of the module in different configurations of it, by using a 6 DoF industrial robot (RV-6SL, Mitsubishi) with a load cell (ATI Mini45) mounted on its end effector. Three conditions were tested: a) base condition (no actuation), Fig. 7a; b) 90 deg bending condition, lateral displacement of 16.5 mm along the *-y* direction, Fig. 7b; c) 90 deg bending condition displacement of 8 mm on the upper base (*-z* direction), Fig. 7c. The tests were carried out both at atmospheric pressure and at the 1.5 psi vacuum pressure. Each test was repeated three times. Forces necessary for the above displacements were recorded.

V. RESULTS AND DISCUSSION

In Fig. 4 the bending angle as a function of the input pressure is presented. For low pressures the increase in the bending angle is low since the expanded chamber is starting to interact with the braided sheath. At higher pressure the interaction becomes more effective due to the volume increase leading to a considerable improve in bending. Beyond 0.55 bar the bending capability seems to reach saturation since the portion of the braided sheath, located externally along the bending plane, reaches its maximum elongation capability and starts limiting the achievable angle. Bending angles of up to 120 deg were measured. When the two chambers are actuated simultaneously a similar behavior is shown, but the saturation occurs at lower angles since the simultaneous activation of the two chambers causes a faster saturation of the available volume. In this case, the reachable bending angle is lower (80 deg) but the bending radius is bigger.

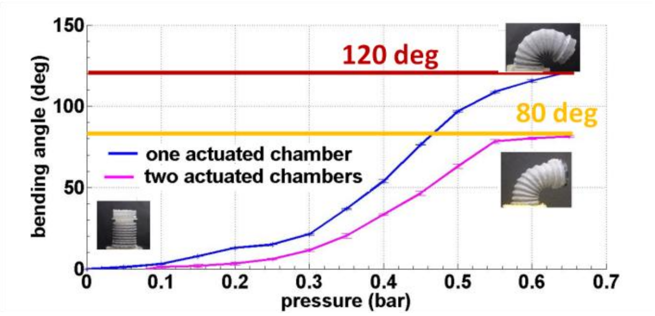

Figure 4. Bending capability of the single module under the action of increasing pressure.

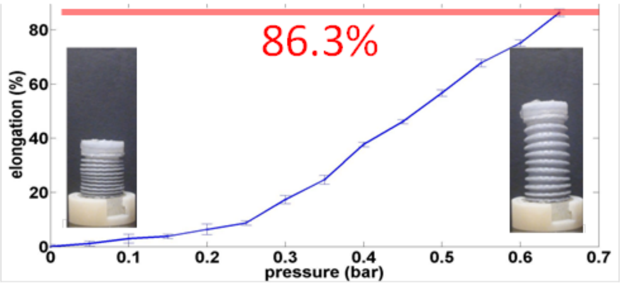

Figure 5. Elongation capability of the module under the action of increasing pressure applied simultaneously to all the chambers (values on *x* axis refer to the pressure of every single chamber).

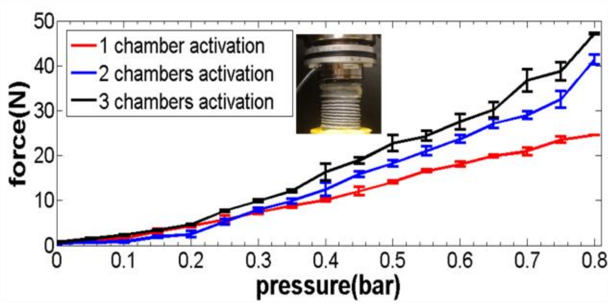

Figure 6. Isometric force developed by the module.

Elongation (Fig. 5) was obtained by activating the three chambers simultaneously: with an activation pressure of 0.65 bar in each chamber, a final length of 83.3 mm was measured, corresponding to an elongation of 86.3%.

The force developed by a single module in isometric conditions and activating different chambers is reported in Fig. 6. One single chamber is able to generate 24.6 N increasing almost linearly respect to the input pressure. In the case of two and three chambers activated the force reaches 41.4 N and 47.1 N respectively.

The activation of the stiffening chamber demonstrated the possibility to change the rigidity of the module. The first test carried out on the module at base condition (Fig. 7a) 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 as expected since the internal channel is deformed together with the module and its cross section is reduced (Fig. 7b, c). In *y* direction the maximum stiffness increase is equal to 12.4%, and in *z* direction it is 17.2%. For low imposed displacements the plots in Fig. 7 show a similar trend resulting 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. In Fig. 7c this phenomenon is not present since the displacement is applied directly to the stiffening channel.

The results underlined that it is not possible to generate a complete shape locking of the module. However, a remarkable increase of the stiffness in the different configurations was demonstrated, leading to an improvement of the stability of the robot during the surgical operation, and enabling to comply with the surgical environment.

VI. CONCLUSION

In this paper the concept design of a new modular manipulator for MIS has been presented. One single module composing such manipulator was fabricated and characterized. The single module successfully combines omnidirectional bending, elongation capability, and selective stiffness changing. In addition, since the module does not contain any rigid components, it can be squeezed by the user for fitting it into smaller diameter holes.

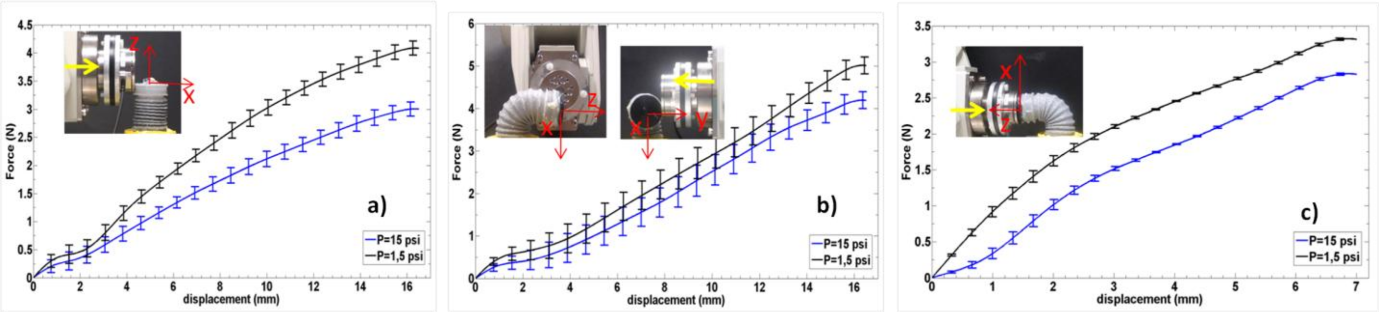

Figure 7. Stiffening variation tests: the module has been tested in base condition (a) 90 deg bending position along y (b) and z (c) direction.

VII. ACKNOWLEDGMENT

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REFERENCES

[1] V. Vitiello, S. Lee, T. Cundy, G. Yang, “Emerging Robotic Platforms for Minimally Invasive Surgery”, IEEE Rev Biomed Eng. 2012.

[2] L. Vyas, D. Aquino, C.-H. Kuo, J. S Dai, P. Dasgupta, “FLEXIBLE ROBOTICS”, BJU International 107, 2011, pp.187-189.

[3] A. Loeve, P. Breedveld, and J. Dankelman, “Scopes too flexible...and too stiff,” Pulse, IEEE, vol. 1, no. 3, 2010, pp. 26 –41.

[4] A. Bajo, R. E. Goldman, W. Long; D. Fowler, N. Simaan, "Integration and preliminary evaluation of an Insertable Robotic Effectors Platform for Single Port Access Surgery," Robotics and Automation (ICRA), 2012 IEEE International Conference on , pp.3381,3387

[5] A. Degani, H. Choset, B. Zubiate, T. Ota, M. Zenati, "Highly Articulated Robotic Probe for Minimally Invasive Surgery," IEEE International Conference EMBS, pp.3273-3276, 2008.

[6] N. Simaan, et al. "Design and integration of a telerobotic system for minimally invasive surgery of the throat." The International journal of robotics research 28.9 (2009): 1134-1153.

[7] P. J. Swaney et al “Minimally-Invasive Intracerebral Hemorrhage Removal Using An Active Cannula” 2013 IEEE International Conference on Robotics and Automation (ICRA), 2013

[8] I.Gravagne, I.Walker, “Manipulability, force, and compliance analysis for planar continuum manipulators,” IEEE Trans. Robot. Autom., vol. 18, no. 3, pp. 263–273, Jun. 2002.

[9] AJ Loeve, JH Bosma, P Breedveld, D Dodou, J. Dankelman “Polymer rigidity control for endoscopic shaft-guide ‘Plastolock’ a feasibility study”. Trans. ASME—J. Med. Dev 2010

[10] M. S. Moses, M. D. M. Kutzer, H. Ma, M. Armand, “A Continuum Manipulator Made of Interlocking Fibers” 2013 IEEE International Conference on Robotics and Automation (ICRA), 2013

[11] G. Salvietti, D. Prattichizzo, M. Niccolini, T. Ranzani, A. Menciassi "A task priority approach for modular robots in minimally invasive surgery" ICRA 2012 workshop: Modular Surgical Robotics: how can we make it possible?

[12] A. Loeve, O. S. van de Ven, J. G. Vogel, P. Breedveld, J. Dankelman. “Vacuum packed particles as flexible endoscope guides with controllable rigidity”. Granular matter 2010: 543-554.

[13] Y.-J. Kim, S. Cheng, S. Kim, K. Iagnemma, "A Novel Layer Jamming Mechanism With Tunable Stiffness Capability for Minimally Invasive Surgery," Robotics, IEEE Transactions on , vol.PP, no.99, pp.1,12, 0

[14] T. M. Huh, Y-J Park, K-J Cho, “Design and analysis of a stiffness adjustable structure using an endoskeleton” International Journal of Precision Engineering and Manufacturing, 2012, Vol. 13, Issue 7, pp 1255-1258

[15] K. K. Smith and W. M. Kier “Trunks, tongues, and tentacles: Moving with skeletons of muscle”, American Scientist 77 (1), 1989, pp. 28–35.

[16] W. McMahan, et al "Field trials and testing of the OctArm continuum manipulator", Robotics and Automation, Proceedings IEEE International Conference on , 2006, pp. 2336–2341.

[17] C. Laschi, et al “A Soft Robot Arm Inspired by the Octopus”, Advanced Robotics (Special Issue on Soft Robotics), 26 (7) pp. 709-727, 2012.

[18] V. Ramses Martinez, et al “Robotic Tentacles with Three-Dimensional Mobility Based on Flexible Elastomers”, Advanced Materials, vol. 25, issue 2, 2013, pp 205–212.

[19] D. Trivedi, C. D. Rahn, W. M. Kier, I. D. Walker, (2008). Soft robotics: Biological inspiration, state of the art, and future research. Applied Bionics and Biomechanics, 5(3), 99-117.

[20] N. G. Cheng, et al "Design and Analysis of a Robust, Low-cost, Highly Articulated manipulator enabled by jamming of granular media", Robotics and Automation (ICRA), IEEE International Conference on , 2012, pp.4328–4333.

[21] R. J. Webster III and B.A. Jones, “Design and Kinematic Modeling of Constant Curvature Continuum Robots: A Review” *The International Journal of Robotics Research*, 2010.

[22] K. Suzumori, S. Iikura, H. Tanaka, "Flexible microactuator for miniature robots", Micro Electro Mechanical Systems, MEMS '91, Proceedings. An Investigation of Micro Structures, Sensors, Actuators, Machines and Robots. IEEE , vol., no., pp.204-209, 1991.

[23] A. D. Greef, P. Lambert and A. Delchambre, “Towards flexible medical instruments: Review of flexible fluidic actuators” Precision Engineering, 33, pp. 311 – 321, 2009.

[24] K. Suzumori, T. Maeda, H. Watanabe and T. Hisada, “Fiberless Flexible Microactuator Designed by Finite-Element Method” *IEEE/ASME transactions on mechatronics*, vol. 2, no. 4, pp 281-296, 1997.

[25] E. Steltz, A. Mozeika, J. Rembisz, N. Corson, H.M. Jaeger,“Jamming as an Enabling Technology for Soft Robotics,” *2010 SPIE Conf. on Electroactive Polymer Actuators and Devices*, San Diego, CA, 2010.

[26] A. Jiang, A. Ataollahi, K. Althoefer, P Dasgupta, T. Nanayakkara, “A Variable Stiffness Joint by Granular Jamming” Proceedings of the ASME 2012 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference IDETC/CIE 2012.