Skins and Sleeves for Soft Robotics:
Inspiration from Nature and Architecture

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Abstract

This paper is on the design, fabrication and testing of skins and sleeves for soft robotics with the focus on the mechanical features of the microstructure of these skins, drawing inspiration from nature and architecture. Biological inspirations drawn from animals are used for designing skin membranes or skin structures for soft robotic actuators, in particular pneumatic actuators, that protect, guide and contribute to the development of the actuated shape. The results presented in this paper will be a new step towards advancing the state-of-the-art of biologically inspired soft robots for minimally invasive surgery. Inspirations from architecture are of particular interest in the areas of formability of design and continuous flow. The report presents a trade-off study using various skin and sleeve technologies of innovative fiber structures and combinations of different materials in different innovative designs, surrounding a pneumatically actuated, soft robot of variable stiffness.

1. INTRODUCTION

There has been much interest recently in soft robotics for many applications such as swimming robots imitating fish,^[1] creeping, crawling robots imitating worms,^[2-3] flying soft robots imitating the soft tissue and connecting membranes of bird wings or insect wings,^[4] antagonistic expansion /contraction soft artificial muscles,^[5] climbing robots with suckers imitating octopus,^[6] multigait soft robots.^[7] Medical applications including diagnosis and robotic surgery are a key application field for soft robotics, ensuring safe interaction with soft tissues and organs, deformation and navigation through narrow orifices and narrow passages between organs, flexibility and maneuverability of soft manipulators with fluid-like motion.

Soft robotics is based on a number of actuation mechanisms, very often involving advanced materials and nanomaterials. Volume changing hydrogels^[8-10] based on water diffusion in (swelling) or out (contraction) lightly crosslinked hydrophilic microstructures under change of pH, temperature, chemical, magnetic or electrical stimulus can act as actuators but with a rather slow response due to the relatively low rate of water diffusion. Electroactive polymers^[11] or carbon nanotube-containing nanocomposites^[12] can reach high degrees of actuation under relatively small electric fields but these are soft materials which also exert a low actuation stress. As a result, although they may provide fast and high level of actuation, the actuated shape is not stabilized with a high degree of stiffening during and after actuation. Stiffening of the actuated shape is an important requirement of robotic surgery if soft robotics is to replace the current robots with rigid manipulators. Photoresponsive polymers and nanocomposites are another family of materials with potential use in soft robotics. Silicone-based carbon nanotube nanocomposites^[13] demonstrate light-stimulated actuation but as soft materials suffer the same problem of low actuation stress and lack of significant stiffening of the actuated shape. Shape memory alloy (SMA) wires may be used to create actuation in soft robotics,^[14] usually in coil or meander shapes to effect a significant degree of deformation: however, they are not very popular in medical robotic surgery due to their cost,

significant stiffness difference between them and the host soft matrix that may cause debonding at the interface under stress, and the power requirements for the associated robotic manipulators.

Pneumatic actuation has always been used for robots and has also become popular in the field of soft robotics, as it has the advantages of fast response, low-cost and great potential for many types of associated designs and corresponding modes of actuation.^[15] Ingenious designs of pneumatic networks can bring intelligent actuation patterns and create coordinated system motion or deformation.^[16] On the other hand individual pneumatic chambers can create bending modes in different directions via mechanisms of chamber elongation or ballooning effect. Figure 1 displays a soft cylindrical module with three pneumatic chambers which upon individual pneumatic actuation offer bending in three directions. Figure 1 presents the bending of the module under pneumatic actuation of one chamber, which causes ballooning in that chamber and elongation overall as is outlined on the photograph of Figure 1. In such cases, although the ballooning effect is instrumental in realizing bending, it displays the disadvantages of a cumbersome volume during navigation and maneuvering through narrow passages and the risk of bursting.

Figure 1. Model of cylindrical silicone module of 25 mm diameter (when underformed) with three pneumatic chambers of semi-circular cross-section; photograph of bending under one chamber pneumatic actuation and ballooning effect outlined with dotted line.

The aim of this study is to explore different types of skin to contain and restrict the ballooning effect while the skin microstructure guides and modifies the actuation shape and mode. The traditional roles of skin in nature are to protect tissues and organs, to control diffusion and osmosis, to control temperature and to sense. However, the focus of this study is on the mechanical performance of specially tailored skins or sleeves around a soft, pneumatically actuating robot arm and how it may be related to its microstructure. Skin in nature is generally made from a web of fibrils (made from collagen, elastin and other related biomaterials depending on the animal) in various configurations: random fibril mat, woven-like pattern, layers of different unidirectional orientation. Of interest in this study are also muscle fiber structures in nature, especially skin underlayers, and their role in mechanical forming depending on fiber orientation. The term “skin” is also used in the field of composite materials where “skin-core” configurations may exist with the skin consisting of fiber-matrix composite material, where the fibers are mainly continuous fibers in the form of layers of different fiber orientation in each layer, woven fabrics, knitted fabrics or braided fabrics. The skin in such cases is critical for the mechanical performance, and its microstructure, including local fiber orientation and fiber volume fraction, plays an important role in deformation, warping and even actuation of such structures. Finally, one may also explore and draw inspiration from architecture with the focus on the formability of design to achieve curvilinear shapes as well as structural and mechanical stiffening.

2. DESIGNS AND RESULTS

Different designs of sleeves and skin structures have been developed, inspired from nature and architectural forms, and their functionality is demonstrated in case-studies. All case-studies incorporate the same soft silicone-type of module, the undeformed model of which is displayed in

Figure 1 with a diameter of 25 mm (when undeformed) and three pneumatic channels of semi-circular cross-section. All case-studies include the test of one-chamber pneumatic actuation, so that the module's response would be one-degree bending. The case-studies include different types of sleeves and skins, their structure and microstructure inspired mainly from nature and in some cases architecture, with the main aim to reduce the ballooning effect and, if possible, to facilitate and guide bending. In all cases, the presentation starts from the source of inspiration, continues with the investigated design of the structure and microstructure of the proposed sleeve or skin mimicking the inspiration, the experimental response of the corresponding skin-covered module under one-chamber pneumatic actuation of the inner silicone module, and in some cases the corresponding results of finite element analysis (FEA), using Abaqus, to clarify mechanisms of deformation and optimize the skin microstructure.

Figure 2(a) displays the skin of an elephant trunk in which ring folds and wrinkles are clearly visible that stretch as the trunk is bent and that part of the skin is extended. The skin of the elephant's trunk is thick, 2.5-3 cm thick. Trunk motion, deformation and grasping takes place via the action of about 100,000 muscles in the core of the trunk that offer good flexibility and excellent strength. Corrugated sheets have been used in designs of foldable structures and feature greatly in the origami technique.

(c)

(d)

Figure 2. (a) Sketch of elephant trunk with ring folds and wrinkles in its skin. (b) Bellow-shaped sleeves for the silicone module of Figure 1 under one-chamber actuation; left: plastic folded sleeve; right: crimped braided sleeve.^[17] (c) FEA of the one-chamber pneumatic actuation of the silicone module of Figure 1 wrapped by the crimped braided sleeve; left: side views; center and right: cross-sections; right: enlarged cross-section detail. (d) One-chamber actuation of the silicone module of Figure 1 wrapped by a crimped Dacron[®] vascular graft-type of sleeve.

Figure 2(b) presents two paradigms mimicking the folded skin in Figure 2(a). In these the pneumatic chamber- actuated, soft elastomeric robot module of Figure 1 is wrapped by a bellow-shaped sleeve that allows axial extension and compression, free rotation and bending while the fact that the bellows can expand to the limit of an extended continuous tubular skin offers the advantage of constraining the ballooning effect of the actuating chamber. The sleeve was either a crimped plastic shell or a crimped tubular braid made from PET or nylon tows.^[17, 18] Such crimped braided sleeve constrains the ballooning effect and maintains constant curvature in the one-degree of freedom bending, as is demonstrated in Figure 2(b). However, such braids are rather rough running

the risk of causing erythema, tissue tears and bleeding^[17] in abdominal robotic surgery. Finite element analysis (FEA) of the one-chamber actuation was carried out for the combined silicone module-crimped braided sleeve using hyperelastic constitutive models^[19] for both silicone and crimped braid. Figure 2(c) presents the Abaqus FEA results: the right hand side mesh-von Mises stress contour shapes refer to the module cross-section where the different meshes can be seen for the different materials (silicone and crimped braid) and the different parts of the design, distinguishing the actuating pneumatic chamber. Upon actuation, it can be clearly seen that the expanded chamber molds itself into the extended braided sleeve, which upon full radial expansion constrains the ballooning effect.

Figure 2(d) depicts the next step in our search of a better soft robotic skin simulating the skin of the elephant trunk. In this case a crimped woven Dacron[®] vascular graft was investigated as the sleeve of the pneumatically actuating silicone module. The actuation proceeded successfully with the “skin” restricting the ballooning effect and maintaining constant curvature in the bent module. The additional advantage of the vascular graft-type of skin in soft robotics for medical applications is that it is relatively soft weave, would not cause any injury to tissues and organs, is biocompatible and well tested for medical applications.

Caterpillars have a segmented body of hydrostats that can be seen from the tight skin fit in Figure 3(a). Soft-bodied hydrostats, such as caterpillars, starfish and octopi have a central cavity filled with liquid surrounded by a well-designed muscle system in the form of fibers forming the cavity wall and skin underlayer of the bodies that activate motion and body deformation while regulating the local pressure. Hydrostatic motion and crawling in caterpillars is achieved by circumferential muscles that exert transverse pressure and longitudinal muscles.^[20] Caterpillar designs in architecture use the huge formability of sequential structural ring structures to develop imaginary aesthetics, which may also combine membrane skins or inflated double membrane skins (as in the

Caterpillar Auditorium designed by Marvin Bradke^[21]) with continuous flow through communicating, open, segmented spaces.

Figure 3. (a) Sketch of caterpillar *Hypsipyla grandela*. (b) One-chamber actuation of silicone module with three pneumatic chambers of semi-circular cross-section (Figure 1) and skin with circumferentially oriented fiber tows. FEA of the one-chamber pneumatic actuation of the silicone Ecoflex 0050 module of Figure 1 wrapped by (c) Sylgard 185 silicone rings, (d) ABS rings and (e) nylon cord rings.

Maintaining the soft silicone module with the three pneumatic channels of Figure 1 and drawing inspiration from the underlayer of circumferential muscle pattern in the caterpillar, a skin incorporating circumferential fiber tows was added surrounding the cylindrical surface of the silicone module. Figure 3(b) presents this paradigm of module in bending under one-pneumatic

channel actuation: the module achieves elongated bending while its surface contour mimics the segmental nature of the surface of a caterpillar body. The designed module in Figure 3(b) demonstrates significant stiffening upon full actuation due to both the remaining ballooning effect and the restraining and pressure-increasing action of the circumferential fiber tows. The disadvantage of this design for medical robotics is that the increase of the internal pressure and multiple surface bumps raise the risk of balloon-bump bursting, especially for the last balloon-bump at the tip of the module which seems to be under the highest pressure.

Figures 3(c)-(e) present FEA simulations (using Abaqus FEA) of three skin designs for the silicone Ecoflex 0050 module, inspired by the appearance of the caterpillar skin surface and the circumferential muscle fibers in the caterpillar skin underlayer. In Figure 3(c) equally-distant bands from Sylgard 185 silicone were placed on the skin, where Sylgard 185 is harder than Ecoflex 0050 but still a different grade of silicone: the skin rings constrain the ballooning to a certain extent but do not eliminate it. In Figure 3(d) they have been replaced by ABS bands, a stiff plastic which totally ties the Ecoflex wall at the position of the bands but there are still very noticeable local ballooning bumps that are almost sure ready to burst. In Figure 3(e) the bands have been replaced by nylon cords at higher frequency than the tows in Figure 3(b): in this case FEA predicts that although there is some small swelling between the cords, there is no huge pressure and swell on the last compartment, but clearly the air pressure is relatively low.

Figure 4. One-chamber actuation of silicone module with three pneumatic chambers of semi-circular cross-section (Figure 1) and skin with a high density of circumferentially oriented fiber tows. Comparison with earthworm form on the left.

The next step displayed in Figure 4 presents another silicone module, pneumatically actuated using three chambers of semi-circular cross-section, currently bending under one-chamber actuation. The difference in the skin structure between Figure 4 and Figure 3(b) is that the skin in Figure 4 has a higher frequency of circumferentially oriented nylon fibers, which are in fact located in a particular dual-fiber pattern with the aim of achieving a compromise in the resulting deformation and ballooning. The so fabricated skin structure is compared to the skin appearance of earthworm with the distribution of its circumferential muscle fibrils in the skin underlayer.

Fiber skins for tubular structures under internal pressure in engineering (e.g. gas pressure vessels) usually include $\pm 45^\circ$ fiber orientations in the form of braided or knitted fiber tows or unidirectional layers of fiber tows at different angles manufactured by filament winding. The silicone module with pneumatic actuation chambers is in this category, hence, a skin with $\pm 45^\circ$ fiber tows was tried. Octopus is an important source of inspiration for soft robotics. Its skin on its tentacles contains suckers which also behave as multi-spot stiffeners and are connected as crosslinking stiffeners to the network of helical $\pm 45^\circ$ fibers^[22] in the octopus tentacles skin underlayer (Figure 5(a)). In the core of the tentacle there is the muscular hydrostat, which for the octopus consists of a system of

radial and longitudinal antagonistic fibers for elongation, shortening and bending of tentacles while the $\pm 45^\circ$ oriented muscular fibers in the skin underlayer cause torsion. The role of the helical fibers is also to provide a restraining and guiding outer network for the muscular hydrostat, in combination with the stiffening crosslinks of suckers.

(a)

(b)

(c)

(d)

Figure 5. (a) Octopus tentacles and tentacle skin with a network of $\pm 45^\circ$ helical fibers in the skin underlayer and crosslinking suckers. (b) One-chamber actuation of silicone module with three pneumatic chambers of semi-circular cross-section and skin with a network of compliant $\pm 45^\circ$ oriented fiber yarns. Two photos on the left: module of 60 cm initial length (Figure 1). The photo on the right: module of 70 cm initial length. (c) Module of 60 cm initial length (Figure 1) under one-chamber actuation with skin of denser network of compliant $\pm 45^\circ$ oriented fiber yarns than in (b). (d) Silicone module under one chamber actuation with skin of a dense network of compliant $\pm 45^\circ$ oriented fiber yarns and circumferential embroidery of chain stitch of nylon yarn.

Figure 5(b) presents a paradigm of the one-chamber pneumatically actuated silicone (with three pneumatic channels) with skin of compliant $\pm 45^\circ$ oriented fibers. Using the short module of 60 cm initial length, same as in Figure 1, did not achieve much bending although the channel expansion was homogeneous along its length. Using a longer module of 70 cm, more bending was achieved as expected while it is evident that the fiber network is smoothing the ballooning effect. Figure 5(c) presents a one-chamber actuating module of 60 cm length with a skin of compliant $\pm 45^\circ$ oriented fiber network denser than the skin fiber network of Figure 5(b). It can be seen that the denser network is guiding the actuation to a larger degree of bending. This is the first time that a homogeneous $\pm 45^\circ$ skin fiber network has achieved bending due to the fact that the current study used compliant rather than inextensible fibers used in previous works. The last study in the literature was that of Faudzi et al^[23] who used a dual fiber network pattern, with inextensible fibers: denser of the side of required compression and light network on the side requiring expansion. Although their design worked for one-degree of freedom bending, it cannot work for a module that has three-degrees of freedom bending (three pneumatic chambers). The compliant fiber network of the current novel skin gives the possibility to the compliant fibers to extend on the outer bending side and compress on the inner bending side (demonstrated in the schematics of Figure 5(c)), as required to effect bending, and in this manner the change in the density of the fiber network is achieved locally by the fiber network itself during bending rather than been prefabricated as Faudzi et al^[23] did. Finally, Figure 5(d) presents an innovative design of skin incorporating the network of compliant $\pm 45^\circ$ oriented fibers as in Figure 5(c) but also a novel, additional, embroidered fiber pattern in the circumferential direction: the aim of this last novel feature was to allow a certain degree of initial ballooning to initiate bending of the module but then to totally extend the circumferential stiff yarn so that it constrains any further radial expansion. This design limits the ballooning effect without the appearance of any local ballooning bumps (as in Figure 3(b)). Bending by more than 90° was achieved and the actuated module seemed very stiff as the constraining circumferential fiber yarns increased the pressure to higher levels than the inputted actuation air

pressure. The lack of any local ballooning bumps makes the module a robust and reliable actuator. Both chain stitch and zig-zig stitch were tried in the circumferential embroidery, with the chain stitch, demonstrated in Figure 5(d), proven more consistent.

Figure 6. (a) Sketch of the Dragon Skin Pavillion-Hong Kong (b) Design and FEA of a module with three pneumatic channels, under one-channel actuation to 90° bending; the Ecoflex 0050 module has a dragonskin layer near the surface with the corrugation gaps filled with the softer Ecoflex 0030 material. (c) Experimental study of the dragonskin containing module of (b) under one channel actuation at increasing pressure.

Inspired by the formability of dragonskin scales, the concept also been used in architecture given the high formability of dragon skin designs (Figure 6(a)), a three-pneumatic channel module was designed made from Ecoflex 0050, with a corrugated sheet of the harder Dragonskin 0030, and the corrugated sheet gaps were filled the soft Ecoflex 0030, as is presented in the CAD model of Figure 6(b). FEA of one-channel actuation to 90 ° bending in Figure 6(b) shows minimum ballooning for the innovative design. This was followed by a corresponding experimental study displayed in Figure 6(c) which shows that the new module can reach large bending angle with small extent of ballooning.

3. CONCLUSIONS

Pneumatic actuation in soft robotics cannot generally hold incompressibility as in the animal hydrostats of nature, in fact it leads to swelling and ballooning. A number of skin structures were designed after inspiration from nature and architecture and were investigated using FEA and assessed in in-plane bending experiments of one-chamber pneumatic actuation of modules with three pneumatic chambers. In a study of crimped skin sleeves, mimicking the folded skin of an elephant's trunk, it was concluded that crimped vascular grafts have the potential to provide a gentle interface between the robot arm and organs in medical applications while they readily provide a tested biocompatible solution. Innovative designs of smooth skin incorporating circumferentially oriented fibers, inspired from the body surface contour, skin and underlying muscular layer texture of caterpillars and earthworms, demonstrated the effects of different fiber distributions on the balloon shaping and degree of bending. Taking into account the $\pm 45^\circ$ fiber structure of the skin of gas pressure vessels made from composite materials in engineering and drawing inspiration from the helical fiber structure of the skin underlayer of octopus tentacles, similar fiber structure in the skin of soft pneumatically actuating modules smoothed the ballooning effect. Combining such $\pm 45^\circ$ oriented compliant fiber structures with restricting circumferentially embroidered fibers further

restricted the ballooning effect, increased elongation and bending, and further stiffened the actuated module. Finally, a combination of three different types of silicone materials of different softness, with the stiffer silicone used as an internal corrugated sheet under the soft module surface seems to offer great flexibility and bending ability with minimum ballooning while it presents a smooth external module surface in possible contact with the external environment.

4. Experimental Section

The main module was made of Ecoflex 0050 in all studies and was of cylindrical shape of 25 mm diameter with three pneumatic channels of semi-circular cross-section. The shape of the semi-circular cross-section was selected as it was concluded from FEA studies [19] that it minimized ballooning upon one-chamber actuation, compared to other shapes of the pneumatic chamber cross-section such as circular cross-section. A mold was used with the appropriate dimensions and inserts for the channels. Dragonskin 0030 was used to make the corrugated sheet structure in Figure 6 and Ecoflex 0030 was used to fill the corrugated structure gaps in Figure 6. All these three materials are different grades of platinum-catalyzed curing silicone of different shore hardness. These silicone materials came in two parts that were mixed together at 50:50 mass ratio. The mixture was subjected to vacuum for a period of 15 minutes to de-air and was then slowly poured in the appropriate mold. The silicone was allowed to cure in the oven at 120°C for one hour.

Acknowledgments

Research partially was funded by the European Commission's Seventh Framework Program under grant agreement 287728 in the framework of EU project STIFF-FLOP. We would also like to thank Miss Vicky Cosmas for the sketches from nature and architecture.

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