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Tendon-based stiffening for a pneumatically actuated soft manipulator

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Abstract— **There is an emerging trend towards soft robotics due to its extended manipulation capabilities compared to traditionally rigid robot links, showing promise for an extended applicability to new areas. However, as a result of the inherent property of soft robotics being less rigid, the ability to control/obtain higher overall stiffness when required is yet to be further explored. In this paper, an innovative design is introduced which allows varying the stiffness of a continuum silicon-based manipulator and proves to have potential for applications in Minimally Invasive Surgery. Inspired by muscular structures occurring in animals such as the octopus, we propose a hybrid and inherently antagonstic actuation scheme. In particular, the octopus makes use of this principle activating two sets of muscles - longitudinal and transverse muscles - thus, being capable of controlling the stiffness of parts of its arm in an antagonistic fashion. Our designed manipulator is pneumatically actuated employing chambers embedded within the robot's silicone structure. Tendons incorporated in the structure complement the pneumatic actuation placed inside the manipulator's wall to allow variation of overall stiffness. Experiments are carried out by applying an external force in different configurations while changing the stiffness by means of the two actuation mechanisms. Our test results show that dual, antagonistic actuation increases the load bearing capabilities for soft continuum manipulators and thus their range of applications.**

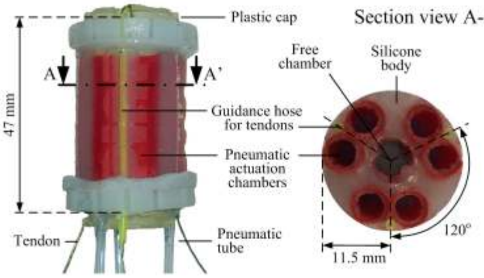

Fig. 1. Sideview and crosssection view of a segment of the STIFF-FLOP manipulator with integrated stiffening mechanism based on the antagonistic principle: three pairs of pneumatically actuated chambers are embedded into a silicone body and combined with three stretchable silicone tubes integrated inside the wall of the manipulator to guide tendons for stiffening. At the tip of the robot arm, the tendons are securely fixed to a plastic cap; one the other end, the base, the tendons are connected to three actuators.

I. INTRODUCTION

Taking inspiration from nature, researchers have created new robotic systems to overcome limitations of traditional robots composed of rigid joints and links [1]. In particular, animals' appendages such as the elephant trunk or the octopus arm have become the focus of studies creating soft, hyper-redundant robots, with capabilities similar to those of the biological role models [2]–[5]. The application of these types of robots can result in significant improvements within a number of fields where traditional robots are currently deployed [6]–[8]. One of these areas is Minimally Invasive Surgery (MIS) - also called laparoscopic or keyhole surgery [9], [10]. Most commonly, during minimally invasive procedures, rigid laparoscopic instruments are inserted through so-called Trocar ports which are in turn inserted into a patient's abdomen through small incisions allowing surgeons to carry out surgical interventions inside the patient's body [11]. In particular during colo-rectal surgery, clinicians have observed considerable challenges when conducting keyhole procedures (such as the Total Mesorectal Excision (TME)) due to the limited manoeuvrability of the available surgical tools which are mostly rigid [11], [12]. It has been reported that soft robotics has great potential to overcome the aforementioned limitations [11]. A soft manipulator structure for MIS is beneficial because of increased dexterity and a more gentle interaction with soft tissue. A decreased risk of injury to healthy tissue is another benefit to be noted. The large number of Degrees of Freedom (DoFs) of a soft, continuum robot provides enhancements when navigating around organs inside the patient's body towards the target, rather than "cutting through". A challenging task when employing soft robots is how to exert effective forces against the environment and how to achieve an increased stiffness where required [13].

An overview on stiffening techniques for continuum robots is presented in Section II. Section III describes the proposed antagonistic actuation principle and summarises the scientific contributions of this paper. The mechanical design of the soft, stiffness-controllable robot arm is presented in Section IV along with the overall control architecture. Section V introduces the experimental methodology to validate the tunable stiffness mechanism and presents the paper's main achievements. Conclusions and future works are discussed in Section VI.

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II. BACKGROUND

In recent years, researchers have investigated several solutions to the complex problem of changing and controling the stiffness of soft manipulators. A silicone-based, pneumatically actuated soft robot arm has been developed as part of the EU-funded project STIFF-FLOP. STIFF-FLOP focuses on exploring the bio-mechanical characteristics of the octopus and attempts to extract relevant biological features to develop medical robotics systems for Minimally Invasive Surgery (MIS) [14] that are integrated with pose and force sensors [15]–[18]. Stiffness variation is realised with an embedded chamber within the silicone body filled with granules that can be jammed by applying a vacuum [13], [19]–[21]. Hence, the robot's configuration can be frozen once a desired configuration is achieved. The concept of polymeric artificial muscles described in [22] to actuate a robot manipulator was furthered in [23] by integrating granule-filled chambers which when exposed to varying degrees of vacuum could actuate, soften and stiffen the manipulator's joints. A similar concept is proposed in [24]. A hollow snake-like manipulator consists of multiple overlapping layers of thin Mylar film. By applying vacuum pressure, the friction between the film layers increases which results in a stiffening capability that is tunable. Researchers have further investigated smart materials to achieve different stiffness levels: A number of design parameters have been simulated and prototypes built/investigated in [25] in order to identify the impact of the overall structure on stiffness variation. In [26], the authors report on a thermally tunable composite for mechanical structures - the used flexible open-cell foam coated in wax can change stiffness, strength, and volume. Altering between a stiff and soft state and vice versa introduces a time delay as the material does not instantly react to the heating-up or cooling-down process. A similar approach has been chosen by [27]: a cPBE-PDMS composite has been created that can change its stiffness with in a duration of 6 s when exposed to an external voltage. Taking inspiration of sea cucumbers, a type of polymer nanocomposites has been explored in [28]. Being stimulated by a chemical regulator, a Young's modulus change was achieved and, hence, a variation in stiffness.

In our recent work, we have presented a new stiffening mechanism [29]–[32] inspired by the collaboration of longitudinal and transversal muscles in the tentacles of octopus. The created manipulator combines a pneumatic and tendon-driven actuation mechanism in an entirely soft outer sleeve. The hybrid actuation mechanism and design of the manipulator result in a new type of robotic manipulator that can collapse entirely, extend along its main axis, bend along the main axis and vary its stiffness. The proposed robot arm is inherently flexible, manufactured from segments that consist of an internal stretchable, air-tight balloon and an outer, non-stretchable sleeve preventing extension beyond a maximum volume. Tendons connected to the distal ends of the robot segments run along the outer sleeve allowing the sleeve to bend when the coorresponding tendon is pulled.

In this paper, the hybrid actuation principle has been transferred to a silicone-based soft robotic manipulator created within EU FP7 project STIFF-FLOP. The contributions of this paper are as follows:

- The antagonistic actuation principle (pneumatic and tendon-driven actuation) is applied to a soft robotic segment made of a silicone structure, extending from the manipulator structure described in [29]–[32], which is composed of a fabric sleeve with an internal latex bladder.
- Pneumatic actuation is used to bend and elongate the robotic arm (i.e. manoeuvring the robot's tip); tendon actuation is used to effectively lock the robot's configuration and, hence, increase its stiffness in the achieved pose.

Our work here shows the potential of "hybridising" soft robots with a tendon-based actuation type, to achieve stiffening, similar to what can be achieved using granular jamming.

III. BIO-INSPIRATION

The work presented in this paper has been inspired by biology - especially by the octopus with its soft tentacles and virtually infinite number of degrees of freedom (DoFs). Biologically studies identified that the octopus arm is composed of longitudinal and transverse muscle groups that are bonded by connective tissue [33]. The octopus is capable of actuating the different types of muscles in such a way that it can control the stiffness of its arm, enabling the animal to catch fish, move stones or even walk across the seabed.

Taking inspiration from the antagonistic behaviour of the octopus arm, our robotic manipulator makes use of two fundamental actuation means, pneumatic actuation and tendon-based actuation, able to oppose each other and thus capable of varying the arms' stiffness over a wide range. The proposed antagonistic actuation method unites the advantages of intrinsic, pneumatic and extrinsic, tendon-driven actuation. Tendon-based actuation is beneficial for applications requiring accurate position control with high payloads in a miniaturised robotic system. This is achievable due to the thin structure and high tensile strength of tendons. Electrical drives used to displace the length of each tendon are located outside the manipulator [34], [35]. Pneumatic actuation is suitable for driving compliant manipulators that operate in the vicinity of humans and, hence, need to be inherently safe. The application of this hybrid actuation principle to a silicone-based soft manipulator has the following characteristics:

- Air pressure is used for stretching out and controlling the motion and direction of the soft manipulator resulting in bending and elongation.
- The compliance of the manipulator is varied by changing the stiffness, through the appropriate control of the two opposing actuation means, pneumatic and tendon-based actuation.

The ability to achieve variable stiffness in a confined operational space of inside a patient's body is what we seek to employ for MIS by exploiting the proposed antagonistic manipulation approach.

TABLE I

TECHNICAL PROPERTIES OF ECOFLEX® $00-50$ SUPERSOFT SILICONE[1]

Shore Hardness	Tensile Strength	Elongation at Break
$00-50$	315 psi	980%

IV. INTEGRATION OF THE ANTAGONISTIC STIFFENING MECHANISM

As mentioned earlier, the work described in this paper is the result of transferring the antagonistic actuation principle presented in [29]–[32] to a soft robot, such as the one developed in the EU FP7 project STIFF-FLOP: one segment of the STIFF-FLOP manipulator (see Figure 2) is a cylinder of silicone made of Ecoflex® $00-50$ Supersoft Silicone with material properties as shown in Table I. The segment has an overall length of 47 mm and an outer diameter of 23 mm. Along the wall of this cylinder, three pairs of fibre-reinforced pressure chambers (6 mm diameter) are implemented and actuated pneumatically. Each pair of chambers is connected to one inlet air pipe creating the ability to bend the segment by increasing the air pressure in one chamber pair relative to the other two chamber pairs. Simultaneous pressurisation of the all dual chambers will result in an overall elongation of the segment. It is noted that the created segment (Figure 2) has an inner free chamber of 9 mm diameter - this space is incorporated to pass through tubes from additional segments and wires when creating a manipulator with a series of multiple segements. A detailed description of the STIFF-FLOP manipulator can be found in [9], [10], [21].

A. *Embedding tendon-driven actuation into a STIFF-FLOP segment*

The tendon-driven actuation mechanism is embedded into a single cylindrical silicone segment modelled after the STIFF-FLOP manipulator [10]. Figure 2 shows a side and cross-sectional view of the robot arm with the integrated antagonistic actuation principle. In this prototype, a stretchable, silicone-based tube (Cole-Parmer Instrument Co. Ltd.) with an outer diameter of 1.5 mm and an inner diameter of 0.8 mm is aligned in between each set of the fluidic chambers, parallel to the longitudinal axis of our robot. The three hoses are placed 120° from each other and housing the tendons for extrinsic actuation. This design will allow the tendons sliding within the tubes and avoiding any cuts into the silicone body. Due to the tube's material properties, the STIFF-FLOP segment keeps its key characteristics of being soft and squeezable; the silicone tubes move in a compliant way when intrinsically actuating the robot.

The used tendons are braided microfilaments (PowerPro Super Line) of 0.15 mm diameter. The three tendons are fixed to a plastic cap at the tip of the robot arm to distribute forces onto the soft tip surface when under tension. The overall structure is shown in Figure 2.

B. *Setup of the antagonistic actuation architecture*

The overall actuation system consists of an air compressor, three pressure regulators, a data acquisition board (DAQ), three stepper motors, and a modified STIFF-FLOP segment as described in Section IV-A. Figure 2 illustrates the logical interconnection between the installed equipment.

As mentioned earlier, a hybrid actuation mechanism is employed here: On the pneumatic actuation side, an air compressor (BAMBI MD Range Model 150/500) supplies the required pressurised air of 5 bar to three independent pressure regulators (SMC ITV0030-3BS-Q). Their outputs, which connect to the three chamber pairs of the soft module, are varied via input signals proportinoally controling associated chamber pressures in a range between 0.001 and 0.5 MPa. Each pressure regulator adjusts the outlet pressure for each chamber pair according to the command received from the computer through a DAQ board (NI USB-6411).

On the tendon side, each tendon is connected to a stepper motor (Changzhou Songyang Machinery & Electronics Co. SY57ST56-0606B) which provides a maximum holding torque of 0.59 Nm. Each stepper motor has a pulley attached to its output shaft which the tendon is wound around. The pulley has a 6.4 mm radius, which results in a maximum of 92.6 N of tension. Since one STIFF-FLOP segment has three tendons, three stepper motors are used. Each stepper motor is driven via a driver (Big Easy Driver ROB-11876) which communicates with the computer via a DAQ board. The computer runs a Windows based operating system; our software is written in C++.

V. TEST PROTOCOL, EXPERIMENTAL RESULTS AND DISCUSSION

A. *Methodology*

Several stiffness experiments have been carried out mounting the module upside down and applying forces to the tip. In all scenarios, a motorised linear mechanism is programmed

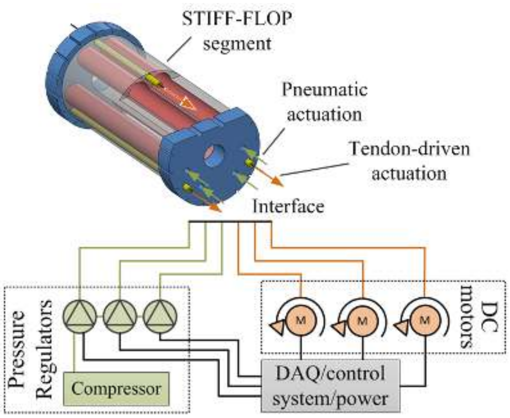

Fig. 2. Schematic overview of the antagonistic actuation setup: The air chambers are connected to three pressure regulators. An air compressor supplies pressurised air to the regulators. Each tendon is wound around a pulley which is fixed to the shaft of a stepper motor. The analogue input for the three motors and three pressure regulator is controlled via a data acquisition board.

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[1] Smooth-On, Inc. *Ecoflex® Series* Available on `http://www.smooth-on.com/tb/files/ECOFLEX\_SERIES\_TB.pdf`, Accessed on May 2015.

to create a displacement of $1\,\mathrm{cm}$ by sliding horizontally along its rails. Reaction forces created by the module to resist this displacement were recorded using a Nano17 Force/Torque sensor by ATI Industrial Automation. Three main scenarios were considered, equivalent to the investigations presented in [9], [14] (Hence, the obtained results will be comparable.):

Scenario 1:

The module is held vertically downwards. The force is applied laterally to the tip as shown in Figure 3(a). In this scenario, four different sub-cases are investigated:

A No air pressure and no tendon tension.

B Equally air-pressurised chambers (i.e. elongation) with no tendon tension.

C No air pressure with initial equal tendon tension.

D Equally air-pressurised chambers with initial equal tension in tendons.

Scenario 2:

The module is held vertically and one of the dual chambers is pressurised to form a 90° curved shape, and the force is applied laterally as shown in Figure 3(b). Two different sub-cases are investigated:

A One pressurized chamber and no tendon tension.

B One pressurized chamber and tension in tendons.

Scenario 3:

The module is pressurised to be configured as in Scenario 2. However, the force is applied opposing the tip as shown in Figure 3(c). Also in this scenario, two different sub-cases are investigated:

A One pressurised chamber and no tendon tension.

B One pressurized chamber and tension in tendons.

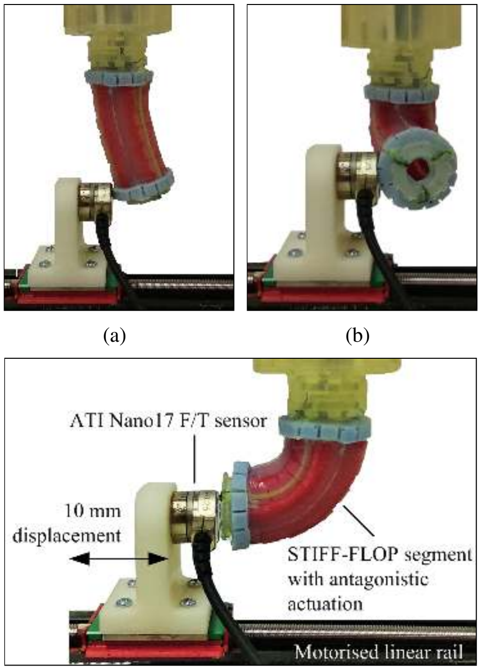
B. *Experimental results*

Data from the ATI Nano17 F/T sensor and the corresponding displacement of the motorised linear rail were recorded at $1\,\mathrm{kHz}$ using a DAQ card (NI USB-6211). Four trials were performed for each sub-case.

Experimental results of all four sub-cases of Scenario 1 are presented in Figure 4(a). When the module is neither pressurised nor stiffened by tendons, the amount of its resistive force subjected to a $1\,\mathrm{cm}$ lateral displacement is about $1.32\,\mathrm{N}$. This value is $0.55\,\mathrm{N}$ when all three chambers are pressurised. When subjected to tendon stiffening, the resistive forces displayed by the module reach values of $2.56\,\mathrm{N}$ and $0.93\,\mathrm{N}$, respectively, showing a 94% and 69% increase compared to the first and second sub-case.

Results of the two sub-cases of Scenario 2 are shown Figure 4(b). When the module is only pressurised, the value of the resistive force is $0.75\,\mathrm{N}$. With tendon stiffening is added to the module, this resistive force increases to $0.98\,\mathrm{N}$ showing a 31% growth.

Results of the two sub-cases for Scenario 3 are presented in Figure 4(c). It can be seen that in the presence of pressure only, the module generates a resistive force of $2.43\,\mathrm{N}$. However, by introducing tendon stiffening, the resistive force due to $1\,\mathrm{cm}$ displacement intensifies to $3.02\,\mathrm{N}$, displaying a 24% growth.



(a) (b)

(c)

Fig. 3. An ATI Nano17 Force/Torque sensor is mounted on a motorised linear mechanism displacing the manipulator's tip by $1\,\mathrm{cm}$: The configurations in (a), (b) and (c) show Scenarios 1, 2 and 3, respectively.

Table II summarises the calculated maximum stiffness results. For each sub-case, the maximum stiffness, hysteresis and percentage of increase is calculated. Hysteresis was calculated by taking the area between the loading and unloading curves, and normalizing it by dividing it by the loading curve.

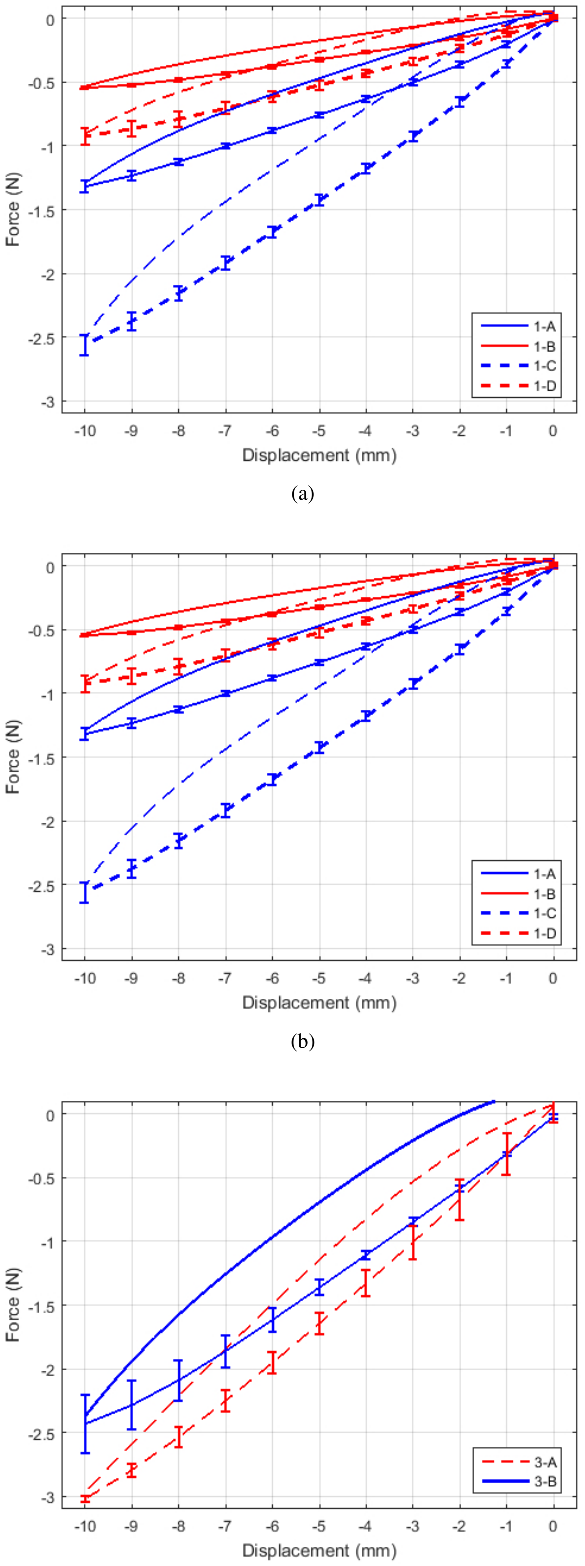
C. *Discussion*

Looking at the summary of the experimental results in Table II and Figure 3, using the antagonistic actuation principle allows us to increase the overall stiffness of the soft manipulator by almost 100%. Hence, the soft manipulator when tensioned using the tendons is more rigid and capable of performing tasks that require larger force exertions - as for example required at times in the tight environment inside a patient's body. This gives the surgeon the ability to move the manipulator about primarily with pressure actuation, and

TABLE II

SUMMARISED CALCULATED RESULTS OF MAXIMUM STIFFNESS K_{max} TESTS FOR SCENARIOS 1, 2 & 3.

Scenarios					K_{max}	Hyst.	Increase
1-A	Tens.	No	Press.	No	$1.32\,\mathrm{N/cm}$	21.6%	n/a
1-B	Tens.	No	Press.	Yes	$0.55\,\mathrm{N/cm}$	27.2%	n/a
1-C	Tens.	Yes	Press.	No	$2.56\,\mathrm{N/cm}$	18.9%	93.9%
1-D	Tens.	Yes	Press.	Yes	$0.93\,\mathrm{N/cm}$	28.5%	69.1%
2-A	Tens.	No	Press.	Yes	$0.75\,\mathrm{N/cm}$	21.8%	n/a
2-B	Tens.	Yes	Press.	Yes	$0.98\,\mathrm{N/cm}$	33.46%	30.7%
3-A	Tens.	No	Press.	Yes	$2.43\,\mathrm{N/cm}$	27.47%	n/a
3-B	Tens.	Yes	Press.	Yes	$3.02\,\mathrm{N/cm}$	14.86%	24.3%



(a)

(b)

(c)

Fig. 4. Experimental data for Scenarios 1, 2 and 3. Forces have been recorded for displacements of 1 cm of the manipulator's tip. Table II summarises the data analysis. The curves including the error bars show the loading cycle.

TABLE III

FORCE RESULTS FOR GRANULAR JAMMING APPLYING A 10 mm DISPLACEMENT AS REPORTED IN [9].

Scenarios	Granular jamming	K_{max}	Increase
1-A	Off	2.2 N/cm	n/a
1-A	On	3.1 N/cm	40.9%
2-A	Off	2.3 N/cm	n/a
2-A	On	2.7 N/cm	17.4%
3-A	Off	2.8 N/cm	n/a
3-A	On	3.3 N/cm	17.9%

thereafter, use the tendon stiffening to acquire not only higher stiffness, but also fine-tune the final position of the end effector, more accurately maneuvering the attached instrument to the desired target.

In [9], a 8 mm diameter channel of granular material, coffee, was embedded into a prototype of the silicone-based STIFF-FLOP segment; the length of this segment was 50 mm with the silicone structure having a diameter of 25 mm. The pneumatically actuated chambers were not reinforced; a crimped, braided sheath of a 35 mm covered the silicone structure and prevented a balooning effect. Neglecting the outer cover, the STIFF-FLOP module has dimensions similar to the ones of the segment described in this paper. The key experimental results for stiffness tests at a displacement of 10 mm are summarised in Table III. The test configurations of three scenarios are equivalent to the ones described in Section V-A - however, granular-jamming-based stiffening is achieved by applying a vacuum.

Comparing Tables II and III, the actual maximum forces F_{max} measured during the experimental tests of Scenarios 1 and 2 are larger using granular jamming. The presence of coffee granulars (under atmospheric or vacuum pressure) integrated into the silicone-based robot results in a stiffer module. Looking, however, at the percentage increase caused by granular jamming on the one hand and the antagonistic mechanism on the other hand, the tendon-based stiffening principle is able to generate a larger increase.

VI. CONCLUSIONS

In this paper, we have transferred the antagonistic stiffening principle presented in [29]–[32] to a segment of a silicone-based soft manipulator. The mechanism is inspired by the longitudinal and transverse muscle fibres that the octopus uses to stiffen its tentacles. In our soft robot, air pressure is used for bending and elongating the soft manipulator. Tendons are used to act in an antagonistic way opposing the pneumatic actuation, increasing stiffness. The experimental results obtained using the antagonistic actuation principle are compared to a similar study where stiffening is achieved using granular jamming. The advantages of pneumatic and tendon-based actuation are the simultaneous ability to control the robot's pose and stiffness. Tendon actuation could not only be used for stiffening as presented in this paper, but potentially allows more accurate position control. Since the tendons are embedded inside the manipulator's wall, this ability is achieved without increasing the diameter of the manipulator.

Future work will include the integration of this hybrid actuation principle into a miniaturised silicone-based manipulator suitable for minimally invasive surgery through a standard Trocar port. In addition, we will mathematically describe the behaviour and motion of a single antagonistically actuated soft manipulator. This model will be based on beam theory as proposed in [36]: the manipulator is divided into a series of layers whose kinematic change due to the effect of internal forces (from pressurised air and from tension applied by tendons) and externally applied forces. The layers are then superpositioned to describe the manipulator's tip position and orientation in space. We also intend to experimentally verify this model.

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