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Full paper

Soft Robot Arm Inspired by the Octopus

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Abstract

The octopus is a marine animal whose body has no rigid structures. It has eight arms composed of a peculiar muscular structure, named a muscular hydrostat. The octopus arms provide it with both locomotion and grasping capabilities, thanks to the fact that their stiffness can change over a wide range and can be controlled through combined contractions of the muscles. The muscular hydrostat can better be seen as a modifiable skeleton. Furthermore, the morphology the arms and the mechanical characteristics of their tissues are such that the interaction with the environment (i.e., water) is exploited to simplify control. Thanks to this effective mechanism of embodied intelligence, the octopus can control a very high number of degrees of freedom, with relatively limited computing resources. From these considerations, the octopus emerges as a good model for embodied intelligence and for soft robotics. The prototype of a robot arm has been built based on an artificial muscular hydrostat inspired to the muscular hydrostat of the *Octopus vulgaris*. The prototype presents the morphology of the biological model and the broad arrangement of longitudinal and transverse muscles. Actuation is obtained with cables (longitudinally) and with shape memory alloy springs (transversally). The robot arm combines contractions and it can show the basic movements of the octopus arm, like elongation, shortening and bending, in water.

Keywords

Octopus, muscular hydrostats, shape memory alloy, soft robot

1. Introduction

The octopus is an invertebrate marine animal (phylum: Mollusca; class: Cephalopoda), whose body has no rigid structures. Thanks to this, the octopus can adapt the shape of its body to the environment and its whole body can be squeezed into very

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small apertures, limited only by the size of its brain capsule. The octopus has eight arms that can twist, change their length and bend in all directions at any point along their length. Despite the lack of rigid skeletal support, the eight arms are effectively used to obtain locomotion on the diverse substrates of the sea bottom, and to reach, grasp and even manipulate objects with unexpected dexterity.

Owing to these features, the octopus arm has sometimes been a source of inspiration in robotics, basically for the development of hyper-redundant robot manipulators [1].

The octopus arms are composed of a peculiar muscular structure, named a muscular hydrostat [2]. The arrangement of muscles in the muscular hydrostat is such that combined contractions of different muscles can control the variation of the stiffness of the arms, to achieve relatively high values and to apply relatively high forces [3].

The control of this large number of degrees of freedom in the octopus is highly distributed and it is simplified by the use of stereotyped movements. Moreover, the morphology of the arms and the mechanical characteristics of their tissues are such that the interaction with the environment (i.e., water), is exploited to simplify control. The octopus represents a biological demonstration of how effective behavior in the real world is tightly related to the morphology of the body. It stands as a good example of embodied intelligence, whose principles derive from the observation, in nature, that adaptive behavior emerges from the complex and dynamic interaction between the body morphology, sensory–motor control and environment [4]. This principle has been adopted in a wide range of current approaches to the development of robots [5]. Thanks to this effective mechanism of embodied intelligence, the octopus can control its high number of degrees of freedom with relatively limited computing resources.

From these considerations, the octopus emerges as a good model for embodied intelligence and for soft robotics. This paper presents the design of an artificial muscular hydrostat and the development of a robot arm prototype based on the muscular hydrostat principle, working in water.

2. Muscular Hydrostats

In the arms of the octopus, muscles are organized into transverse, longitudinal and obliquely orientated groups [6, 7], as illustrated in Fig. 1. This special muscular organization forms the structures called muscular hydrostats, whose main property is that their volume is constant during muscle contractions [2]. The result is that if the diameter of a muscular hydrostat decreases, its length increases and *vice versa*. Elongation of a portion of the arm is obtained by contraction of the transverse muscles, because their arrangement decreases the cross-sectional area. In contrast, shortening of the arm results from the contraction of the longitudinal muscles. Torsion of the arm results from contraction of the oblique muscles. Bending of the arm can be obtained by contraction of longitudinal muscles on one side of the arm

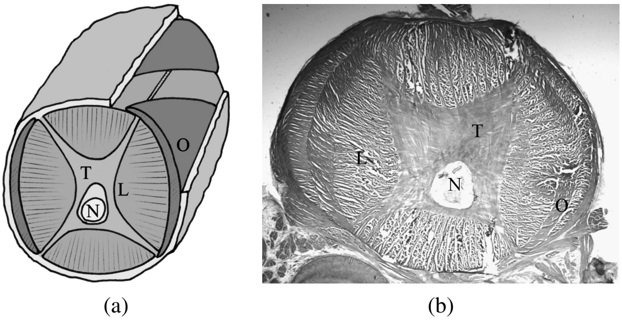


Figure 1. (a) Scheme of the muscle arrangement in the octopus muscular hydrostats (figure by Virgilio Mattoli, 2008): four main longitudinal muscles (L) are arranged along the arm length; transverse muscles (T) are arranged in a radial configuration, along four arcs connecting the external connective tissue with the central channel, containing nervous fibers (N), with fibers interspersed within the longitudinal muscles; oblique muscles (O) wrap the whole muscular structure with an orientation between 50° and 60°. (b) Histological transverse section of octopus arm, showing the longitudinal muscles (L), the transverse muscles (T), the central nervous fibers (N) and the oblique muscles (O).

and, simultaneously, by contraction of the transverse muscle in order to resist the longitudinal compression forces caused by contraction of the longitudinal muscles [2]. The transverse and longitudinal muscles can be considered to have a reciprocal antagonistic action, enabling the muscular system to serve as a modifiable skeleton, essential for the transformation of force into movement, with the possibility of both right- and left-handed direction of twist.

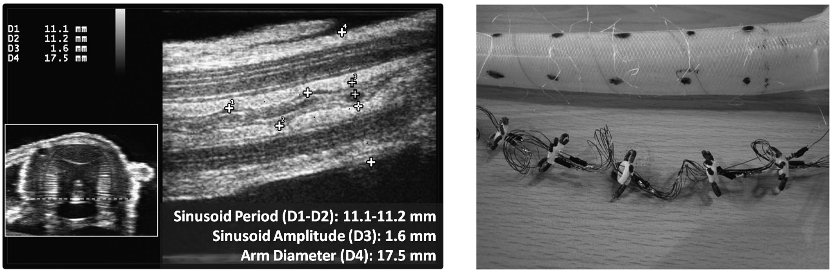
3. Specifications for the Robot Arm from Measurements of the Octopus Muscular Hydrostat

The specifications for the performance and the design of the actuators and the structure of the robotic arm have been derived from *in vivo* measurement of octopus biomechanics and analysis of arm morphology.

Results from direct measurements of octopus elongation showed a mean elongation of 70% of the arms, with a 23% of diameter reduction at the base [8–10]. Consequently, the value of 20% has been set as the specification for the transverse actuators of the artificial muscular structure.

Measurements of the muscular fiber lengths and areas *in vivo* were obtained from sonographic examination of the octopus arms [11]. Ultrasound imaging allows a non-invasive study of the internal morphology under natural conditions and real proportions, with accuracy and repeatability. Thus, the method overcomes the drawbacks of more invasive techniques and helps in the study of structure roles. The analysis was also carried out for the nervous tissues, showing that the nerve cord in the inner part of the arm has a sinusoidal arrangement, which allows arm elongation and preserves the nerve cord from stretching (Fig. 2a).

The conical shape of the robot arm is specified by the morphology of the octopus arm, as analyzed by histological techniques. In Ref. [12], 10 animals were tested



(a) (b)

Figure 2. Helicoidal arrangement of the octopus nerve cord (a) and of the robot arm wires (b).

for morphological characterization (around 400 measurements from each animal). With statistical methods the decrement ratio of the diameter along the arm length has been identified as 6% [12].

Histological analysis also shows the arrangement of the fibers of the connective tissue, which is considered for designing the robot arm structure. The octopus has a braided net of connective tissue fibers to which the muscles are attached [7]. The connective tissue is described as composed of fibers oriented at about 68–75° with respect to the longitudinal axis of the arm. Its role in the biomechanics of the arm is not completely clear, but it is likely mainly for containment and support purposes, as well as for providing stable insertion points.

4. Design of an Artificial Muscular Hydrostat

The basic principles of the smart muscle arrangement of the octopus arm are applied to the design of a robot arm working in water [13]. The key principle of the biological muscular hydrostat taken as inspiration is the arrangement of longitudinal and transverse muscles on normal planes. The main advantage is that this smart muscular structure simplifies some of the movements of the octopus arm, and reduces the complexity of the required mechanisms and actuators, as some of the muscle deformations are in fact passive (i.e., the elongation of longitudinal muscles by transverse contractions).

The artificial muscular hydrostat unit is based on four longitudinal actuating elements (L in Fig. 3), representing the four longitudinal muscle bundles, and a layer of actuators radially arranged (T in Fig. 3), representing the transverse muscles.

The actuators are mechanically fixed to a support structure (S in Fig. 3), whose design derives again from the biological model and specifically from the arrangement of the fibers of the connective tissue [7]. The mechanical properties should allow the high deformations expected from the arm, presenting high flexibility and preserving the arm motion capabilities. A central channel in every unit is available for electric wires (W in Fig. 3), in analogy with the nerve chord channel in the octopus arm.

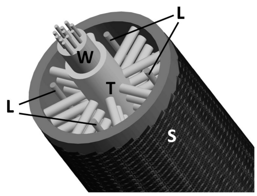


Figure 3. Schematic design of the artificial muscular hydrostats with four longitudinal actuators (L), a number of transverse actuators (T), the support structure (S) and the central wires (W).

5. Prototype of an Octopus-Like Robot Arm

The octopus-like robot arm is based on a series of artificial muscular hydrostat units, having a conical shape with progression of geometrical parameters analogous to the biological model. Each component and their integration in the arm are described in the following subsections.

5.1. Longitudinal Actuators

Four longitudinal artificial muscles made of UHMWPE synthetic fibers run along the arm length, in an up/down/right/left arrangement [14].

The parameters of the cables have been set on the basis of the values of force applied by an octopus arm, as measured experimentally and reported in Section 3. A model is presented in Ref. [15] of the deformations given by longitudinal cables on a compliant (silicone) cylindrical body. Specifically, two models describe the shortening and bending, with validation on purposive experimental platforms.

5.2. Transverse Actuators

The transverse muscles have been designed as radially arranged layers of actuators. The number of actuators for each layer and the number of layers determines the resolution of the arm movements. One of the main consequences is the discretization of the system with respect to the continuity that the biological model can implement. The most evident effect is ‘barreling’, both in longitudinal (proportional to the distance between layers) and in transverse (proportional to the distance between actuators) directions. Shape memory alloy (SMA) technology has been used for the development of active springs, as transverse actuators, able to contract when electrically activated. The choice of this kind of technology fits well with our specifications, in particular in terms of light weight, flexibility, work density, and possibility of miniaturization and customization. On the other side, the use of SMAs is often affected by the presence of several drawbacks, like low strain achievable, high current need and nonlinear behavior (low controllability), but in the present application some strategies have been developed to overcome or to limit these effects. SMAs cannot reach a very large deformation when used in a straight shape (5–8% maximum), but when forged in a spiral shape they can reach more than 300% of deformation. Moreover, an optimized cooling system allowed the optimization of the working cycles (1.5 s for a heating and cooling cycle). Finally, low controllability issues have been solved using an all-or-nothing activation strategy and exploiting the antagonistic effect of the longitudinal cables.

On the basis of the mechanical properties of the alloys and on spring theory, a semiempirical model has been developed to design the optimal shape of the SMA springs with respect to the force specifications, which resulted in a helicoidal shape. The choice of the geometrical parameters has been made on the basis of an algorithm for the calculation of the force exerted by the springs in all possible configurations and characteristics. Inputs for this algorithm are the wire diameter, spring diameter, number of coils and position inside the arm. All results are sorted in force or stroke order, to allow the choice of the spring that best suits the specifications. Figure 4 shows an example of visualization of the spring configuration inside the arm.

A radial contraction of 20% has been used to set the target for the spring performances from the measurements in the octopus (see Section 3), leading to the choice of specific heat treatments and of the following parameters:

- Wire diameter: 200 μm.
- Internal spring diameter: 1 mm.
- Number of coils: 6–10 (depending on the position along the arm length).
- Spring index: 6.

The resulting springs present a stiffness that ranges from 0.10–0.24 N/mm when inactive (depending on the position along the arm length) to 0.24–0.6 N/mm when electrically activated. The springs are subjected to a current of 1.2 A that guarantees

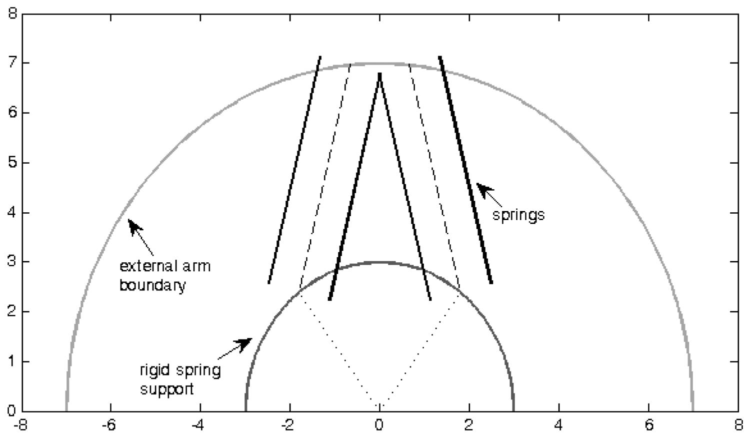
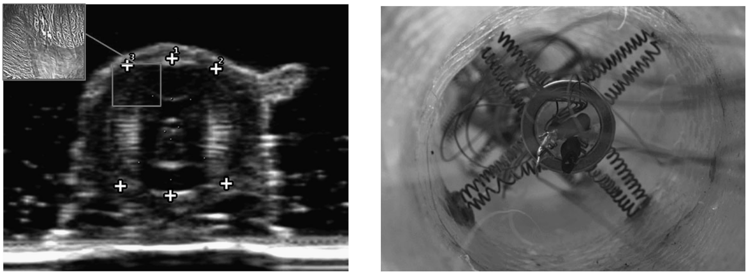


Figure 4. Visualization of the results for the design of the spring characteristics and their configuration inside the arm. Numerical values on the axes are expressed in millimeters. The outer curve represents the external arm surface, the inner curve represents the rigid link that connects all the springs, the dashed black line identifies the position of the springs and the solid black line identifies the external spring profile.



(a) (b)

Figure 5. (a) Echographic image of the octopus arm on the transverse plane, showing the arrangement of transverse fibers and trabeculae. (b) Arrangement of transverse actuators in the artificial muscular hydrostat.

the complete activation of the springs and the maximum deliverable force. At this stage the springs follow an on/off activation control and thus there are no intermediate values of force achievable. In terms of performance this means that each single SMA module always produces the same effect, but the position and the number of activated modules determine the behavior of the arm as a whole.

Transverse actuators have then been arranged in a radial configuration (Fig. 5b) to achieve the most efficient mechanism in diameter reduction and to obtain large passive elongations, in analogy with the biological model (Fig. 5a).

To reduce the electric power consumption, a 50-μm PTFE sheath was used to cover the SMA wires. This cover minimizes the heat dissipation during heating, without increasing the cooling time.

The thermodynamic behavior of the SMA has been described by a finite element model that was used for dimensioning the current required for activation. The same model was then used for calculating the heat transfer coefficient between the wire and the surrounding environment; in this way, the external sheath was appropriately dimensioned.

The number of modules needed to obtain a homogeneous radial contraction of the arm was found experimentally, maximizing the distance between the modules. The minimum number of actuators was employed to reduce the power consumption whilst maintaining contraction, and thus arm elongation properties. Twelve SMA spring transverse modules have been built. Every module consists of eight springs manufactured using the same continuous SMA wire and thus they are electrically in series (decreasing the number of wires required). The space among them is the result of a precise calculation aimed at maximizing the spring performance and minimizing the total wire length (and consequently the power consumption). The SMA spring series is then fixed on a ring that maintains the radial arrangement of the module and leaves a central circular channel where electrical wires will be lodged.

In order to keep the number of electrical wires required for the activation of the SMA springs low, one wire is in common for all the modules and one wire for each

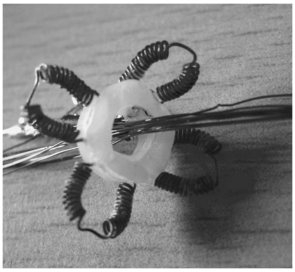


Figure 6. Example of SMA spring transverse module in free contracted position.

module for closing the circuits. With regard to the fabrication of the actuators and the integration of the actuators in the arm, the goal was to minimize the stiffening of the final artifact due to the electric cables. For these purposes the cables chosen are very thin enameled copper wires, crimped together with the SMA spring extremities. The resulting elements are shown in Fig. 6.

The wiring of the modules follows a sinusoidal arrangement (as specified in Section 3) that leaves complete freedom of movement during elongation (see Fig. 2b).

5.3. Robot Arm Support Structure

The robot arm support structure consists of a braided sleeve. It not only provides perfect mechanical support and containment functions, but it generates passive elongation by diameter reduction. The design of the sleeve is based on a study of how the geometry and the material influence the passive properties of the entire structure.

In the literature there are several works on the characterization of braided and woven textile from a mechanical view point, but the approach tends to take into account their use as fillers and thus they are finalized to the prediction of the mechanical properties of the resulting composite structure [16–18].

For our purposes, the main features to study regard the elongation capability (to obtain the best performance) and the propagation of the local deformations (to prevent the barreling effect).

We developed an analytical model and a finite element method (FEM) simulation for this study. The first one uses a simplified version of the geometry of common braided sleeves and its aim is to envisage the optimal elongation performances; the FEM analysis, on the contrary, takes into consideration all the physical quantities, and it gives more accurate information about the required forces and the longitudinal effect of the radial compression.

Available analytical models usually used to describe the quantitative behavior of the braid are based on the fact that braided wires cannot be stretched. Moreover, the symmetry of the structure allows the study of one single cell fiber without loss of generality [19]. In the case of a cone, the dissertation is more complex, due to the diameter change in the vertical direction. The aim of this model is to express the shape change starting from the variation of one of the main parameters.

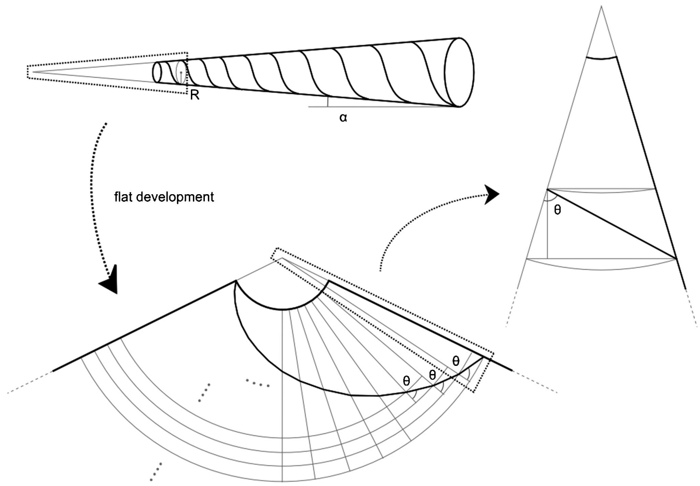


Figure 7. Three steps of the model (from top-left): the truncated cone with one fiber is transformed into a complete cone; the added tip and the first turn of the fiber are developed in a flat pattern (not in scale) and the fiber's path is divided into sectors and concentric arcs; every sector is studied to find a relation between the braid angle and all the other geometrical parameters.

In the case of the cone, the flat development of the solid shape is a sector of an annulus and it can be studied by dividing it into smaller parts (elementary parts). The model can be divided into three parts: in the first part the truncated cone is transformed in a complete cone with the same larger base; then the cone is developed in a flat pattern; finally, the cone development is divided into radial sectors and longitudinal arcs (Fig. 7).

From geometrical considerations it is possible to derive the dependencies among α, θ and R of Fig. 7, and the height of the structure, thus describing the shape change of the structure. Moreover, they can be used in the Cartesian analytical description of a conical spiral to visualize the elongation performances of the braid (Fig. 8).

The analytical model of the conical braid takes into account neither the undulation nor the barreling effects, but it envisages the best performances of the structure. It describes the ideal situation where the entire structure is deformed homogeneously. In a real case, the effect of the local deformation propagates along the arm for a limited space. A more realistic scenario considers a more complex geometry, as well as the interaction among the fibers. To this purpose a FEM analysis software (MARC Mentat 2010; MSC Software) has been used to reproduce the physics of the system, considering both geometric quantities (like type of braiding, sinusoidal fiber path, fiber thickness and cross-section) and material properties (like Young modulus, Poisson coefficient and friction). A small part of the braided sleeve has been virtually reconstructed and all the mechanical properties of the material have been set. The geometry shown in Fig. 9 has been used for the simulation. It

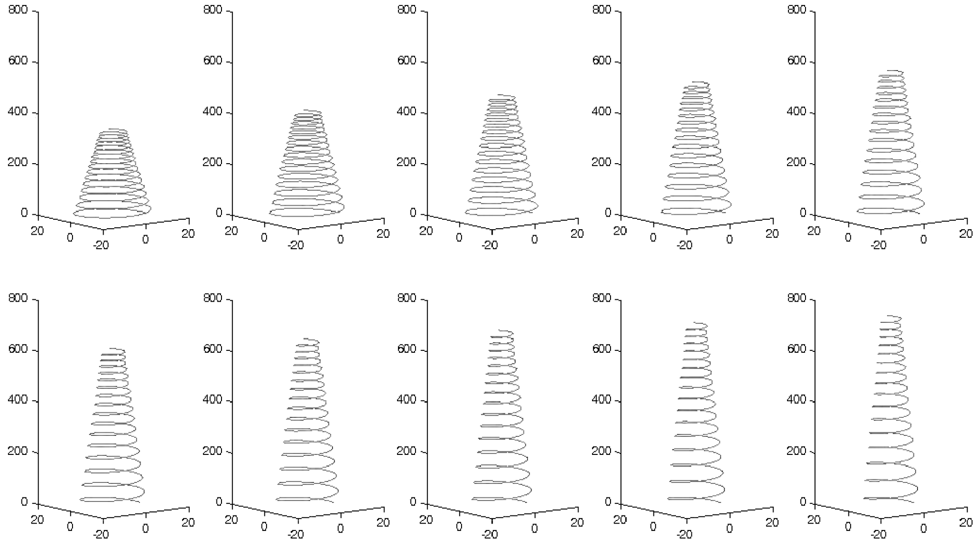


Figure 8. Example of elongating cone described by the analytical model, where the variation of the base radius is imposed and the elongation is calculated.

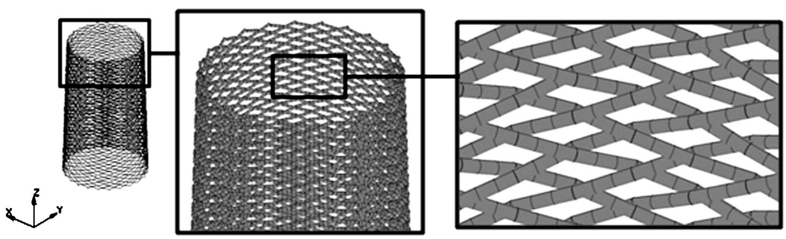


Figure 9. Sample of braided sleeve virtually reconstructed for FEM analysis.

has 48 fibers (24 right-handed and 24 left-handed), the same braiding architecture and octopus arm proportions.

Since the behavior of the braid is completely independent from the device that generates its deformations, the issues regarding the actuators are decoupled from the interface used and this allows simulating the effect of the SMA springs on the structure with four local radial forces. Such forces have been applied incrementally until the 20% of radial reduction has been reached (which is our goal).

For the analytical model, two kinds of tests have been carried out: one using a braid that shows a negligible barreling effect to validate the goodness of the model and one using the braid with the thinnest fibers to evaluate the limitations of the model when barreling becomes more evident.

For the FEM simulation, samples of 60 mm have been virtually replicated. Four forces (simulating the effect of eight coupled SMA springs) have been applied radially. The resulting elongation has been evaluated and compared with experimental tests.

The experimental validation of the analytical model revealed a very good agreement with theoretical data (lying inside an error that ranges between 0.2 and 1.4% due to the manual measurements of the final braid length) when a thick-fiber braid is used; however, as expected, it becomes inadequate (more than 27% of error) when a thin-fiber braid is used or when the longitudinal distance among the actuators positions becomes too high. In this case the barelling effect becomes too evident. Thus, on the other hand, this underlines the necessity of a model that is able to take into account this effect; on the other hand, one can think of increasing the number of actuators to avoid this effect. This could fix the problem, but in the meantime it also increases the power needs and the number of required electrical cables. Thus, the solution is a trade-off among fiber thickness (to increase the longitudinal propagation of the diameter reduction), number of transverse modules (the higher, the better) and distance among them (the lower, the better). In order to try to describe in more detail the barelling effect and quantitatively characterize the phenomenon, the FEM model and the experimental results have been compared. An example is shown in Fig. 10. The local reduction of the diameter causes an elongation of the structure in a way that is consistent with the FEM results: the circular shape is maintained, and the diameter reduction has a maximum elongation effect at the center of the structure, and decreases upwards and downwards (Fig. 10). Quantitatively the FEM model can predict the elongation capabilities of the real braid with an error lower than 3%. At the integration stage this effect has been taken into account by setting a distance among the transverse modules that guarantees an overlapping action among them.

Results demonstrate that inside the explained limitations both the models show a good matching with experimental results. Thus, the analytical model can be used

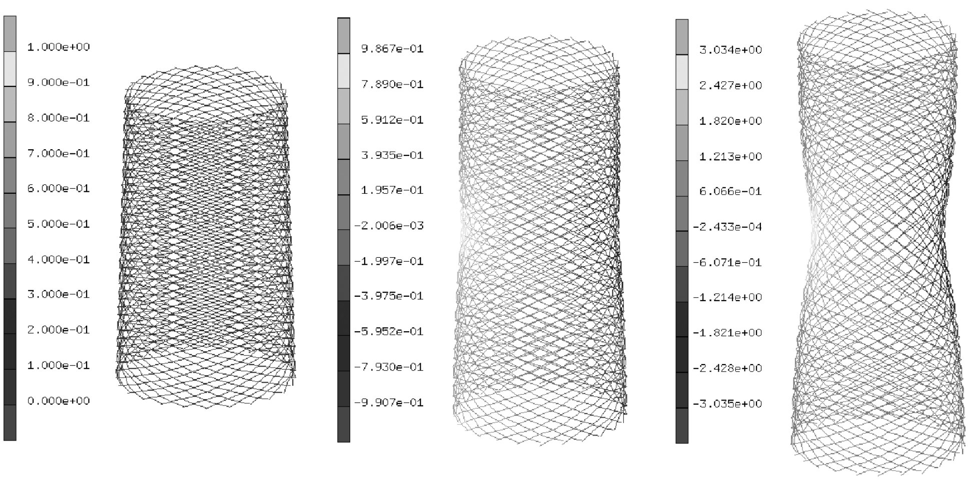


Figure 10. Example of a braid sample subjected to the barelling effect: the FEM model is able to predict the limited longitudinal propagation of the diameter reduction (vertical bar indicates the radial displacement values).

to envisage the elongation performances when thick fibers are used and the FEM simulations can be used in case the barreling effect is more evident (thin fibers). Moreover, the FEM can be used to estimate the force necessary to obtain the desired deformations and can be used to design the SMA springs.

5.4. Integration of the Octopus-Like Robot Arm

The chain of 12 modules of eight SMA springs (see Fig. 2b), together with the electric wires, is inserted in the conical braid and fixed to its yarns. Once put in place inside the braid, each SMA spring is tied to a yarn crossing in order to create a stable connection without limiting the relative rotation of the yarns during the deformation of the braid.

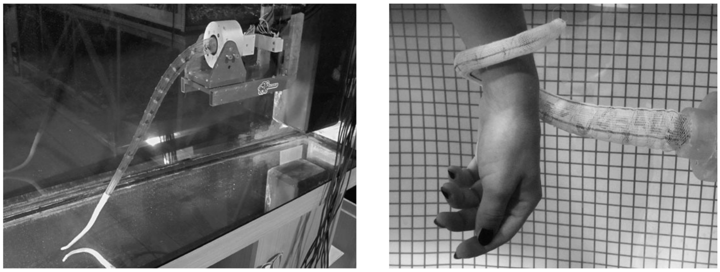
The longitudinal cables are arranged along the whole structure, starting from the base to the end of the braid. One end of the four cables has been fixed directly to the distal part of the braid and the other one is let free to go out from the base. Inside the braid they are placed close to the fibers to maximize the bending capability. To prevent the possibility that cables interfere with SMA springs during contractions, some loops of nylon yarn are used to maintain the cables close to the braid. Even if the loops are not the only solution for this issue and for sure not the most elegant, they guarantee that cables remain in this delocalized position with respect to the springs and present a very low friction. Thus, the relative movements between the cables and the braid do not present resistant forces that could negatively affect the performances of the structure.

For manufacturing reasons, the braid cannot cover the entire length needed for building the complete arm. The distal part of the braid does not have the right size for the tip of the robot arm, as its diameter is still too large with respect to the proportion of the natural arm. A 120-mm silicone cone has been added as an arm tip. Even if it has no active roles, it allows us to reach the right proportions and helps in reproducing a more natural movement, also considering that the very distal part of the arm is used in a passive way by the animal, too, in reaching and grasping tasks [8].

The arm base is inserted on a cylindrical rigid structure that, on the one hand, has a ring that can lodge the base of the braid and, on the other hand, has four small holes where the longitudinal cables pass and one large central hole where the electric wires pass. The resulting structure is shown in Fig. 11.

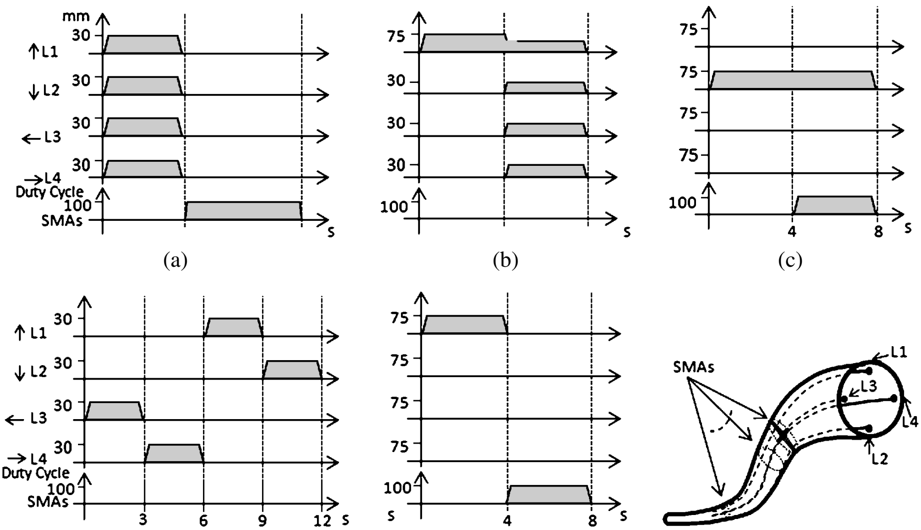
6. Experimental Results

In order to characterize the performances of the arm, different kinds of tests have been carried out in water. The three main movements have been analyzed separately: bending, shortening and elongation. A global bending in each direction can be obtained by pulling a single longitudinal actuator or a combination of two actuators (e.g., retroflection is obtained by activating the upper longitudinal actuator). Pulling all the cables at the same time causes the shortening of the arm and restores



(a) (b)

Figure 11. Octopus-like robot arm prototype in water: (a) at rest and (b) wrapping a human hand.



(a) (b) (c)

(d) (e) (f)

Figure 12. (a) Shortening and elongation. (b) Recovery of initial position after retroflection by longitudinal actuator activation. (c) Recovery of initial position after retroflection by transversal actuator activation. (d) Bending in the four main directions. (e) Increase of curvature by contraction of transverse actuators. (f) Schematic representation of the actuator positions.

the straight shape if the arm is bent. SMA actuators are used to elongate the arm or to increase its stiffness if longitudinal actuators are simultaneously activated and used as antagonistic actuators. Restoring the straight shape is possible also with this method. When a single longitudinal cable is pulled and the SMA actuators are activated, bending is increased because the actuated cable avoids the arm elongating linearly.

In the experimental trials, the main movements have been produced according to the following protocol (Fig. 12):

- Elongation is produced by contracting all the transversal actuators.
- Shortening is produced by pulling the four longitudinal cables of 30 mm.

Table 1.
Characterization of the robotic arm

Elongation	
maximum	35 mm (13%)
speed	8.7 mm/s
time for maximum extension	4 s
diameter reduction	
spring 1	12%
spring 2	10%
spring 3	8%
Shortening	
maximum	30 mm (10%)
diameter increase	
spring 1	7%
spring 2	3%
spring 3	2%
Global bending	
radius of curvature	63 mm
recovery time by longitudinal actuation	4 s
recovery time by transversal actuation	6 s
Equivalent flexural stiffness	
flexural stiffness	0.01 N/mm

- Global bending is obtained by pulling one single cable of 75 mm.
- Recovery of the straight position can be obtained by pulling the four cables or activating all the transversal actuators.
- Flexural stiffness is measured by applying a load to the arm between two constraints positioned at 60 and 180 mm from the arm base.

All the results are collected in Table 1.

Elongation is a measure of the transverse actuator performances: the mechanics of the braided structure forces the elongation of the arm when its diameter is decreased by the activation of SMA springs. Characterization involves diameter reduction, speed of elongation and maximum elongation reached.

The shortening depends on the action of all the longitudinal actuators together: maximum shortening and diameter augmentation has been measured.

Dynamics of bending has been recorded during retroflection movements and the tip has been tracked. The middle line of the arm has been tracked for four conditions: initial, final and two intermediate positions during movements (Fig. 13), and the maximum curvature has been derived from the last frame.

Passive properties have been described as the time taken by the arm to return to the initial position from the retroflexed position.

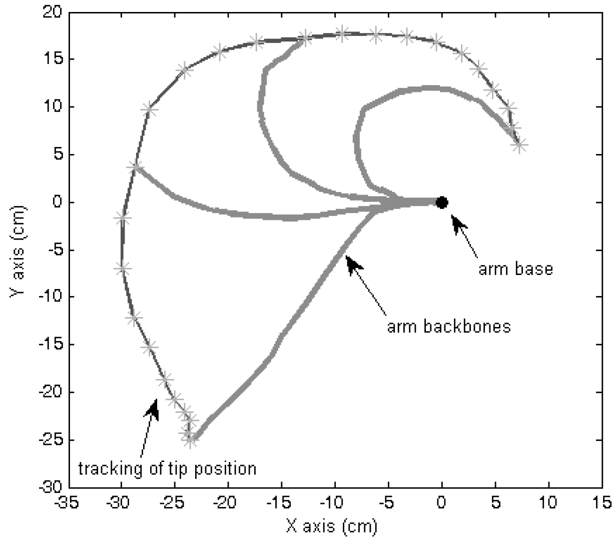


Figure 13. Tracking of tip and backbone of the arm during retroflection. Arcs represent the backbone of the arm at four moments of the movement. The outer curve is the trajectory of the tip, while markers are the tip position tracked every 500 ms.

Finally, the stiffness of the arm has been considered as the ratio between a weight loaded at a certain position between two constraints and the resultant deflection of the arm.

The results listed in Table 1 are under the target expected, mainly regarding elongation and speed. The performances of the reduction diameter and, consequently, also the elongation are under the design expectations mainly for manufacturing issues. The manual fabrication of the springs introduces small errors in the geometrical dimensions of the springs and in the passive wire length between two adjacent springs. The performances of the actuators are very sensitive to these geometrical parameters and thus they are consequently under expectation. In order to exclude any other error deriving from the model, a supplementary test has been carried out. Even if the model has been already validated, the numerical experimental results listed in Table 1 have been used in the model to predict the elongation of the structure under such conditions. The resulting elongation is 33 mm (against 35 mm measured), which confirms the model goodness and suggests that a reduction of 20% in the diameter would ideally lead to 89% elongation.

However, slow elongation speed is partially due to intrinsic friction of the structure, and the load and inertia that has to be opposed to reach the maximum extension. To solve this issue, oversizing the force exerted by the springs is taken into account after an experimental investigation. In this way, resistant forces of the arm become less influential on the elongation dynamics and do not decrease the movement speed.

7. Conclusions

This paper presents the first prototype of an octopus-inspired robot arm, reproducing the basic mechanism of the biological muscular hydrostat.

The robot arm demonstrates the octopus muscular hydrostat principle by possessing the key elements, such as longitudinal and transverse contractions, external mechanical support structure allowing large deformations but keeping the shape and sinusoidal arrangement of internal fibers.

The prototype presented in this paper is completely soft and compliant when relaxed, with the possibility of bending in all directions at any point along the arm, of stiffening and of elongating.

The longitudinal actuators produce bending along four main directions, reaching a radius of curvature of 63 mm. When actuated simultaneously, they produce a shortening of 10% and a diameter increase of 7%.

The transverse actuators produce diameter reductions and consequently an elongation of 13%, with a relation between elongation and diameter reduction corresponding to the model of the braid deformation, coherent with the deformation mechanism of the muscular hydrostat.

Even though the current prototype, built with the current manual manufacturing process, does not match the values of elongation of the octopus arm, it demonstrates the validity of the muscular hydrostat concept. It demonstrates that it is possible to reproduce the key mechanism of the muscular hydrostat with robotics technologies, and that it is possible to obtain a completely soft and compliant robot arm, with good dexterity.

This same prototype is being improved with more accurate manufacturing to achieve better performance in terms of contraction range and time, but it provides principles and it opens up perspectives for the development of soft robots, even with different technologies.

In conclusion, this work represents an example of biomimetics (i.e., of effective translation of biology into robotics) because it applies the key principles of the biological model and it demonstrates a concept of general applicability.

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