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# A 3D printed monolithic soft gripper with adjustable stiffness

## Abstract

Soft robotics has recently gained a significant momentum as a newly emerging field in robotics that focuses on biomimicry, compliancy and conformability with safety in near-human environments. Beside conventional fabrication methods, additive manufacturing is a primary technique to employ to fabricate soft robotic devices. We developed a monolithic soft gripper, with variable stiffness fingers, that was fabricated as a one-piece device. Negative pressure was used for the actuation of the gripper while positive pressure was used to vary the stiffness of the fingers of the gripper. Finger bending and gripping capabilities of the monolithic soft gripper were experimentally tested. Finite element simulation and experimental results demonstrate that the proposed monolithic soft gripper is fully compliant, low cost and requires an actuation pressure below -100 kPa.

## Keywords

stiffness, soft, adjustable, monolithic, printed, 3d, gripper

## Disciplines

Engineering | Science and Technology Studies

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# A 3D Printed Monolithic Soft Gripper with Adjustable Stiffness

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***Abstract*—Soft robotics has recently gained a significant momentum as a newly emerging field in robotics that focuses on biomimicry, compliancy and conformability with safety in near-human environments. Beside conventional fabrication methods, additive manufacturing is a primary technique to employ to fabricate soft robotic devices. We developed a monolithic soft gripper, with variable stiffness fingers, that was fabricated as a one-piece device. Negative pressure was used for the actuation of the gripper while positive pressure was used to vary the stiffness of the fingers of the gripper. Finger bending and gripping capabilities of the monolithic soft gripper were experimentally tested. Finite element simulation and experimental results demonstrate that the proposed monolithic soft gripper is fully compliant, low cost and requires an actuation pressure below -100 kPa.**

***Keywords—soft gripper, monolithic, compliant actuator, 3D printing, variable stiffness.***

## I. INTRODUCTION

Robotic manipulation is an extensively studied research field that requires successfully gripping an object and maintaining the gripped configuration. Grippers have a long history in conventional robotics for handling targeted objects. Developing a universal gripper is yet a challenge in order to handle various objects with different shapes, form and surface texture. Conventional robotics focuses on rigid link and fixed degree of freedom robots that can perform required tasks with a high precision. Control of these robots are also relatively less sophisticated due to their unchanged link dimensions and known kinematics. Recent research efforts in robotics is towards more biologically inspired robotics with robots mimicking continuous body deformation of their natural counterparts such as elephant trunk [1, 2], an octopus arm [3-5], a snake [6-8], a fish [9], a worm and a caterpillar [10-12]. Namely, soft robotics, as an emerging research field, focuses on exploiting material properties in order to realize novel robotic systems and devices with more natural kinematic motions. Soft robotics is a multidisciplinary research field bringing expertise from various disciplines such as materials science, mechanical, electrical and control engineering, biology, chemistry, and many more [13].

The soft robots reported in the literature are primarily bio-inspired robots that are fabricated using soft and stretchable materials with low elastic moduli in order to enhance their deformability. These robots exhibit not only high dexterity and compliance but also they are conformably adaptive to their environments when in contact with an object. Such properties are desired especially when the robot will perform its tasks in a near-human environment. Adaptability, in other hands, of a soft robotic structure is used as an advantage to actuate these robots with a single input making them under-actuated. This feature is highly advantageous for robotic systems for grasping tasks such as a robotic gripper or prosthetic fingers and hand [14-16] making them conformable to the grasped object without needing additional sensory feedback and force control. Similar to a conventional robotic system, a soft robot consists of three major components; mechanical structure, actuator(s) and sensor(s). However, soft robots can incorporate actuator design within the structure eliminating external actuation system such as using pneumatic networks (PneuNet) [17].

While various actuation systems are proposed for soft robots in the literature, two major groups of actuation stand out: external actuation or actuation through a structural material (i.e. internal). Pneumatic [14, 17] or hydraulic actuation [18], tendon cable driven by an electric motor [16], more recently combustion power [19] are external actuation methods used in soft robots. Conducting electroactive polymers [20], dielectric elastomers [21], hydrogels [22], shape memory alloys [12] belong to the secondary actuation method are partially or fully incorporated within the structure of a soft robot. External actuators are for macro-sized soft robots where they can generate relatively high force output. On the other hand, up-to-date active materials have been found either to generate a low force output in comparison to external actuation systems or to have a very low energy efficiency. Conducting electroactive polymers require as low as 1.0 V electrical potential and have a high force output to weight ratio, however, their actual force output makes them suitable for micro- or mili-domain robotic applications. In comparison, dielectric elastomers require high operating voltages above 500 V. Hydrogels have recently been proposed as soft actuator materials that change their shape and volume under different hydration and temperature conditions. However, their response time is quite high and reversibility is one of their major challenges. Shape memory alloys that are also potential candidates as soft actuators replacing tendon cable driven type actuation eliminate the use of an external motor. Their efficiency is quite low due to energy loss to heating and dissipating the heat gained is yet a challenge that is directly related to the reversibility of the shape memory alloy actuators [23].

Fabrication techniques for soft robots are limited due to lack of compatible materials. These methods primarily molding techniques [24, 25] and shape deposition manufacturing (SDM) [26]. Various types of silicone rubber such as EcoFlex, which has been mostly used, have found a place within the structure, actuator and sensor part of soft robots. Depending on the complexity of the topology of a soft robot, a number of steps are followed to fabricate various parts of the soft robots entirely from silicone rubber or partially from rigid materials to provide extra support within the structure. As a state of art technology and their increasing availability, additive manufacturing techniques (a.k.a. 3D printing) are also employed either to fabricate molding parts or directly soft components of a soft robotic device. However, the higher is the complexity of the component or entire soft robot, the higher are the number of operations or fabrication steps and parts of the robot. The monolithic fabrication approach that is based on directly using an additive manufacturing method would provide significant momentum in fabrication of those soft robotic devices with highly complex shapes. Some of the recent studies use 3D printing as a direct fabrication method to tailor soft actuators using photo curable resin with stereolithography-digital light processing (SLA-DLP) [27] or a flexible filament with fused deposition modeling (FDM) [28].

3D printing can be used to fabricate a soft robot monolithically as one piece that is ready to operate out of one-step-fabrication. In this study, Fused Filament Fabrication (FFF) type additive manufacturing method has been used to fabricate monolithic soft grippers. FFF, interchangeably used with FDM, has a number of advantages over other additive manufacturing methods. FFF method has gained popularity due to primarily the material availability, its cost effectiveness and accessibility among other additive manufacturing methods such as SLA-DLP or SLS printing that are also employed for 3D printing rigid as well as soft materials. However, the FFF method is usually referred as an unreliable fabrication method for particularly airtight robotic structures unless the printing wall thickness is set larger than 1mm. Our previous work [31] demonstrated that airtight lower printing wall thicknesses can be achieved using this method. In this study, we designed two different monolithic soft grippers; one with passive finger bellows and the other with adjustable finger stiffness. These structures are simulated and were fabricated as airtight monolithic soft grippers, and their characterization were conducted. We optimized printing settings to fabricate very thin-wall monolithic soft grippers with an average wall thickness of 0.58 mm. The monolithic soft grippers were pneumatically actuated and their bending capabilities and force outputs were tested. Middle pneumatic chamber of the monolithic soft gripper is vacuum-actuated and fingers are pressure-actuated.

## II. Additive Manufacturing Methods and Materials for Soft Robotics

Aforementioned fabrication methods, molding and SDM, for building a soft robot require not only a long procedure but also fabrication skills developed in order to ensure a repeatable outcome. Additive manufacturing (AM) are alternatively very promising for fabricating parts of a soft robot or entire robot as simple as a cantilevered-beam-like bending actuators [28] or as complex as a prosthetic finger or hand including sensors [29].

Rapid prototyping has been commercialized and used since early 1980s in order to test scaled models of products using AM techniques [30]. 3D printing is nowadays used as a synonymous term for many additive manufacturing technologies including fused deposition modelling (FDM) or fused filament fabrication (FFF), selective laser sintering (SLS), stereolithography (SLA) and powder bed fusion (PBF). In this study, FFF method has been used in order to fabricate the monolithic soft grippers due to accessibility and low cost in comparison to other AM methods.

### *A. Design and Fabrication of the Monolithic Soft Gripper*

Design of the monolithic soft gripper developed in this study relies on the pneumatic actuation incorporated with all-in-one-piece fabricated topology. In other words, it is a fully compliant mechanism, using the FFF 3D printing. The design of the grippers are inspired from a bellow-structure, which performs contraction – extension by folding – unfolding its bellows when an internal negative (vacuum) or positive pressure is applied. Positive pressure is a commonly used method to actuate a soft actuator to perform bending, extending or twisting. In our previous work, we demonstrated a soft gripper by incorporating the bending type soft actuators within same structure for monolithic fabrication by using positive pressure, so-called fingers of the gripper performing a grasp [31].

In this study, we develop two types of monolithic soft grippers: (i) a soft gripper with a variable finger length and (ii) a soft gripper with adjustable finger stiffness, as demonstrated in Fig. 1. Negative pressure was used to actuate (contract) the middle bellow in the monolithic soft gripper that is the main actuation element for gripping. The fingers of the monolithic soft gripper are either not pressurized or filled with positive pressure for varying their stiffness. The fingers can be actuated with one pressure source in order to vary its properties simultaneously or can be actuated with two-pressure sources individually for gripped-manipulation (in hand manipulation). Gripped manipulation is out of scope of this paper. Interconnecting links with a thickness of 2 mm, and flexure hinges with a thickness of 0.9 mm are designed to connect the fingers to the middle bellow in order to provide compliance and provide finger flexions through the middle bellow contraction. We design the wall thickness of the gripper bellows as 0.5 mm. The overall dimensions (height, width and depth) of the monolithic soft gripper are 49.7 mm, 47.7 mm and 12.5 mm, respectively. We design a wall with pockets in the fingers (Fig. 1b) in order to adjust the finger stiffness of the soft gripper by varying the positive pressure in the fingers. The pockets on the stiffness wall ensures the air passage throughout the finger as well as constrains the fingers expanding and lengthening.

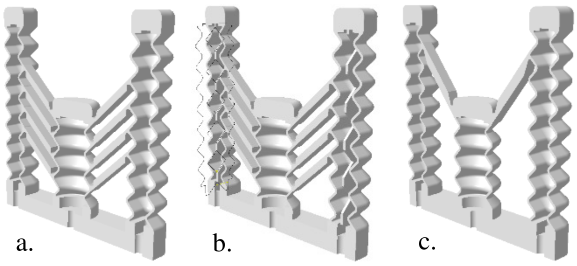


Fig. 1. Soft monolithic gripper designs: a. a halved model of the gripper without stiffening wall, b. a halved model of the gripper with stiffening wall and c. a halved model of the gripper without stiffening wall with one interconnecting-link.

By employing an FFF type 3D printer (Flashforge Creator Pro), the monolithic soft grippers were fabricated. We used an open source slicing software (Slic3r) to prepare the printing patterns and settings. The 3D printing z-resolution was set to 0.1 mm while the printing speed was set to 10 mm/s. The extrusion temperature was set to 235 $°C$ to ensure adequate adhesion between the layers. The printing parameters were adjusted carefully to achieve airtightness. We applied 5mm retraction with a speed of 40 mm/s in order to eliminate jump lines which occur due to stretchability of the thermoplastic elastomer filament material. A fabricated bellow sample and the soft gripper with its CAD model are presented in Fig. 2 in Fig. 3, respectively.

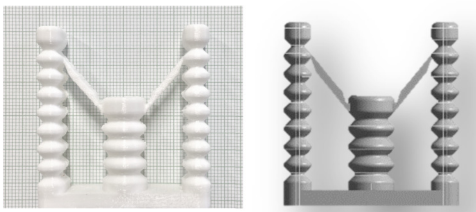

Fig. 2. 3D printed soft monolithic gripper (fabricated on the left and the CAD model on the right).

## *B. Materials*

ABS, PLA and nylon filaments, which are thermoplastics (TPs) are commonly available FFF based 3D printing materials which are rigid when solidify after extrusion. These materials can exhibit a reasonable flexibility and strength; however, softness and stretchability are the desired properties from a material to be used for fabricating a soft robot. A number of commercially available thermoplastic elastomers (TPEs) and thermoplastic polyurethanes (TPUs) that have recently been developed are physically mixed copolymers. We identified the NinjaFlex (NinjaTek) as a suitable candidate for our monolithic soft grippers that has a slightly higher elastic modulus than the FilaFlex (Recreus) [32].

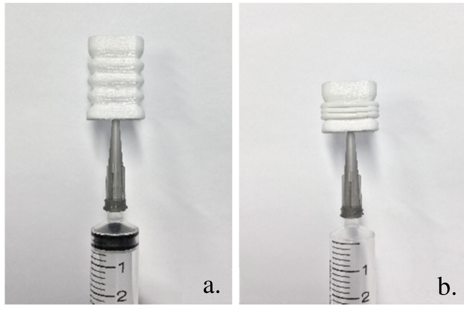


Fig. 3. A 3D printed airtight bellow sample a. in it is neutral state and b. in its under-vacuum state.

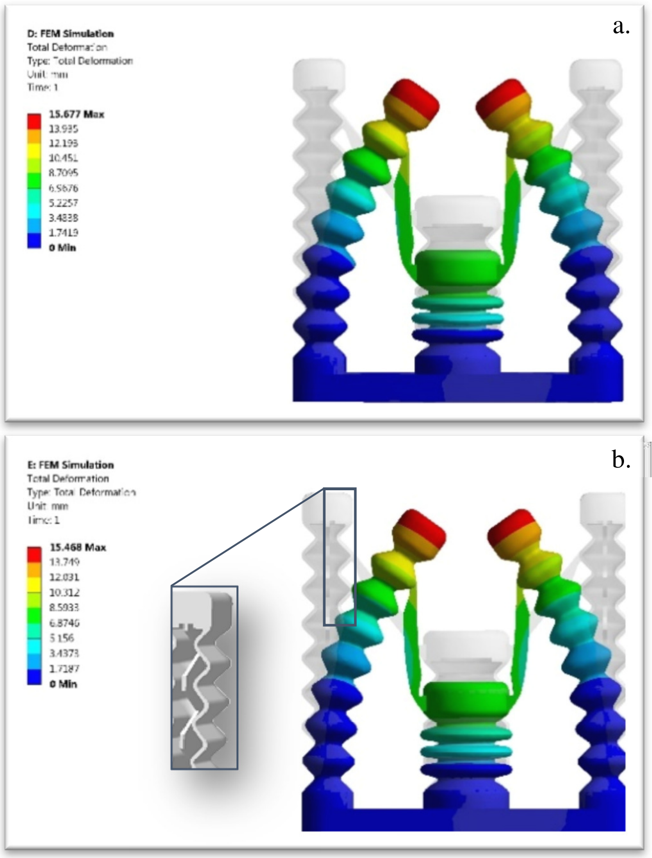


Fig. 4. FE model (on the middle) and simulation results of a. without stiffening wall, and b. with the stiffening wall outlined and internal structure is presented on the zoomed image.

## *C. Finite Element Analysis (FEA)*

Finite element (FE) simulations are conducted to estimate the bending behavior of the gripper as well as optimize its shape (including the number of interconnecting links), gripping, finger bending capabilities and stroke. Ninjaflex is modeled as a hyperplastic material using a 2-parameter Mooney-Rivlin Hyperelastic model fitted to experimentally obtained strain-stress results for the material. The non-linear FE simulation is conducted in ANSYS Workbench using the Static Structural Analysis. While the bottom part of the model of the gripper is fixed, various pressure inputs are applied on the internal surface of the bellow chambers in the model. FE model deformation results for both grippers with and without stiffness wall are very similar when the fingers are not pressurized. These FE simulation results are shown in Fig. 4. A preliminary shape optimization has been conducted to optimize the gripper chamber design, which has rectangular cross section (CS) for fingers and circular CS for the middle bellow. The number of interconnecting-links and their arrangement has also been included in this preliminary optimization process with a criterion of increasing grasping capability of the soft gripper.

## III. Experimental Results and Discussion

Experiments were conducted to verify the FE models of the monolithic soft gripper. The grippers were actuated by applying a negative pressure to the middle bellow. Images of the grippers were taken with a grid paper parallel to the operating plane of the gripper using a digital camera (Nikon D5600). The bending rates of the fingers of the gripper were analyzed using the images of the gripper. A standard vacuum pump (Single Stage Rotary Vane) was used as a negative pressure source. In order to apply the positive pressure to the fingers of the gripper, a programmable logic controlled (PLC) pneumatic system was used. A photo of the experimental setup is shown in Fig. 5.

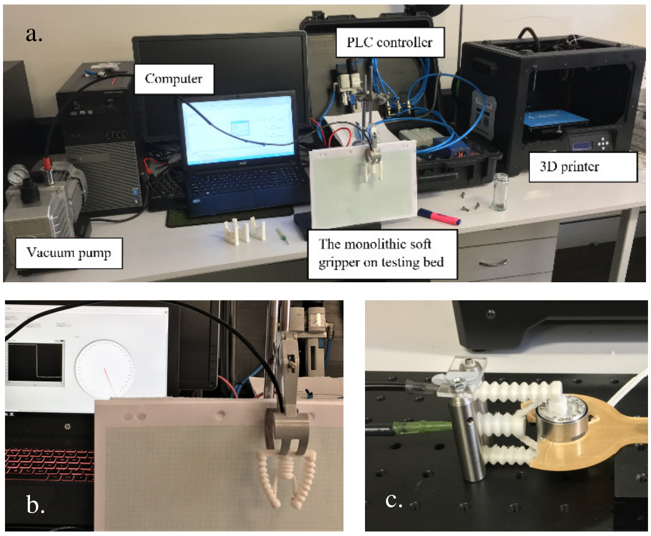


Fig. 5. a. Experimental setup, b. Displacement measurement and c. Blocking force measurement rig.

It was observed that the negative pressure applied to the middle bellow of the gripper played a key role for the actuation, therefore, bending of the finger bellows and gripping capabilities, as presented in Fig. 6 and the blocking force output measured from the tip of the finger bellow without and with stiffening effect in Fig. 7. On the other hand, the positive pressure applied to the finger bellows showed less significance on changing the finger length of the monolithic soft gripper; it exhibited a stiffening effect on the fingers. Similarly, the monolithic soft gripper with the stiffening wall in the finger bellows showed an increase in the stiffness of the fingers while not showing any geometrical dimensional changes seen in the gripper without the stiffening wall. The stiffness wall constrains the finger bellows and prevents expansion either in longitudinal or in depth directions and provides not only stiffer fingers for a higher force gripping but also complements bending of the finger bellows and helps close the gripper. In the width direction, negligible expansions were observed. However, the length of the finger bellow did not show any change in its dimensions. The stiffening wall behaves as a constraint on the finger bellows similar to a tire that is inflates a soft chamber with inextensible fibers. Gripping capabilities of the monolithic soft grippers are shown in Fig. 8; the stiffness increase helps enhance the load carrying capacity of the monolithic soft gripper. The use of fibers or inextensible materials as the secondary material in the soft robotic structures and actuators have been used in the literature in order to facilitate the directional deformation of the soft robotic fingers. Based on the monolithic topology of the grippers reported in this paper, our design provides not only simplicity but also eliminates the need for a secondary material, which complicates the fabrication of the soft robotic devices. This study provides a simple and efficient solution to this problem. While the bellows of the soft gripper were pressurized or negative pressure was applied, no control algorithms has been considered in this study: pressure was on and off for stiffening effect. As the primary purpose of this study is to demonstrate the concept of the 3D printable all-in-one piece soft gripper with variable stiffness, this paper reports on the design, fabrication and testing the soft gripper, and control design for stiffness variation is planned for future directions of this study.

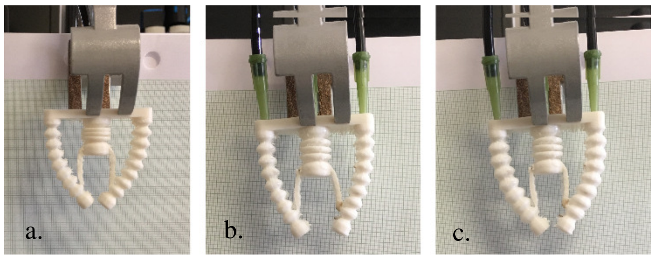


Fig. 6. Experimental results: a. The soft gripper without stiffenning wall was actuated by vacuum only in the middle bellow, b. The soft gripper with stiffenning wall was actuated by vacuum only in the middle bellow and c. The soft gripper with stiffenning wall was actuated by vacuum only in the middle bellow and pressure in the finger bellows.

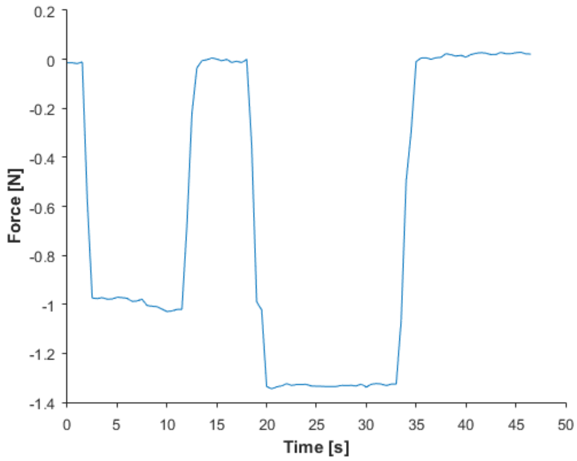


Fig. 7. Blocking force measurements and stiffening effect (Blocking force measurement test rig is presented on the photo (force values are in compression).

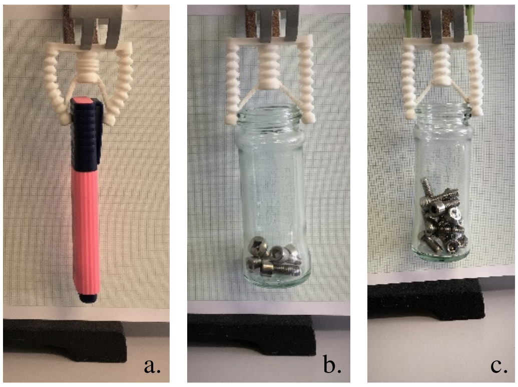


Fig. 8. Testing the monolithic soft grippers: a. and b. without and c. with stiffening wall holding a marker, a jar with maximum weight of 100 g and 180 g, respectively. (-100kPa vacuum was applied into the middle bellow at a. and b., and -100kPa vacuum was applied into the middle bellow and 100kPa into the finger bellows)

## IV. Conclusions and Future Directions

A monolithic soft gripper has been developed and simulated using non-linear finite element analysis in order to predict its bending and gripping capabilities. A stiffening wall design is introduced to adjust the stiffness of the fingers of the monolithic soft gripper. A preliminary shape optimization has been conducted to optimize the gripper chamber design. The monolithic soft gripper was fabricated by employing an FFF type 3D printing, with an average wall thickness of 0.58 mm, and actuated using a negative pressure in the middle bellow. In addition, the finger bellows were tested with a positive pressure in order to validate the variable stiffness of the fingers of the gripper.

Our future work will focus on a detailed optimization of the monolithic soft gripper while using a combination of negative and positive pressures applied to the gripper. Designing a control scheme for stiffness regulation will also be studied.

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