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Octopus-Inspired Soft Arm with Suction Cups for Enhanced Grasping Tasks in Confined Environments

Barbara Mazzolai, Alessio Mondini, Francesca Tramacere, Gianluca Riccomi, Ali Sadeghi, Goffredo Giordano, Emanuela Del Dottore, Massimiliano Scaccia, Massimo Zampato, and Stefano Carminati*

Octopuses have impressive manipulation capabilities empowered by the intrinsic adaptation of their soft arms combined with distributed suckers. Drawing inspiration from the arm morphology and abilities of the octopus, the integrated design of a conical soft robotic arm endowed with suction cups is presented herein. The proposed arm exploits soft robotic technologies as in materials (combining stiff and soft silicones) and actuation (tendons to drive motion and fluidic channels for suction cup actuation) for retrieving objects in confined spaces of unknown shapes and sizes. The soft arm is able to grasp varied and complex-shaped objects, to move in air, water, and oil, and to retrieve items immersed in a 70 mm diameter pipe, under pressure (up to 18 bar). Suction cups enable the arm to retrieve objects that would be impossible to grasp without them and help in improving the grasping force up to ≈1.4 times in air, ≈2.4 times in water, and ≈12.5 times in oil. The enhanced holding force (up to 3.3 N, ≈3.9 times arm weight) and a wide spectrum of objects negotiable by the arm make it a universal tool for object retrieval in confined spaces and wet conditions.

1. Introduction

Exploration and manipulation in harsh environments and complex areas remain an interesting and challenging issue for robotics.[1,2] Working environments, such as those represented by the oil and gas sector of the energy industry, are difficult to access, due to their potentially explosive atmosphere and the combination of high pressure, high temperature, and aggressive fluids.[3] There is thus a huge demand for new abilities in robots to enable them to quickly conform and adapt their body and behavior, while safely operating in those conditions.[4,5]

Soft robotics has gained importance due to many of the above challenges, aimed at transferring the working principles from soft-bodied living organisms to robotics.[6] The passive and safe adaptation of soft-bodied robots has been widely explored in relation to manipulation activities,[7] also considering difficult operative conditions. For instance, soft grippers have been adopted in unknown, unstructured environments such as the deep sea,[8,9] to grasp unfamiliar objects with variable and irregular shapes[10] or hazardous surfaces.[11] Soft robotic arms have been successfully tested in real-world applications with challenging configurations or limited resources.[12–18] Softness, in these cases, is exploited to improve and simplify grasping tasks by reducing control complexity: the high precision required by rigid grippers and manipulators is here entrusted to the intrinsic compliance of soft systems. Soft robotics and bioinspiration are therefore useful and effective approaches to push robotic systems where it was not possible before.

Dr. B. Mazzolai, Dr. A. Mondini, Dr. F. Tramacere, G. Riccomi, Dr. A. Sadeghi, G. Giordano, Dr. E. Del Dottore, Dr. M. Scaccia
Center for Micro-BioRobotics
Istituto Italiano di Tecnologia (IIT)
Viale R. Piaggio 34, 56025 Pontedera, Italy
E-mail: barbara.mazzolai@iit.it

G. Giordano
The BioRobotics Institute
Scuola Superiore Sant'Anna
56025 Pisa, Italy

The ORCID identification number(s) for the author(s) of this article can be found under https://doi.org/10.1002/aisy.201900041.

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S. Carminati
Research and Technological Innovation Center
Eni S.p.A.
Via F. Maritano, 20097 San Donato Milanese, Italy

M. Zampato
Technical Division
EniProgetti S.p.A.
Via Antonio Pacinotti 4, 30175 Venezia, Italy

Dr. M. Scaccia
Advanced Robotics Department
Istituto Italiano di Tecnologia
Via Morego, 30, Genoa 16163, Italy

Research in this field is very dynamic and has attracted the interest of companies.[19]

For instance, in the oil and gas sector, the need for robotic technologies typically converges on the inspection, maintenance, and repair of plant facilities.[20] Considering harsh environments and the strict operative requirements of the energy industry, in-pipe inspection soft-bodied robots can offer a different paradigm in robotics, as they are able to conform their shape and morphology to the external objects and environment, opening new application scenarios and tasks not achievable with rigid working tools.

In this view, a bioinspired approach in soft robotics represents an innovative way to rethink robot design proposing new strategies, new patterns of movement, and new sensing or actuation abilities to build innovative robotic systems, supporting the effectiveness of soft bodies, as living organisms exploit soft tissues and compliant structures to move in complex natural environments.[21–24]

Among many organisms that can provide new ideas for designing robots useful in inspection and grasping in confined and unstructured environments, octopuses show many of the abilities required for this particular application (**Figure 1**a).[25] These animals have a completely soft body that can bend, elongate, and squeeze to fit inside very narrow apertures.[26,27] Their eighth arms are continuous structures of muscular hydrostats composed of three differently arranged muscle fibers (Figure 1b): transverse (tm), longitudinal (lm), and oblique (om).[28] This arrangement allows the octopus' arm to bend, elongate or shorten, by selectively contracting transverse and longitudinal muscles, and twist through the contraction of oblique muscles.[26] The peculiar body of octopuses, with no rigid skeleton, is one of the fundamental elements that enable their morphological adaptation, allowing them to accomplish articulated manipulation tasks:[29] their soft and flexible arms can bend at any point and in any direction, to easily conform to differently shaped objects and delicately manipulate them, but are also able to stiffen to exert the required force and precise motion.[28,30,31] This way, octopuses show virtually infinite degrees of freedom and a continuously reconfigurable skeleton-like structure.[32,33]

Another peculiarity of their body is the presence of suckers, distributed all over the ventral side of their eight arms (Figure 1c) and used by the octopuses to attach to any surface, grasp and manipulate objects,[34,35] as well as greatly improve locomotion.[33,36]

The structures and biomechanics of octopus' suckers have been deeply studied,[37–39] demonstrating their effectiveness particularly in wet conditions, where negative pressures (ranging from 0 to −65 kPa) can be generated to apply strong adhesion.[34]

Two characteristic and widely studied macromovements of octopuses are reaching and fetching, in which all the above conformable and adaptable abilities are particularly evident.[29,32,33,40] Reaching is used by the octopus to catch a prey or object and fetching to feed themselves or move an object from one point to another. In the reaching movement, the octopus extends an arm by starting a bending at the base and propagating, with a wave-like transition, the bending up to the distal side of the arm, while directing the suckers toward the target. The suckers are then used to strongly adhere to the target.[40] The fetching movement is achieved creating two virtual joints (points of bending) in the soft arm structure, and three link-like segments, similar to vertebrate appendages, that allow the octopus to bring the food to the mouth.[32]

Drawing inspiration from the mutual benefit of the muscular-hydrostat soft body and suckers in octopuses, this paper proposes the design and prototype of a tendon-driven soft robotic arm endowed with suction cups for retrieving nonstandard objects from a well, a pipe or a tank, or in any confined environments, during production or maintenance in industries. This is achieved by partially imitating the reaching and fetching movements of octopuses.

The solution addresses challenging conditions, spanning from air to oil media, pressurized chambers (up to 18 bar), confined spaces, fluid and surface dirtiness and/or roughness, and, in general, those conditions that would benefit more from a compliant system rather than from a rigid one, with an accurate control whose precision would otherwise be difficult to achieve.

The octopus has been already used as a model for developing stretchable and camouflaging skin,[41,42] soft octopus-like arms,[13,15,30,43–46] or octopus-like suction cups.[47–51] Yet, the

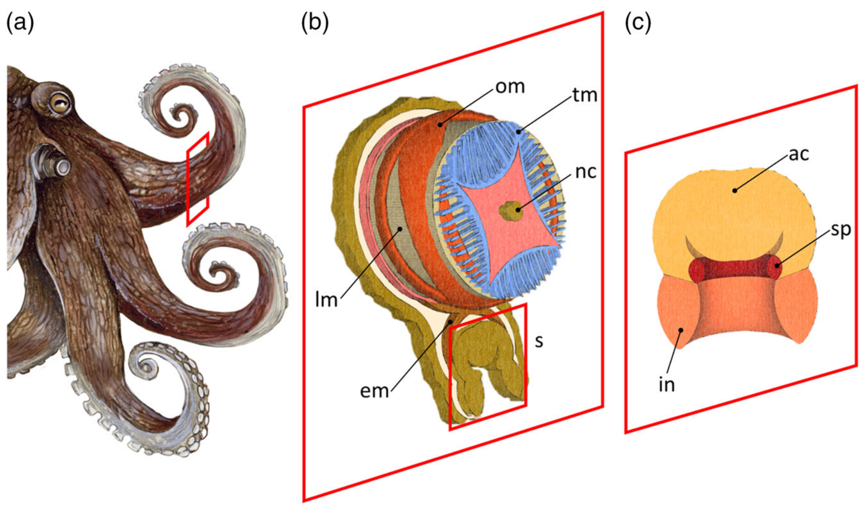

Figure 1. a) Drawing of an octopus (photo by Annalisa and Marina Durante/Shutterstock.com). b) Diagram of the octopus arm showing 3D arrangement of internal structures: nc, nerve cord; tm, transverse muscles; om, oblique muscles; lm, longitudinal muscle; em, extrinsic muscles; and s, sucker. c) Diagram of the octopus sucker: sp, sphincter; ac, acetabulum; and in, infundibulum.

previously proposed designs have not presented an integrated view of a soft arm with suction cups or demonstrated the enhanced manipulation capability of the arm endowed by suction cups. To the best of our knowledge, the TentacleGripper[52] developed by Festo is the only state-of-the-art example of a gripper with integrated suction cups inspired by the octopus. This gripper has a soft silicone structure, pneumatically actuated, with two rows of suction cups arranged on the inside of the tentacle. The gripper can bend inward, wrapping around different objects and adapting the gripping to the object size. Moreover, if assembled on a three-section high dexterous pneumatic arm (inspired by the elephant trunk),[53] it can achieve a high level of dexterity and operate efficiently in free space. However, the gripper alone with its 2D motion (inward bending) can only have in-plane deformation and thus handles a limited set of objects. This solution may be insufficient for retrieving complex-shaped objects and has major limitations when moving in a confined environment, as the object to be retrieved can be difficult to approach or completely inaccessible laterally. In this paper, we propose an octopus-inspired soft arm able to move inside a 70 mm diameter pipe and with the ability to perform different kinds of 3D grasping strategies and thus retrieve a broad set of objects that can be lost in industrial pipes, by exploiting the adaptability of the soft arm and different configurations of suction cups. In addition, the proposed octopus arm has been designed to work in pressurized environments and operate in low-friction conditions (oil bath).

Our integrated design is introduced in Section 2.1, describing the arm and suction cup fabrication and design. A complete and compact prototype for the overall system is presented in Section 2.2. The arm was tested in air, water, and oil and its motions demonstrated in pipe with oil from 0 to 18 bar of pressure. Results regarding the grasping task with different objects are reported together with a comparison of the grasping force achieved by the arm with and without active suction cups and in different media. The results are accompanied by a discussion, followed by the conclusions in Section 3.

2. Results and Discussion

2.1. Integrated Design

The soft arm was designed to mimic the elongated conical shape of a real octopus arm and guarantee a certain degree of maneuverability in confined spaces. A length of 370 mm was selected to enable effective twisting around objects with diameters up to 30 mm (selected maximal diameter of the objects to be retrieved). Consequently, a maximum diameter of 30 mm at the base of the arm and a minimum diameter of 4.5 mm at the distal side represents the maximum section obstruction, which guarantees the spatial coexistence of the object to be retrieved and the soft arm in a 70 mm diameter environment.

It was made with an external softer cover (Young's modulus of 0.07 MPa) and an inside stiff core (Young's modulus of 0.34 MPa). The soft cover ensures the required morphological adaptation to the object to be retrieved; whereas, the stiff core works as a spring-like backbone that helps in recovering the arm rest configuration after actuation. **Figure 2** (left side) summarizes the procedure for arm fabrication. Two molds are necessary: mold A1, used for manufacturing the core, and mold A2, to cast the external cover.

Three cables are used for actuation and arranged in different configurations, similar to octopus muscle fibers, to obtain three different motions: dorsal bending, ventral bending, and twisting.

The cable responsible for twisting (yellow cable in Figure 2) has an oblique-like configuration: it starts from the bottom-left ventral side, runs longitudinally to the arm until reaching about the middle of the arm where there is a change in direction to reach the top-right corner of the ventral side, whereas, the ventral bending cable (green cable in Figure 2) and the dorsal bending cable (red cable in Figure 2) run straight along the arm, in a longitudinal configuration.

The cables are inserted in the arm during casting and passed through rigid supports, which are embedded in the core to guide the cables and protect the silicone from damages (see Experimental Section for details). The actuation cables are endowed with nodes that allow them to anchor to the supports during tension: the twisting cable is anchored at the distal part of the arm (RS1), the ventral cable is anchored to the second and third rigid ventral supports (RS2 and RS3), and the dorsal cable is anchored to the second dorsal support (RSII). This strategy, together with five flexible joints, which are used as mechanically weak points directly cast in the core matrix, allows better control of the bending and twisting configurations and facilitates the motion of the arm in constrained spaces. Three fluidic channels are also assembled inside the arm core for the actuation of three groups of suction cups. At this stage, silicone for the arm core is poured into the mold (see Experimental Section for materials).

In parallel, another procedure (summarized in Figure 2, right panel) involves casting the suction cups. In fact, the ventral side of the arm is equipped with nine suction cups of decreasing diameters (from 14 to 9 mm) from the base to the distal part.

The developed suction cups are composed of a semicircular body and a flexible stalk that behaves similarly to a spherical joint to enhance the ability of the suction cup to adapt to irregular surfaces. Three types of suction cups were made, characterized (see Supporting Information), and integrated into the arm in three groups over the three fluidic channels according to their functionalities. The first type is an open suction cup (type A, Figure 2), where the actuation channel, which passes through the stalk, directly interfaces with the external medium. In the other suction cups (types B and C, Figure 2), the fluidic system is separated from the medium by a membrane. Particularly, type B has a flat membrane that closes the cup and deforms, permitting the suction cup actuation when flow is activated (suction for attachment and inflation for detachment). Type C has a concave membrane that adheres (with a small gap) to the semicircular body of the suction cup and permits the passive attachment to a close object (without activation of the fluidic circuit, a preload between 0.5 and 1 N is enough to establish attachment, see Supporting Information) and the controlled detachment when the fluidic channel is activated (which inflates the membrane). This choice was taken to exploit all the benefits derived from each type. Specifically, the open suction cup, which allows a stronger adhesion with respect to a membrane-based suction cup (see Supporting Information), was integrated at the distal part

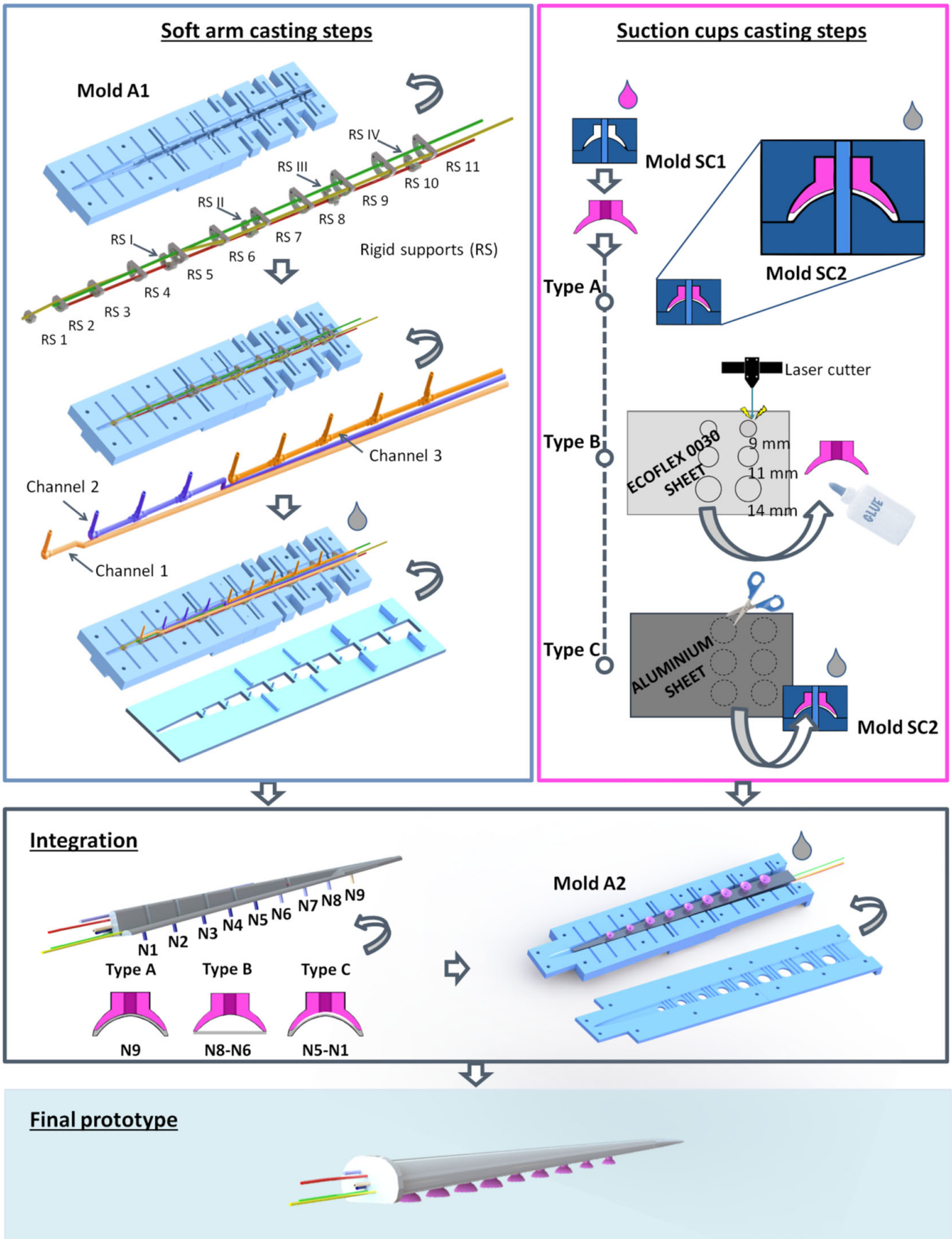

Figure 2. Fabrication and integration of the soft arm and suckers. Top left) Mold A1 is used for the arm core casting. The core integrates three actuation cables (details of the spatial configuration are shown in Figure S5–S7, Supporting Information), positioned by means of rigid supports located both on the ventral and on the dorsal side, and three fluidic channels, used for the actuation of suction cups. After the positioning of cables and channels, the casting of silicone is performed. In parallel, top right) the suction cups are fabricated by casting a semispherical body and a flexible stalk by mold SC1. Then, three different types of cups are realized with different steps. For type A, a second mold (mold SC2) is used to add a 1 mm coating layer of soft silicone. Type B is realized by gluing a flat silicone disc (1 mm thick) at the borders of the suction cup, resulting from mold SC1. Type C is realized with an analogous process of type A but, before curing the soft silicone, an aluminum sheet is added to obtain an empty space between the suction cup and membrane (the soft silicone layer). Middle) The arm core and the suction cups are assembled into mold A2 and then a soft silicone is cast and cured at room temperature for 4 h. (Bottom) The soft arm is removed from the mold and is ready for the integration in the actuation unit.

of the arm (N9) and used to retrieve objects that the full arm is not able to reach or when coiling is not feasible (e.g., small objects).

Suction cups with a flat membrane (N8–N6) are integrated at the center of the arm and connected in a series to a second fluidic channel. This configuration is a twofold strategy: on the one hand, the membrane isolates the fluidic channel from the environment, protecting the fluidic system from dirt; on the other hand, thanks to the self-sealing action of the membrane, the suction cups that are not correctly attached to the object do not create hydraulic leakage for the other cups.

Suction cups with a concave membrane (N5–N1) are connected in a series to a third fluidic channel and placed on the upper part of the arm, where the conformability and grasping ability are more limited. These suction cups can thus be more easily used for passive attachment and mechanical interlocking. As with type B, the membrane both protects the fluidic channel from particles and prevents hydraulic leakage in an array configuration.

The suction cups were designed using two sets of 3D-printed molds (Figure 2, top-right panel). Mold SC1 permits the realization of the suction cup body that is common to the three types. Mold SC2 permits to add 1 mm material to the suction cup (used for the production of type A and C); thus, a multimaterial open suction cup was produced with a very homogenous layer of soft silicone directly attached at the interface in a two-step casting process (type A).

The flat membrane-based suction cups (type B) were fabricated by gluing on the edges of the cups a 1 mm thickness disc film of Ecoflex 0030. Whereas, for the concave membrane (type C), a film of aluminum was placed in the cavity of the suction cup before casting by mold SC2. After curing, the aluminum film was removed by collapsing it into a small ball shape and sucked from the central stalk gate of the suction cup.

After fabrication, each suction cup was placed in relation to the channels according to their grouping.

The arm core together with the fluidic channels and the suction cups was assembled inside the second mold of the arm (mold A2), and cover casting was performed to obtain the final integrated soft arm prototype (Figure 2 bottom).

To test arm performance, a light, compact, and portable robotic prototype was developed. This integrates the arm with all the actuation components, together with a locomotion unit (**Figure 3**), allowing vertical movements inside 70 mm diameter pipes, and rotary motion to the whole arm, to improve the working space and orient the suction cups toward the target (see Experimental Section for details). The whole manipulator is teleoperated by a common joystick. In addition, ad hoc pressurizable chambers were designed and developed to mimic the constraints of the proposed energy industry scenario (see Supporting Information).

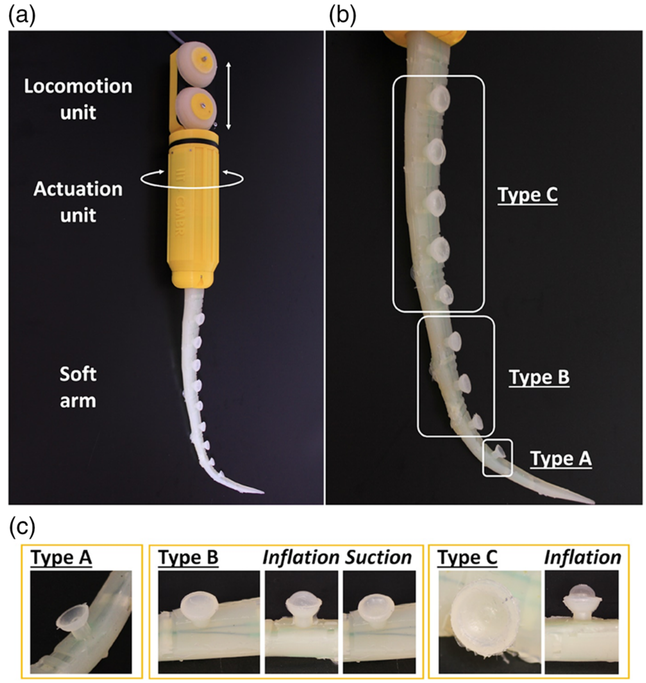

Figure 3. a) The soft arm prototype includes a compact and lightweight locomotion unit for linear motion inside 70 mm diameter pipes and an actuation unit for embedding pumps for the actuation of the fluidic channels, motors for tendon actuation, motors for rotation and linear motion, and electronics for control. b) Close-up of the soft robotic arm with the three groups of activation highlighted, characterized by different types of suction cups. c) Close-up of each type of suction cup integrated in the arm: 1) type A, open suction cup; 2) type B, flat membrane-based suction cup. By inflating this cup, a small dome-like structure is shaped that helps during detachment. When suction is activated the membrane collapses inside the concave structure, permitting attachment; 3) type C, the concave membrane-based suction cup. This cup, when inflated, shows a very pronounced dome-like structure, which is useful during detachment, and it can be passively attached, with no suction.

2.2. Validation

2.2.1. Working in Confined Spaces

The planned movements are obtained (**Figure 4**) by actuating every single tendon (see Experimental Section and the quantitative results in Table S1, Supporting Information). By pulling the yellow cable, the arm is twisted (Figures 4a,b) with a maximum force of 13 ± 0.5 N in 8 cm displacement of the cable. The actuation of the red cable obtains dorsal bending (max force 6 ± 1 N in 3.5 cm displacement) and helps gain arm rest configuration (Figures 4c,d); ventral bending is obtained with a maximum force of 15 ± 0.9 N in 8 cm displacement by pulling the green cable (Figure 4e,f). The combination of these motions, together with the rotation and vertical movement, enables the arm to explore all the tubular working spaces (see Supporting Video).

From these motions, some of the fetching movements in octopuses are recognizable. In fact, when twisting, typically the first sharp bending of the soft robotic arm (P1 in Figure S4, Supporting Information) is at about 15 cm from the base, in correspondence with the change in the direction of the internal twisting cable. The second point of sharp bending is at the ventral rigid support number 2 (P2 in Figure S4), where internal nodes are used to limit the sliding of the ventral and twisting cables. Two joint-like points and three link-like segments are thus established (Figure S4, Supporting Information), which are quite similar to the quasi-articulated structure that octopuses establish in their fetching movement.[22]

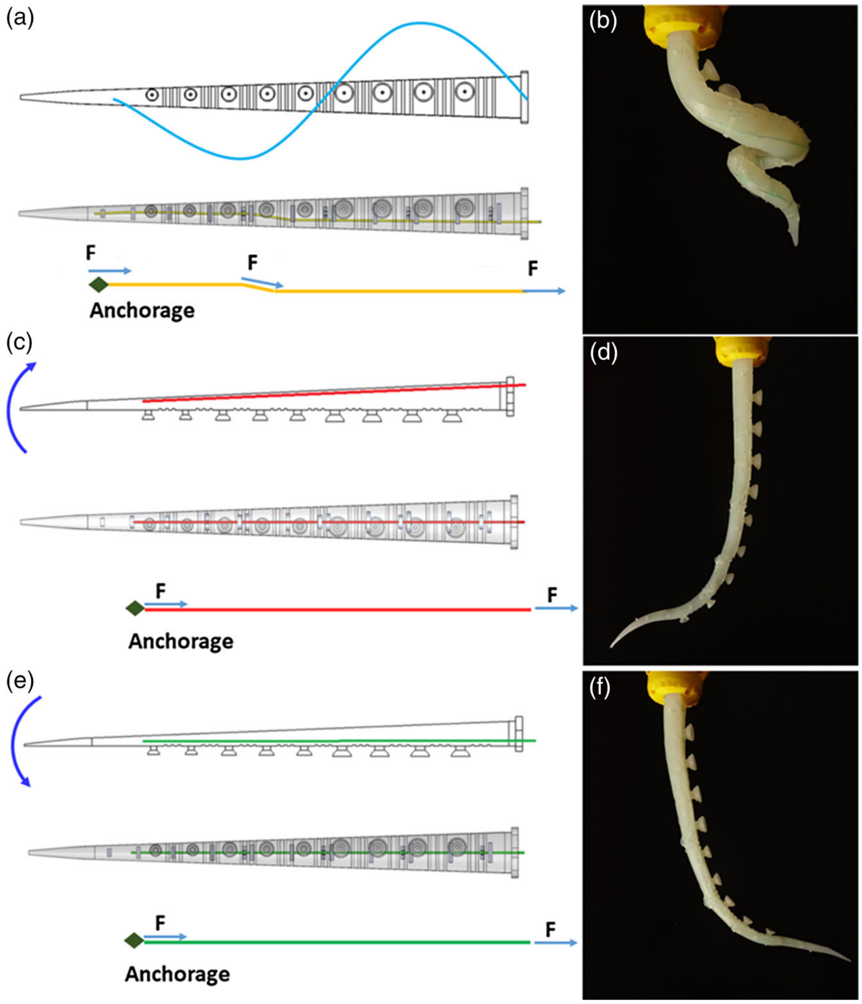

Figure 4. The three types of basic motion activated in the arm by tendon pulling. a) The actuation of the cable (yellow line) causes a twisting of the arm. It runs along the arm changing its direction at about 15 cm from the base. The blue curvilinear line traces the arm's expected motion. b) Arm configuration after twisting tendon actuation. c) The dorsal cable (red) position and the expected motion (blue arrow). d) The motion obtained in the arm by pulling the dorsal cable. e) The ventral (green line) cable positioned in the arm and the expected direction of motion (blue arrow). f) The motion obtained by the arm when pulling the ventral cable.

2.2.2. Enhanced Manipulation Abilities

The manipulation ability of the arm was measured by evaluating its performance in retrieving a set of objects with different sizes and shapes, specifically, a cylindrical (O1), a small (compared with the arm) (O2), a flat (O3), and a spring-like object (O4) (sizes and weights are reported in **Figure 5** top row).

Grasping of the objects was obtained by the actuation procedures reported in **Figure 6**. Generally, in those steps, as in the reaching movement of octopuses,[40] the ventral side of the soft robotic arm, which includes the suction cups, is first exposed toward the item to be retrieved and then the suction is activated to establish the attachment. The robotic arm is able to grasp all the selected objects (Figure 5 bottom row) by adapting its fetching strategy (Figure 6) according to each particular shape, likewise in real animals.[25] In particular, objects O2, O3, and O4 cannot be possibly retrieved without the use of suction cups. The arm exploits the suction cups most during top, lateral, and racket grasping (i.e., when interlocking between the arm and the object is used). In racket grasping, the adaptation of the robot's soft body is particularly exploited: the entire arm is able to 1) slip inside a nonstandard object (spring with an internal diameter of 55 mm), 2) conform its shape to the object, and 3) interlock with it by means of the suction cups (Supporting Video). Herein, the suction cups are not used for their attachment abilities but for the mechanical interaction of the stalks with spring coils, ensuring the interlocking of the arm with the object. Lateral grasping could also benefit from the group of suction cups with a flat membrane (N8–N6). In fact, this type of cup is able to grasp up to 0.15 kg each (Supporting Information), and the cluster of cups can easily adapt from flat to cylindrical surfaces. Dorsal and ventral configurations can thus also be used in grasping movements (exploited in top and lateral grasping), using the open active suction cup (N9). Ultimately, also the twisting grasping

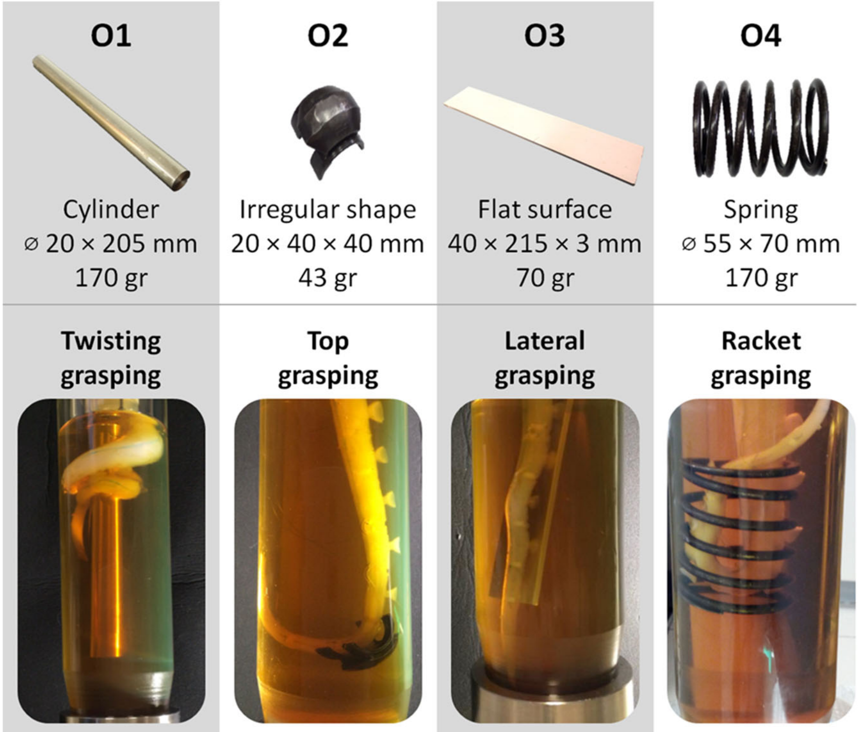

Figure 5. Four examples of object retrieval by using the soft robotic arm, at 18 bar of pressure, inside a 70 mm diameter chamber in oil. During the tests, the arm motions and suctions are not affected by pressure and the robotic arm is able to grasp and collect the objects with different surfaces, weights, and complex shapes. O1) Long and thin objects are retrieved by wrapping the arm around them and activating the suction cups to improve the grasping force; O2) small and lightweight objects are retrieved by activating the more distal suction cup (N9); O3) long and flat objects, not possible to retrieve by twisting, are collected by exposing the dorsal side of the arm to the object and activating all the suction cups; O4) spring-like objects are retrieved by exploiting the morphological adaptation of the arm able to enter in the hollow structure, creating a mechanical interlock between the suction cups and the object.

(Figure 5 and Supporting Video) benefits from the presence of suction cups. In fact, the stresses acting perpendicularly and tangentially at the contact points between arm and object surfaces are amplified by the attachment forces deriving from the suction cup. In particular, the arm with active suction cups, compared with the one with inactivated suction cups, always shows higher lifting capabilities (**Figure 7**) in different environmental conditions (air, water, and oil), for different grasping configurations and for different objects (20 and 30 mm diameter of steel tubes) (see "Grasping force tests" in Experimental Section for details).

The arm with the active suction cups was configured in three twisting levels with 0.5 (weak), 1 (medium), and 1.5 (tight) coils around the objects (corresponding respectively to positions I, II, and III in Figure 7a–f). In position I, the lack of a complete twist around the object makes it impossible to retrieve the objects in all the media. On the other hand, by activating the suction cups (N6–N9), the objects can be grasped (with all the weight sustained by the suction cups) with holding forces of up to 3.1 N in air and 1.25 N in oil. In coil 1 configuration (II position), the arm with the inactivated suction cups is also able to apply a holding force (up to 1 N in air) by exploiting the friction between silicone and the objects.

However, the forces generated in these conditions are always lower than those obtained with the activated suction cups. In particular, in oil, where there is almost no friction between the arm and the object, the holding force of the arm with inactivated suction cups is close to zero (about 0.1 N). By increasing the coiling (1.5 coils—III position), the friction increases, decreasing the gap between the holding forces obtained with and without activated suction cups in air and water. In oil, friction is too low to sustain the grasping without suction cups (a maximum holding force of 0.1 N was generated). Interestingly, the maximum holding force in the case of activated suction cups is not strongly affected by the number of coils and tightening force but instead is limited by the maximum tangential force generated before the initial sliding of the suction cups onto the object. Further, although viscous fluids can facilitate the axial adhesion between the suction cups and the object,[48,50] in our results the maximum holding force of the arm decreases in wet conditions (with a reduced performance in oil) with respect to air, due to the decreased shear force caused by the resulting lower friction induced by the lubricant component.

2.2.3. Working under Pressure

In oil and the pressurized chamber, the grasping capability of the arm did not significantly change regarding the force on the tendons at different pressures (15 ± 1.3 N on average, see "Tendon force tests under pressure" in Experimental Section for protocol details); this means that the compensation channels worked properly. In addition, the attachment capability (Figure S1D,

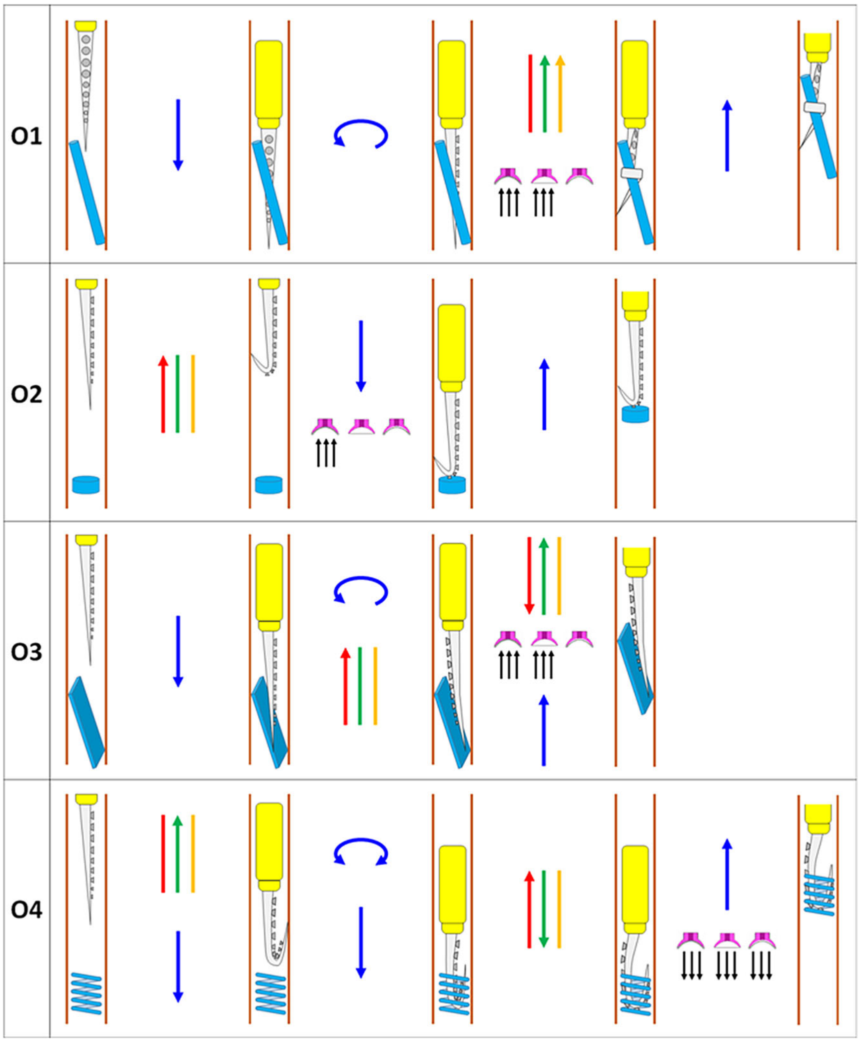

Figure 6. Sequential steps of the procedures for grasping the objects. O1. 1) Lower the arm until it laterally reaches the cylindrical object. 2) Rotate the arm until it touches the object with its upper part. 3) Actuate the twisting cable (yellow) until the arm has coiled around the object. 4) Actuate the suction cups from N9 to N6. 5) Tighten the object with the ventral cable (green) to improve grasping force. 6) Lift the object. O2. 1) Actuate the dorsal tendon (red) to approach the item with the most distal suction cup—N9. 2) Lower the arm until it touches the object. 3) Actuate the N9 suction cup. 4) Lift the object. O3. 1) Lower the arm until it reaches the flat object laterally. 2) Rotate and stiffen the arm with the dorsal cable (red) until it places the suction cups near the object. 3) Actuate the ventral cable (green) and release the dorsal cable until the suction cups touch the object. 4) Actuate the suction cups from N9 to N6. 5) Lift the object. O4. 1) Actuate the ventral cable (green) until the object is approached with the arm dorsal side and the latter is aligned with the central hole of the spring. 2) Lower and rotate the arm until it conforms and goes inside the object. 3) Flip the arm releasing the ventral cable (green) and actuating the dorsal one (red), to interlock the suction cups with the spring pitches. 4) Activate the pumping system to avoid suction cups' attachment to the tube surface. 5) Lift the object.

Supporting Information) of the suction cups showed stabilized forces ($\approx 4 \pm 0.032$ N) after ≈ 3 bar, suggesting that higher pressures would not really change the performance of the arm during attachment.

3. Conclusions

This article proposes a robotic soft arm inspired by the reaching and fetching movements of octopus arms and their attachment capabilities, endowed with soft suckers. The robotic arm is actuated by tendons, made up of a combination of soft materials—i.e., silicones with Young's modulus of 0.07 MPa (Ecoflex 0030, Smooth-On®) and of 0.34 MPa (Dragon Skin 10, Smooth-On)—and fluidically active suction cups. The conformability of the adopted materials, the continuum-like arm design, and the attachment properties of the suction cups allow the robot to show enhanced manipulation capabilities in different media—such as air, water, oil, and constrained environments.

Two main results were achieved: 1) strong grasping forces (up to ≈ 3.6 N in air, ≈ 2.3 N in water, and ≈ 1.3 N in oil with a 30 mm cylindrical object), improving the grasping force achievable by the arm without suction activation (up to ≈ 2.7 N in air,

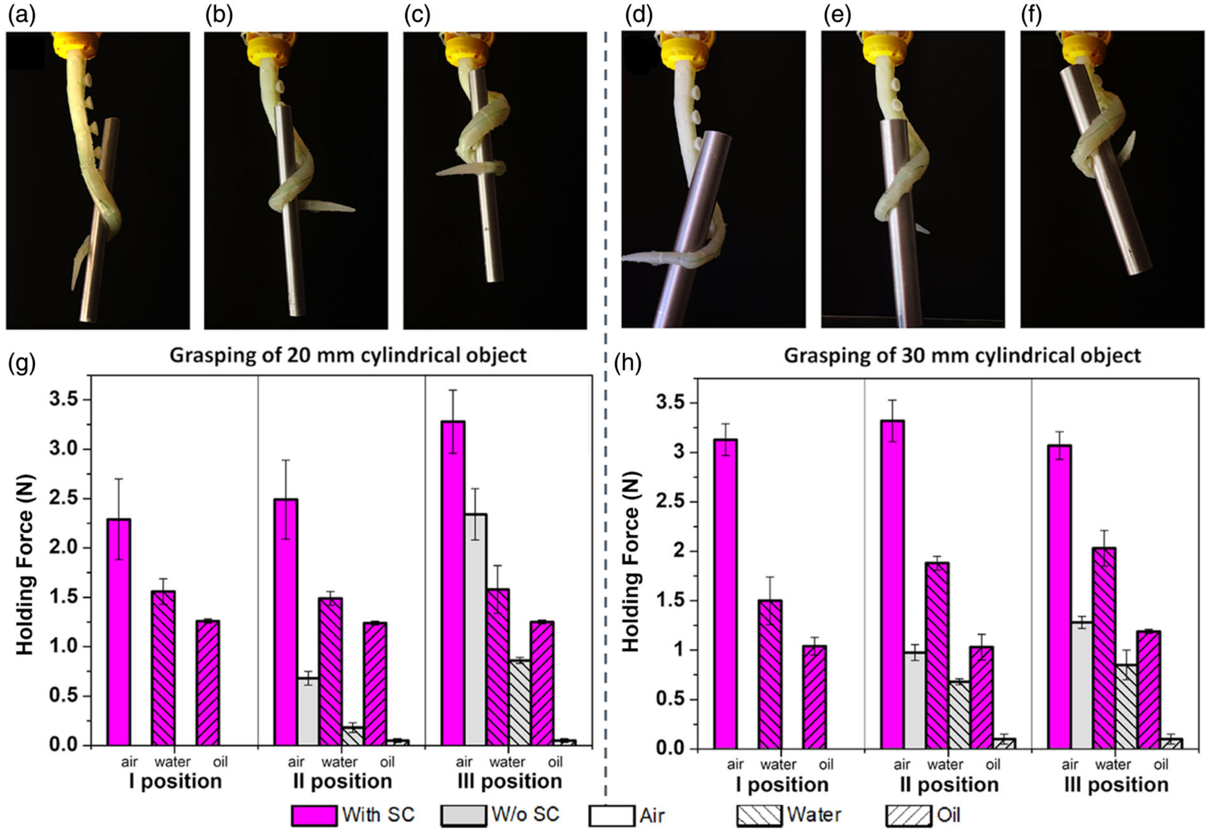

Figure 7. Results of the grasping force tests. From a) to c), the tubular object (steel) with 20 mm diameter is grasped with three different configurations: a) 0.5 coil (I position), b) 1 coil (II position), and c) 1.5 coil (III position). From d) to f), analogous configurations are used for the 30 mm diameter object (the cylindrical object in steel). The histograms at the bottom show the maximum holding force obtained with the three arm positions, in different environments (air, water, and oil). The results show the comparison, for each combination, between the force reached by the arm with active (with SC) and inactive (w/o SC) suction cups. g) The holding forces obtained during grasping the 20 mm diameter cylinder and h) the 30 mm diameter cylinder.

≈0.9 N in water, and ≈0.6 N in oil) and 2) a wider variety of objects that can be grasped, thanks to the presence of suction cups combined with the softness of the arm and its intrinsic morphological adaptation.

In large and free-space environments, where objects typically lie on the floor and are easily accessible, other soft solutions (e.g., jamming-based grippers)[10] can be more efficient and effective. However, in confined environments the objects can assume complex configurations, for example, remaining suspended or stuck between the walls or having a total lack of lateral access.

The proposed design addresses the retrieval of unknown objects, usually rigid, that can fall down into very confined spaces, such as tanks or pipes, which may also present harsh conditions, such as high pressure, viscous media, and rough surfaces. Typically, in industries, the retrieval of objects from pipes or tanks is performed by tools which have object-specific grippers. The proposed soft-bodied robotic arm is a single universal retrieval tool that can negotiate different kinds of objects, in terms of shapes, materials, and weights (including delicate and fragile objects—see Figure S8, Supporting Information), and by having different approach strategies it can provide the desired flexibility and adaptability for retrieving objects from confined spaces.

Our results show that the arm can move into 70 mm diameter pipes and adapt its configuration according to the object. By controlling the three tendons individually, which imitate the longitudinal and oblique arrangement of muscles in octopuses, the arm can reach three main configurations (ventral and dorsal bending and twisting), increasing the possible grasping strategies by a combination of them. In our tests, the adaptation of the arm was exploited over a variety of objects to conform the grasping for irregularly shaped objects, e.g., to enter and interlock with a spring.

In addition, three different designs of suction cups were integrated into the arm for different functionalities. The suction cups demonstrated the ability to adhere to very rough surfaces (e.g., $R_a = 7$ μm and $R_z = 36.5$ μm) and support the grasping task for different geometries, with higher (3 N, for a single open cup) or lower forces (max 2 N, for a single membrane-based cup). However, each suction cup demonstrated its benefits and drawbacks in addressing different scenarios: open cups better sustain object grasping, but they are less effective in dirty conditions, whereas membrane-based cups can lengthen the lifetime of the system when working in dirty media, by filtering particles that may enter into fluidic channels and can work in parallel, thus grasping a wide set of objects.

Both the soft arm and suction cups demonstrated their resistance and did not show any performance change when operating at different pressure conditions (0–18 bar) in oil.

In summary, the adaptation of the soft arm and the interaction with suction cups are key features for addressing nonstandard recovery from wells, pipes, or tanks of a variety of objects without any a priori knowledge about their sizes and shapes.

Our prototype was tested using teleoperated tasks with only visual feedback. Arm motion in confined spaces can be affected by the interaction with the pipe walls and the object to be retrieved. The external forces acting on it can change its configuration and movement, inducing unpredicted behavior, which in our conditions can only be understood and exploited after a user training phase. Complete autonomy of the system can be achieved through the integration of sensory feedback to optimally control the grasping strategies (e.g., by monitoring the tendon positions and the pulling tendon forces) and, in particular, through evaluating the correct attachment of the suction cups (e.g., by monitoring the pressure in the fluidic channel) when teleoperation is not suitable, and this will be the aim of future investigations.

To date, this system is a unique task-oriented prototype able to address specific real issues of the energy industry.

4. Experimental Section

Soft Arm Manufacturing Details: The first step of the process involved laser cutting the rigid supports (made in PolyOxyMethylene Copolymer [POM C]). They had a central semicircular structure and two lateral wings. The two lateral wings of the rigid supports were fundamental for correctly positioning the supports into the mold and were removed at the end of the manufacturing process to obtain holes along the arm structure. These holes acted as pressure compensation points, as they put the tendon channels in direct contact with the working environment, preventing the arm from collapsing on the tendons at high pressures. There were four rigid supports on the dorsal side and 11 on the ventral side. To prevent damage to the soft materials when pulling the cables (made from Kevlar fishing lines), two strategies were adopted: 1) an ad hoc distance among rigid supports (28 mm) and 2) the insertion of pieces of Teflon tubing (0.83 mm of inner diameter, ≈20–25 mm long) along the length of the actuation cables. The insertion of these segments preserved the soft materials all around the cables and facilitated sliding the actuation cables into the rigid supports. Before pouring the constitutive arm material (silicone) into the mold, wax was deposited at the extremity of the Teflon tubes to prevent silicone from penetrating inside the tubes.

Two curing steps were used to fabricate the arm: 1) core casting performed with Dragon Skin 20, Smooth-On and 2) cover casting performed with Ecoflex 0030, Smooth-On. During casting of the cover, the suction cups were integrated with the soft arm.

The suction cups were composed of a body, obtained with Dragon Skin 10, Smooth-On, and a membrane (membrane-based suction cup) or a soft thin interface layer (open suction cup) realized in Ecoflex 0030, Smooth-On.

Both internal and external surfaces of the suction cups had spherical geometries and the intersection of these two spheres resulted, for instance, in the case of the 14 mm diameter suction cup, in a cavity with a 12 mm circumference diameter and 3 mm depth inside the suction cup. The rubber stalk with 7 mm diameter and 3 mm length in the back of the suction cup provided a flexible connection to the soft arm.

The silicones, of both arm and suction cups, were cured at room temperature for 4 h.

Tendon Actuation: Each tendon was managed by an independent motor (placed in the actuation unit) with an integrated encoder (1000:1 Micro Metal Gearmotor HP 6V with Extended Motor Shaft, from Pololu) and connected to a pulley with 12 mm diameter. The pulleys were orthogonal to the tendons that came out from the arm. An eyebolt (one for each tendon) was used to transfer the cable tension to a load cell (LSB200, 10 lb, FSH03875, Futek) and correct the alignment from the pulley to the arm tendon.

Fluidic System: The three-channel fluidic system was composed of silicone tubes (VMQ, 1 mm inner diameter, 2 mm outer diameter). Hydraulic fittings were used to connect each suction cup with the suction main channel (Figure 2). Each channel was controlled by a dedicated pump (D220BL, RS PRO) located in the actuation unit close to the arm to reduce the pipe length and consequently to minimize pressure drop. The fluidic channels were filled with ambient fluid (air, water, and oil) before testing the arm in each medium. Closed suction cups were filled through small holes realized in the membranes that permitted the fluid to pass if the arm was immersed in it while the pumps were actuated at a low flow rate.

Actuation Unit: The proposed actuation unit (Figure 3a) was a compact module able to manage three tendons, three pumps of the fluidic system, and supply a rotary motion to the whole arm to improve the working space and the ability to orient the suction cups toward the target. Rotation was via a fourth motor that rotated the actuation unit with respect to the locomotion unit, thus avoiding any twisting of tendons or electrical cables. The overall unit, which was 160 mm long with a diameter of 65 mm, was connected by a slip ring to the locomotion unit, for transferring power, communication (over UART), and connection to the motor for pipe climbing.

Locomotion Unit: The locomotion unit (Figure 3a) was used to move the arm vertically along a pipe. It is 150 mm long and it was composed of two wheels of the same dimensions: one active, connected to a powerful motor (Metal Gear Worm Motor, FIT0489-D, DFRobot), and one passive to keep the alignment of the whole assembly with the tube. The wheels were covered in silicone (Dragon Skin 10, Smooth-On®) to obtain good friction along the tube. The wheels were then driven to the tube wall via a spring mechanism from the opposite side.

In oil, a screw-like mechanism was adopted for vertical sliding instead of wheels to prevent slipping.

Control: The overall system was managed by an embedded control unit composed of a microcontroller (PIC32MX150F128D, from Microchip), five motor drivers (three for tendons, one for rotation, and one for vertical movements—LV8548MC, from ON Semiconductor), and three load cell amplifiers (INA122UA, from Texas Instruments). The whole arm can be connected to a PC and managed by a joystick or programmed to autonomously perform predefined movements.

Tendon Force Tests: The tests were performed using a Zwick/Roell Z005 Universal Testing Machine at room temperature and pressure. A frame was created to fix the arm to the machine with tendons connected to the load cell (max 50 N). Each individual tendon was pulled and the force was acquired as a function of tendon displacement. These experiments were not designed to test grasping.

Grasping Force Tests: These tests were performed to acquire the holding force exercised by the arm when grasping tubular objects of 20 and 30 mm of diameter. The tests were performed using a Zwick/Roell Z005 Universal Testing Machine at room temperature and standard pressure. The arm was inserted in the frame of the slider in the testing machine and the load cell (max 50 N) was fixed at the bottom. The items were connected to the load cell and the arm positioned in a twisting configuration around the object, setting suction cups from N9 to N6 in contact with the item. Grasping was executed both with and without activated suction cups, in three different media: air, water, and oil. The grasping was tested with three different curling positions of the soft arm controlled through the displacement of the twisting cable. The first position was obtained by pulling the cable for 34 mm, the second for 48 mm, and the third for 62 mm. The arm configurations with the positions were pictured sequentially for each object in Figure 7a–f. At these positions, the flat membrane-based suction cups and the open active one were shown to the objects. Each group of suction cups was activated with dedicated pumps that generated a suction pressure of ≈0.55 bar. The maximum force was thus acquired with five repetitions for different combinations of the parameters: tendon displacement, medium, object diameter, and suction activation.

Tendon Force Tests under Pressure: To perform tests under pressure, an ad hoc pressurizable chamber was developed (Supporting Information in Section 3). These experiments assessed the tension of one tendon (twisting tendon) as a function of the pressure inside a chamber with oil (Mobil 626 with 0.89 kg L^{-1} of density and 68 centistokes (cSt) of kinematic viscosity), without suction (by keeping the fluidic channels open). A load cell (LSB200, 10 lb, FSH03875, Futek) was installed over the twisting tendon and used to measure the tension variation during pulling, repeating the test ten times at four different pressure conditions: 0, 5, 10, and 18 bar. The arm was coiled around a cylinder of 20 mm during the tests, and the forces were measured at half and full tendon displacement.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords

grasping, manipulation, octopus-like arms, soft robotics, suction cups

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