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New STIFF-FLOP module construction idea for improved actuation and sensing

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***Abstract*— MRI compatibility, which often is a requirement for the new medical soft robot projects, greatly reduces available actuation methods and sensors. An example of such project is STIFF-FLOP, which aims to develop a soft silicone manipulator actuated by pressure. The current arm construction and method of actuation cause several undesirable effects, which pose problems for actuation and sensing. In this paper, the authors identify the source of those negative effects and propose improvements over the current construction to eliminate or limit their influence. The new construction concept is tested and compared with the current one. Possible ideas for further development are also proposed.**

I. INTRODUCTION

A. STIFF-FLOP manipulator

Biological structures, such as the elephant trunk and the octopus arm, are inherently compliant when passively interacting with the environment, but their stiffness can be selectively varied and controlled to transform force into motion [1]. For this reason they have been largely considered as inspiration source for soft robotic arms and manipulators [2]–[8]. In the context of robotic surgery the advantages of using soft and compliant devices are undeniable at least from a safety point of view. But what really makes the use of a soft robotic instrument a dramatic innovation is the possibility to actively change its passive properties. This allows high mobility and dexterity in achieving the operation site and enables the capability of producing relatively high forces when necessary. This is the base concept instilled in the STIFF-FLOP manipulator [9]. Among the other possibilities, a combination of fluidic actuation (for omnidirectional bending and elongation) and a granular jamming based system (for stiffness variation) results to be the most effective both from performance and safety point of view [10]. Flexible Fluidic Actuators (FFA) have been already introduced in the medical field since a few years, but to the knowledge of the authors this represents the first attempt of combination of fluidic-based technologies to obtain such capabilities. Moreover, further then the already mentioned safety advantages, the use of soft materials implies the absence of metals, which confers a complete MRI-compatibility.

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Despite the complete description of the manipulator modules can be found in [9], here the main features are recalled for reader convenience (fig. 1). The module is composed of three fluidic chambers equally spaced in a radial arrangement embedded in an elastomeric cylinder (EcoFlex 00-50, Smooth-on Inc.). In the complete version the central part houses the stiffening channel which consists of a cylindrical membrane filled with granular material. Three length sensors are also housed in the space between the chambers and used to assess the spatial configuration of the modules while moving [15]. The entire structure is surrounded by a crimped braided sheath that limits the radial expansion of the chamber when inflated with a fluid enabling an effective and controllable motion of the actuator. Finally, despite not shown in this paper, structures like these can form multi-module manipulators by stacking and connecting more modules as shown in [8]. It is worth mentioning that the actuation system arrangement and the dimensions are still not optimized for any specific applications, but, in the current embodiment, the manipulator could be already suitable for retraction as well as for approaching and grasping organs. These kind of tasks require a safe and compliant interaction with tissues without high precision and the capability of changing stiffness when required. Moreover these prototypes resulted useful for early mechanical performance assessment and for identifying fabrication and interference issues (as demonstrated in the remainder of the paper).

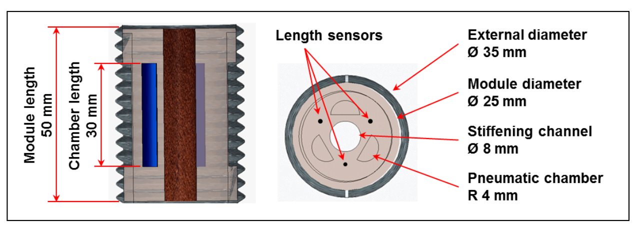


Fig. 1: Longitudinal (left) and transversal (right) section of the STIFF-FLOP manipulator module. The main components are reported: the central stiffening channel; the semi-cylindrical pneumatic chambers, the length sensors and the external braided sheath.

Once the functionalities of the integrated module have been demonstrated and quantified [9], the optimization process required the resolution of some basic issues related to the interference among the internal components of the module and in particular to the invasiveness of the fluidic chambers during their inflation. While the FFAs are very difficult to replace with other suitable and equivalent technologies, the stiffening variation can be obtained also exploiting other simple mechanisms. For example by introducing longitudinal cables which can be pulled to produce an antagonistic action to the chambers elongation. For this reason the current investigation is focused on the pressure chamber behavior, neglecting the granular jamming mechanism.

B. Sensing and actuation issues

The current STIFF-FLOP module design causes certain issues in sensing and actuation. Because the use of external braiding efficiently restrains outward inflation of the pressure chamber, its expansion is mostly directed in inward direction, which modifies the internal structure of the module. Among undesirable effects caused by this change of geometry are: nonlinear actuation, length sensor readings dependence on chamber pressures and complicated modeling. In the following sections the authors analyze the direct causes of those problems created by the braiding solution. The analysis is based on observation of module behaviour during several tests. To determine the character of internal processes inside the manipulator during actuation, special module had been fabricated. This module had been cut in the middle and sealed using transparent plexiglass tile, which allowed for observation of its interior.

1) Change of the chamber cross-section area: Application of pressure into actuation chamber causes it to change its cross-section area. Moreover, the area depends not only on the pressure inside the actuated chamber, but also on other chamber's pressures. Increase of the cross-section area causes the force resultant from the pressure acting on that cross section to increase its value. This results in the relation between internal force and pressure to be nonlinear. Because the cross-section area increase, the chamber sensitivity to pressure changes rises.

2) Chamber cross-section center displacement: The chamber internal inflation is not uniform. When actuating a chamber its initial semi-circular cross-section shape is not retained, because of constraints like other chambers and the external braiding. This causes the position of the chamber cross-section center to change depending on the pressure value. When actuating two chambers simultaneuosly, one can observe that the resulting bending angle is much lower that the one achieved when actuating a single chamber with the same pressure. This situation is presented on fig. 2. The source of the deformation of the module is a bending moment caused by pressure-induced forces. Assuming the pressure value p is constant at every point of the chamber volume, the value of interal force acting on a certain cross section center can be easily calculated [14]. Labeling vectors from the center of the cross-section to centers of each chamber as $\vec{r_1}$ and $\vec{r_2}$, the resulting moment bending the module can be expressed with:

$$M = (\vec{r_1} + \vec{r_2})F \tag{1}$$

The right hand side of fig. 2 presents the situation with pressure applied to two chambers simultaneously. The shape of the chamber cross-section changes and its geometrical center moves. Because of the internal layout of the module, the chamber centers shift towards the module center. This results in a decreased length of the net vector $\vec{r} = \vec{r_1} + \vec{r_2}$, which, in turn, leads to reduction in the value of the net bending moment deforming the module (eq. 1.

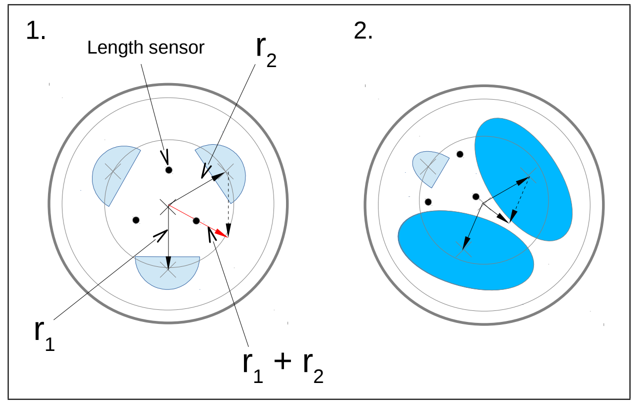


Fig. 2: Chamber cross-section center shift during two chamber simultaneous actuation. (1) presents unactuated state. In (2), the change of chamber cross-section shape causes the geometrical center shift and reduce the distance from module center. This, in turn, causes the resulting bending moment to be decreased

3) Silicone-sheath friction: The sheath applied to the module to prevent external chamber expansion has influence on its actuation behavior. In general, this causes the outcome of actuation to be dependent on the sequence of pressure application. Interaction between the outer silicone surface and the sheath causes a certain part of energy of the actuation to be wasted on friction, what results in achieving lower elongation for the affected chamber. An example of effect caused by this occurs when two chambers are actuated sequentially (fig. 3). Applying pressure to one of the chambers causes it to expand and increase its cross-section. This expansion pushes the module surface to make contact with the sheath and constrain the other two chambers. When actuating the second chamber with identical pressure, its volume is not allowed to expand to the same extent as the first one. The latter chamber expansion during actuation is therefore hampered by two factors: already expanded chamber volume and silicone-sheath friction. As an effect, the module is not capable of efficient bending in the directions requiring multiple chambers to be actuated, which greatly impacts the shape of achievable workspace when using constant pressure.

4) Sensor interaction: In the STIFF-FLOP project, one of the most important sensors used for estimation of the spatial arm configuration are three optical length sensors [15]. The sensors measure the length of three channels hollowed out in parallel to the pressure chambers. The channels are located on a circle coaxial with the module axis of symmetry (fig. 4). The effect of chamber expansion has significant influence on shape of the channels, which causes the sensor readings to additionally depend on pressure applied to the chambers.

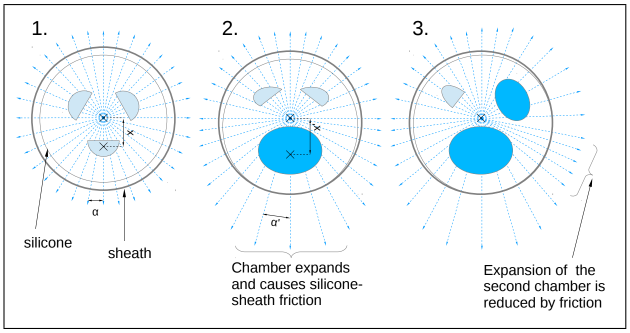


Fig. 3: Module cross-section during a two module actuation sequence. (1) presents the cross section with no pressures applied to the chambers. No friction between the sheath and silicone occurs. In (2), pressure is applied to one of the chambers. The chamber expansion causes the external sheath to make contact with the module body. The second chamber is constrained by the inflation and friction with the sheath (3)

The measured length is not the desired channel elongation, the value is increased by the channel deformations caused by chambers expanding. This effect makes sensor fusion unnecessarily complex.

Another critical source of information is the tactile sensor array, which is located on the surface of the manipulator. It provides data on the level of interaction with the environment. Use of external braiding around the whole robot creates issues with mounting such sensors. Integrating them with clean silicone surface that is available using the solution proposed in this paper is an easier task. More information on this type of sensors can be found in [16].

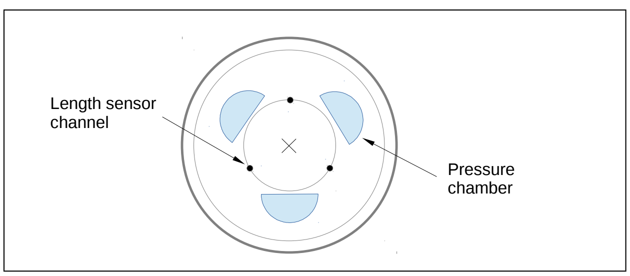


Fig. 4: The length sensor channel placement presented in a module cross-section. The channels are placed on a circle coaxial with the module axis of symmetry

C. Survey of possible solutions

The external braiding adopted as a possible solution in the current module demonstrated to be effective from a macroscopic point of view to limit the outward inflation and maximize the longitudinal effect of the chamber inflation, but due to the negative interferences with the module components other solutions have to be introduced. Similar examples of constraint can be found in the works by Whitesides and colleagues, that facing the same ballooning effect [5] developed a manufacturing process which allow the internal patterning of the chambers (PneuNets), reducing the lateral space available to produce outward expansion [12]. A different and simpler approach has been tried by Brock and colleagues with their PneuFlex, where inelastic yarns are placed all around the squared-section chambers [13]. This second approach has the advantage of being simpler and faster from the manufacturing point of view and as effective as the first one despite involving a manual fabrication step.

II. PROPOSED MODULE DESIGN

The authors of this work propose to eliminate or at least reduce the effect that is the source of the problems described in I-B, which, basically, is the change of chamber geometry during actuation. The key idea is to, instead of constraining the external expansion of all chambers with one external sheath, employ braiding around each chamber, constraining their expansion individually. The use of braiding around the chamber imposes limitation on its circumference. The chamber behavior during actuation will aim to maximize its cross-section area, and will finally reach a circular cross-section shape (without any external constraints like other chambers). Therefore, the authors propose to change the current shape of the actuation chamber to cylindrical. This solution also has the advantage of simplifying the manufacturing process. The concept is presented on fig. 5. The chambers are braided using a thin thread, which is applied in a tight helix around the chamber. This pattern allows for expansion in longitudinal directions and hampers the radial inflation.

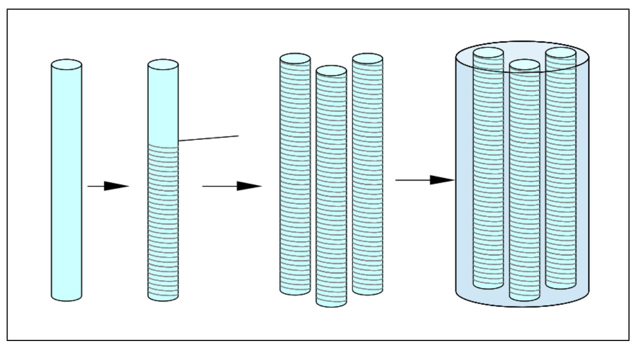
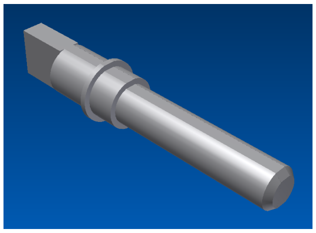


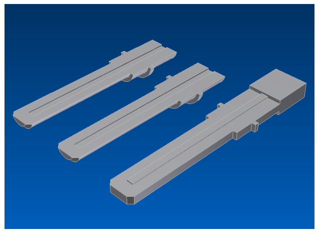
Fig. 5: Chamber braiding concept

III. MANUFACTURING

The manufacturing process consists of several silicone molding steps. First, three special chamber rods are prepared before the braiding step. Each rod is a cylinder with removable core (fig. 6). A 0.5 mm silicone layer is deployed onto each rod (fig. 7). Next, the rods with silicone layer are tightly braided using a low-diameter thread. The chambers prepared in this way are then inserted into the final mold, where the main silicone module cylinder is produced (fig. 8). After the silicone cures, the chamber rods are removed by first removing their cores. The last steps involve sealing the base of the module, inserting rubber or silicone tubes and hardening the top with an additional silicone layer.



(a) Chamber core assembled.



(b) Chamber core rod parts

Fig. 6: Chamber core rod design

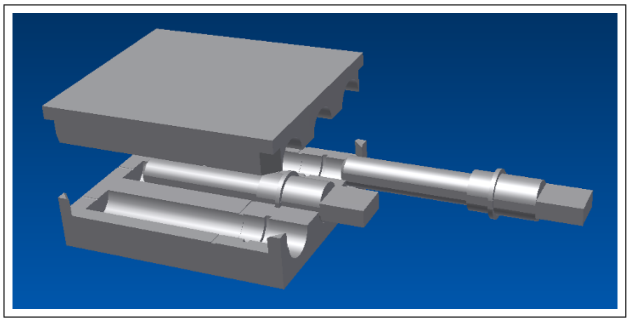


Fig. 7: Step one of the manufacturing process – molding a 0.5mm silicone layer on the chamber core rods

IV. TESTS

A STIFF-FLOP module for testing purposes has been crafted using the manufacturing process described in section III. Several tests have been performed on the new design in order to characterize it and assess the scope of undesirable effects that are present in the previous construction. The module geometry has been preserved, with two exceptions, the first one being the modified chamber cross-section shape described in section II. Additionaly, the stiffening chamber hollowed out in the center of the module has been omitted, as already explained.

A. Air actuation

Actuation using air is the basic method of actuation used in the STIFF-FLOP project. First, bending of both designs have been tested for the relation between pressure applied to chambers and resulting bending angle. For this, a range of pressure values has been applied to single and two chambers of the new module and, for comparison, the current module. The test setup is presented on fig. 9. The pressure applied has been measured by a digital pressure sensor, which is not visible in this picture. The plots from figures 10 and 11 present the results for the current and new design, respectively. It can observed that the new design operates on higher pressure values. This can possibly be explained the fact that in the current design, the chambers are allowed to expand internally and, to some extent, externally. The increase in the chamber cross-section causes greater force to be exert with the same value of pressure applied. This results in bigger sensitivity with increasing pressure, while ideally, with non-expanding chambers, the relation between the achieved bending angle and pressure applied to the chamber should be linear [14]. The increased linearity introduced by the new design indicates successful limitation of the internal expansion effect.

While the function for the current design saturates at high pressures, disallowing achieving of more bent shapes, the new design is capable of reaching greater bending angle values. When pressure is applied to two chambers of the current module simultaneously, the resulting bending angle values are lower, when compared to single chamber actuation with the same pressure. This is probably caused by the effect described in section I-B.2. The new design does not display such behavior - for the same pressures applied, the bending angle values for two chamber actuation are higher that one chamber actuation.

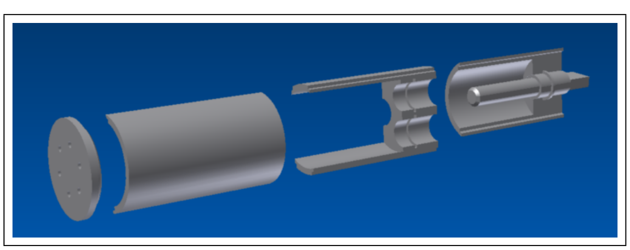


Fig. 8: Step two of the manufacturing proces – molding the final module cylinder with braided core rods inside

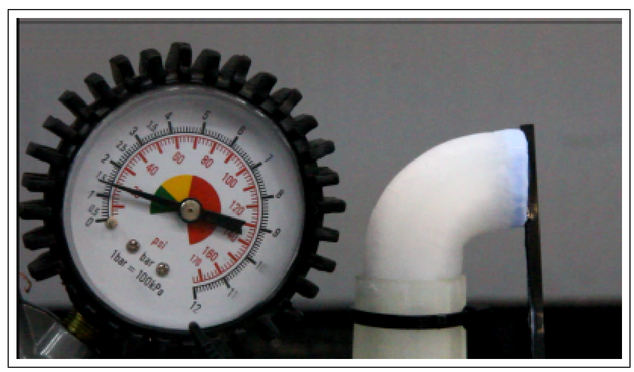


Fig. 9: Test setup for measuring module bending by applying pressure into module chambers

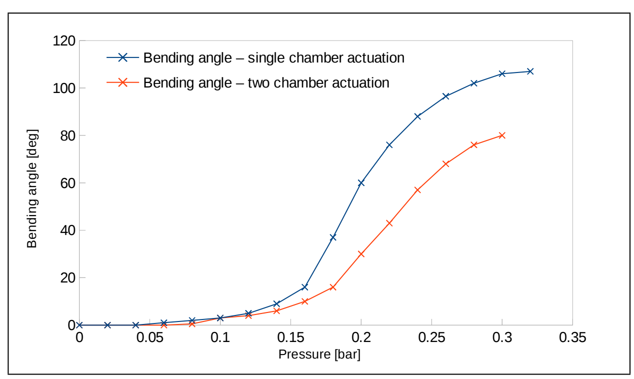


Fig. 10: Bending angle achieved for certain values of pressure applied for the current design

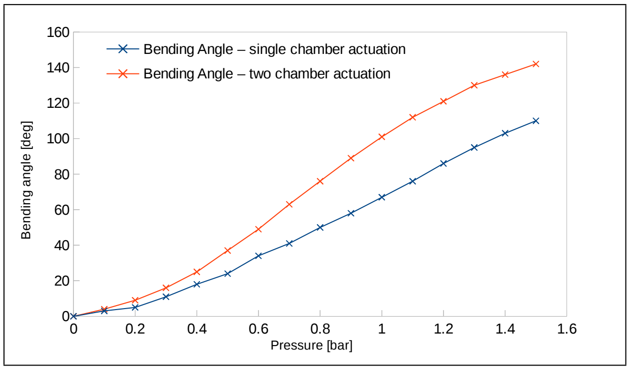


Fig. 11: Bending angle achieved for certain values of pressure applied for the new design

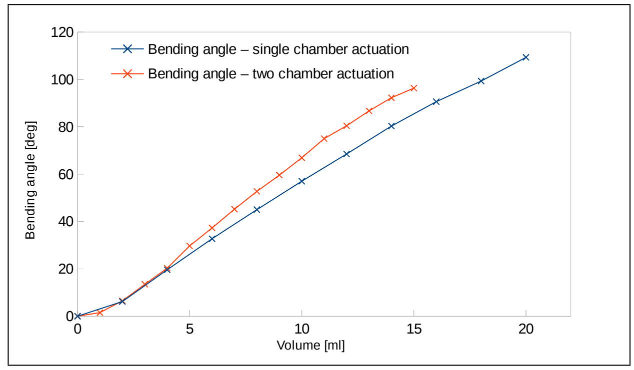


Fig. 13: Bending angle achieved for certain values of liquid volume injected into chambers of the current module

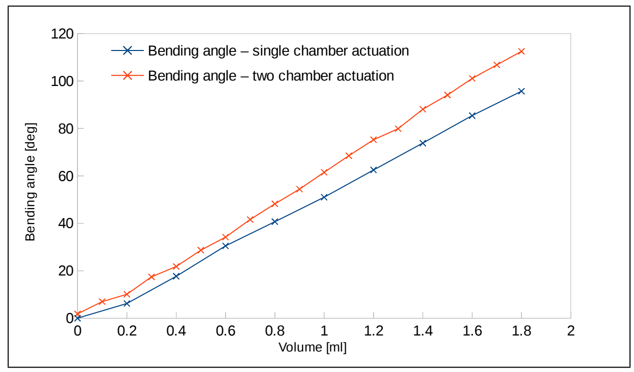


Fig. 14: Bending angle achieved for certain values of liquid volume injected into chambers of the new module

B. *Water actuation*

For further proof of the limited chamber expansion effect in the new design, both modules have been also directly for the chamber volume increase for achieving certain bending angles. An incompressible liquid such as water has been used for injecting into the chambers. The liquid has been injected into chambers using syringes. The test setup used for this experiment is presented on fig. 12. The bending angle/volume injected relation for the current and the new design are presented on plots from figures 13 and 14, respectively. It can be observed that drastically lower volumes of liquid are required by the new module to achieve a certain bending angle. The relative increase of volume to achieve certain bending angle values is approximately ten times greater for the current module (2500% compared to 250% for the bending angle of 110 degrees)

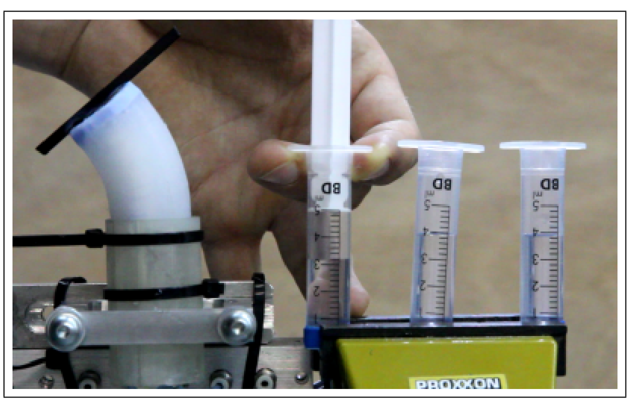


Fig. 12: Test setup for measuring module bending by injection of certain amount of incompressible liquid

C. *External force*

Another test has been performed in order to determine whether the new internal braiding has negative influence on the module behavior during bending by external forces. The bending angle caused by application of external force has been measured for two modules: with and without braiding around the actuation chambers. The test setup is presented on fig. 15 and the resulting plots on fig. 16. It can be observed that the influence of the presence of individual chamber braiding has effects, which our measurement setup have not detected. For our purposes, it is correct to assume that the braiding has no influence on the module bending by external force.

Tests for determining the influence of the braiding on elongation have also been performed. A range of longitudinal force values has been applied to the same modules as in the previous test, using an analog force gauge. The test setup is presented on fig. 17 and the results on fig. 18. Again, the influence of chamber braiding on has not been captured during this experiment, and it is safe to assume that it has no influence on elongation.

V. CONCLUSIONS

Tests performed on the new module design have confirmed the limitation of the negative effects caused by chamber expansion. This allows for easier data fusion and modeling, and influences positively other areas of the STIFF-FLOP projects. Moreover, other FFA-based soft robots can also benefit from this solution. The next step for development of this idea can be automating the manufacturing process, especially the chamber braiding step. Additionally, different actuation chamber setups will be tested to maximize the unused space inside the silicone cylinder, which is important for different pressure tubes and sensor cables running through from upper modules to the base.

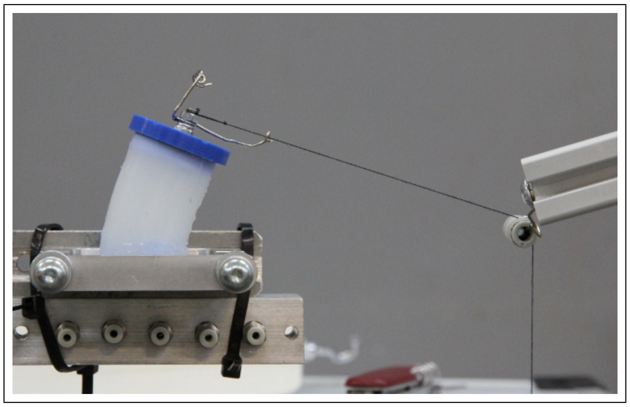


Fig. 15: Test setup for measuring the individual chamber braiding influence on module bending by external force

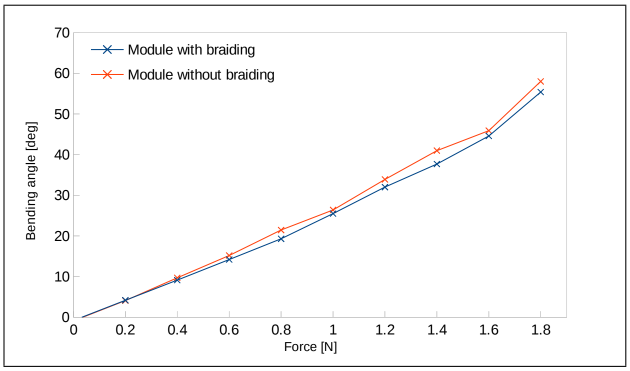


Fig. 16: Bending angle achieved by the modules with and without individual chamber braiding when applying external force

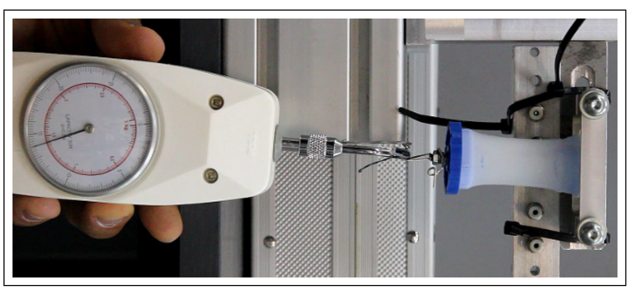


Fig. 17: Test setup for measuring the individual chamber braiding influence on module elongation by external force

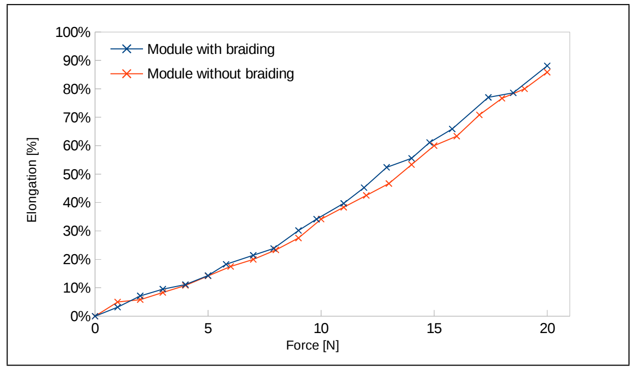


Fig. 18: Elongation achieved by the modules with and without individual chamber braiding when applying external force

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