Bioinspired 3D Printable Soft Vacuum Actuators (SOVA): Towards Fully 3D Printed Soft Robots

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I. Introduction

We report on novel bio-inspired 3D printable soft actuators that can be actuated through vacuum (Fig. 1A and B). The actuation concept was inspired by the sporangium of the fern tree (Fig. 1E). More specifically, the concept was inspired by the structure and function of the annulus of the sporangium. The thin outer walls of the annulus allow water to evaporate from the cells when the sporangium is exposed to air (1). Consequently, the annulus bends, due to a negative pressure developed in each cell, which forces the radial walls to collapse (2). Our 3D printable actuators can achieve bending motion using the same principle when air is evacuated from each cell. When the cells collapse they shrink in volume and bend.

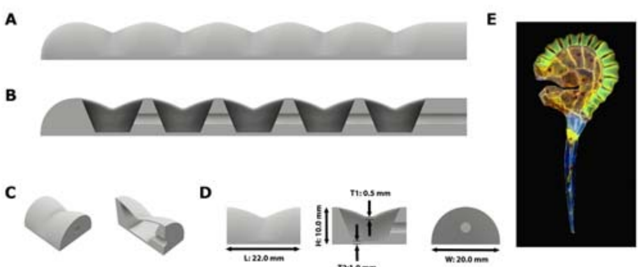

Fig. 1. Soft vacuum actuators (SOVA). (A) Soft actuator computer aided design (CAD) model (B) Section view of soft actuator CAD model. Pneumatic hinges are connected through a 3.0 mm diameter hole. (C) Pneumatic hinge CAD model (D) Pneumatic hinge dimensions. L: Hinge Length, T1: Hinge Wall Thickness, T2: Hinge Base Thickness, W: Hinge Width (E) Annulus of fern sporangia (Used with permission) (4).

Our bio-inspired soft actuators have many advantages. First, the soft actuators are fully 3D printed which allows easy, efficient and rapid manufacturing and customization. Second, soft pneumatic hinges can be printed separately which allows the realization of modular designs. The modular hinges allow the realization of soft actuators with multiple degrees of freedom and variable length. Third, two or more of such bending actuators can be connected in parallel to produce a linear actuator with a rectilinear stroke and a higher force output. Fourth, the actuation is accomplished through vacuum which eliminates the possibility of burst and bulging as in conventional pneumatic actuators and, therefore increases the lifetime and reliability of the actuators. Finally, many soft and hybrid robots, grippers and artificial muscles can be developed and activated using these soft vacuum actuators (SOVA) proposed in this study (3).

I. Blocked Force

The blocked force of the actuator (F_B) was measured using a force gauge (5000g, FG-5005, Lutron Electronic Enterprise CO., LTD) (Fig. 2A). Two soft actuators were placed and fixed facing each other (Fig. 2B). The two actuators generated $F_{B,Dual} = 31.41$ N under 90% vacuum. Since the actuators are placed symmetrically it can be concluded that a single soft actuator can generate $F_{B,Single} = 15.71$ N. In addition, the relationship between the force and pressure is nearly linear. The pressure was ramped up and down by a step of 10 kPa reaching a maximum negative pressure of -70 kPa. The very small hysteresis in the blocked force can be attributed to the fact that the actuator does not change shape in this specific setup.

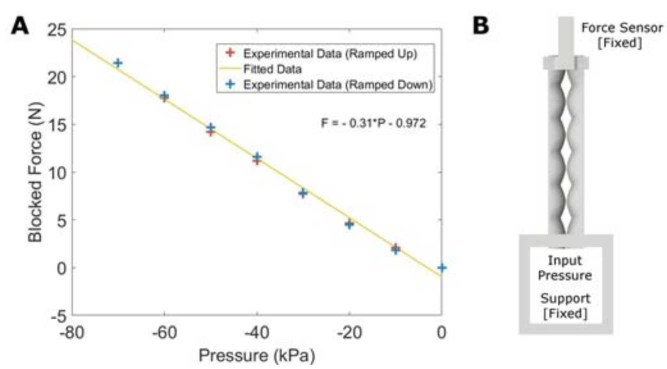

Fig. 2. Blocked force of SOVA. (A) Blocked force curve (B) Blocked force experimental setup.

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II. WALKING ROBOT

A walking robot was fabricated and actuated using four soft legs (Fig. 3A). Each leg is composed of two chambers. The main body of the actuator is made of 3D printed ABS plastic. The robot can move forward, backward and steer. In this scenario, the front and rear legs can be actuated independently. Ideally, each leg should be actuated separately so that the robot can steer by actuating specific legs. The presented robot is a proof of concept and will be further developed into an autonomous robot in future work. The actuation was achieved by applying vacuum for 900 ms and then returning the internal pressure of the legs to ambient pressure by opening a solenoid valve for a duration of 150 ms. The robot can move with an average forward speed of $v_f = 3.54\ cm/s$ which is $v_{fb} = 0.25\ body - length/s$.

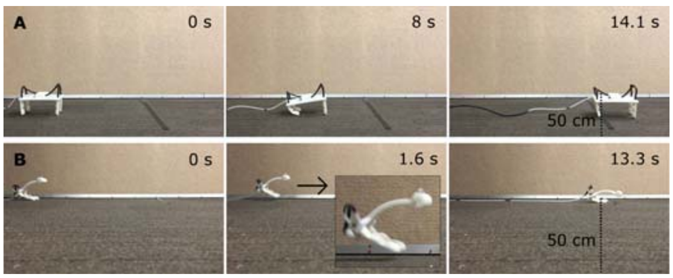

Fig. 3. Locomotion robots based on SOVA. Time sequence of locomotion robots (A) Walking robot (B) Hopping robot – Gongaroo

III. HOPPING ROBOT ('GONGAROO')

A hopping robot named Gongaroo inspired by our city of Wollongong and Australian kangaroos was fabricated and actuated using two main legs (Fig. 3B). The hopping is achieved by applying vacuum for 400 ms to the legs and quickly returning their internal pressure to the atmospheric pressure through a solenoid valve that opens for 150 ms. The average hopping speed of the robot is $v_f = 3.75\ cm/s$ or $v_{fb} = 0.39\ body - length/s$. The total weight of the robot is $m_{Gongaroo} = 64.62\ g$. The typical weight of a red kangaroo is 90.0 kg and its average height is 1.30 m. These animals have an average hopping speed of $4.81\ body - length/s$.

IV. ARTIFICIAL MUSCLES

The actuators can be used as an artificial muscle to rotate an elbow joint and move an arm (Fig. 4A). Two actuators were placed in parallel to each other. The ends of the muscle are free to move. The top ends are connected to the vacuum tubes and the bottom ones to the link representing the forearm through tendons. The maximum angular stroke of the muscle is $\theta = 115°$ when no load is applied. It took 1.03 seconds to reach the final position when vacuum was applied. In this specific scenario, the muscle lifted a mass of $m = 28.48\ g$ by a height of $h = 30\ cm$.

V. MODULAR ROBOTS

One important feature of the SOVA is the capability to 3D print pneumatic hinges that allow the construction of modular SOVAs. The hinges can be attached together through magnets (Fig. 3B and C). Small rare-earth ring and rod magnets are inserted in the hinges to connect them together. Here, we have demonstrated a soft actuator made of five hinges. The pneumatic hinges were connected using small plastic tubes. When negative pressure was applied, the modular actuator bent. The modular hinges can be designed in a way that each one can be actuated separately instead of being connected through plastic tubes to achieve multiple degrees of freedom. Therefore, the new actuation concept can be adapted to realize distinctive designs according to specific needs.

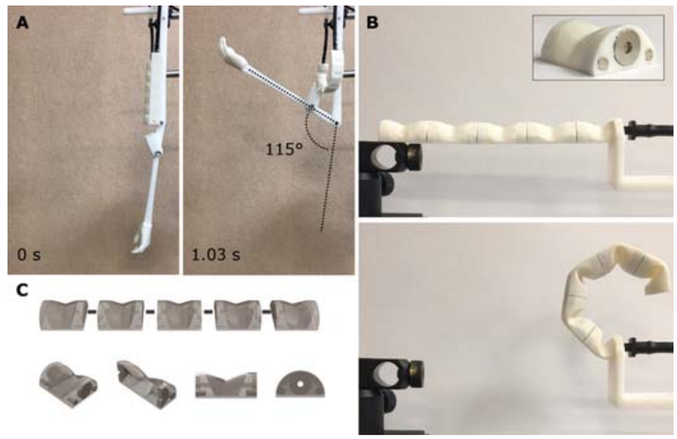

Fig. 4. Soft artificial muscles and modular actuators based on SOVA. (A) Soft artificial muscle – elbow angular stroke (B) Bending behavior of modular SOVA (Inset: 3D printed soft pneumatic hinge with magnets) (C) 3D computer aided design (CAD) model along with a single hinge model for the modular actuator

VI. CONCLUSION

We have developed bioinspired soft pneumatic actuators, SOVA, that can be actuated using negative pressure. The actuators have many distinctive advantages compared to conventional positive pressure soft pneumatic actuators. These actuators are fully 3D printed and customized according to specific applications. The characterization of the actuators showed that they could achieve high actuation frequencies and generate significant output forces. In addition, the behavior of the actuators can be well predicted using finite element analysis which can significantly enhance the design and optimization process. Therefore, the newly developed soft actuation concept can play a significant role in the development of soft actuators and soft robots.

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