Available online at www.eccomasproceedia.org
Eccomas Proceedia SMART (2023) 64-75

ECCOMAS Proceedia

X ECCOMAS Thematic Conference on Smart Structures and Materials
SMART 2023
D.A. Saravanos, A. Benjeddou, N. Chrysochoidis and T. Theodosiou (Eds)

ADDITIVE MANUFACTURING OF FUNCTIONAL RUBBER BASED STRUCTURES FOR SOFT ROBOT GRIPPERS

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Abstract. New and more advanced soft robotic applications increasingly also shift the research effort towards the development of advanced manufacturing techniques. Besides silicone casting, additive manufacturing has developed to one of the most well known and most popular manufacturing techniques for soft robots. Additive manufacturing enables the efficient manufacturing of complex geometries, such as functional infill structures. However, so far additive manufacturing of soft robots was mainly limited to 3D printing of silicone and flexible thermoplastic polymers (TPE) such as TPU. While the fabrication process for these materials is relatively easy, the material properties of rubber are superior for many soft robotic applications. However, the printing of rubber material is still an open question. In this contribution, the 3D printing of rubber based soft robots by means of a Direct-Ink-Writing (DIW) process is presented. In this context, the integration of functional structures into different rubber made soft fingers for gripping purposes is shown. These are compared to conventionally fabricated soft fingers out of silicone without infill structures. Thereby, experimental results and the chances and current limitations of this fabrication technique for soft robot grippers are discussed in detail.

Key words: Additive manufacturing, Direct Ink Writing, EPDM, rubber, soft robots, grippers

1 INTRODUCTION

Soft material robots are an emerging and fast-growing field of research with potential application in various areas. Unlike conventional robots, which are usually made of high-stiffness materials such as steel, soft robots are mostly fabricated out of soft materials like, silicone, rubber or foam. Soft robots are mainly used in new areas of robotics, such as human-machine

Peer-review under responsibility of the organizing committee of SMART 2023.
doi: 10.7712/150123.9765.448180

interaction, medical applications, or gripping of delicate and differently shaped objects. For example, their soft design allows for very flexible use, e.g. for different gripping tasks, while their softness also protects delicate objects from damage.

The dominant manufacturing technique for soft robots is currently silicone casting. However, especially for rapid prototyping and more complex designs, additive manufacturing becomes more and more important and opens new design perspectives: The use of infill, which is very common in 3D printing, allows very lightweight designs, which is important, especially for larger soft robots. Additionally, also functional structures can be integrated. This e.g. allows anisotropic behavior, like stiffening the robot in a certain load direction while keeping it soft in another direction. Functional structures can also be used to achieve complex movements and deformations while keeping actuation and control simple. This is widely known as "Morphological Computation". In gripping applications, this allows the gripper to adapt to the shape of very differently shaped objects. In addition, gripping forces can be more easily distributed across the gripped objects to avoid damage from local stress peaks.

1.1 State of the art for manufacturing of soft robots

1.1.1 Conventional manufacturing methods for soft robots

The dominant conventional manufacturing techniques for soft materials are silicone casting and various compression, injection and transfer molding processes for rubber materials. The conventional processing of rubber materials usually requires high investment costs for the precise manufacturing of the required metallic molds [1]. For soft robotics, this can be an application hurdle, as many design iterations and test cycles are often required in the design and manufacturing of soft robots [2]. Silicone molding, on the other hand, is commonly used in soft robotics. The necessary two-component systems are relatively inexpensive to acquire and can be processed in a relatively short time without extensive knowledge and without costly molds and machines. The molds are widely manufactured using 3D printing [2, 3, 4]. However, manufacturing involves a high degree of manual steps [5] and for many applications the material properties of silicone are inferior to those of rubber. Common casting processes for silicone can be subdivided into three main categories: lamination casting, casting with removable pins, and casting with lost wax [3]. A common disadvantage of casting processes is that complex geometries, especially those with many undercuts, can only be produced at great expense using multi-part and lost molds. This limits design freedom and makes it difficult to integrate functional structures into soft robots.

1.1.2 Additive manufacturing methods for soft robots

With additive manufacturing processes, even complex structures and small lot sizes can be produced with comparatively little effort. However, direct 3D printing of soft robots is a new field and only a few materials are available so far [6]. Existing techniques include stereolithography (SLA) [7], polyjetting [8], fused deposition molding (FDM) [9] and silicone Direct-Ink-

Writing (DIW) [5]. In the SLA process, the build platform is located in a reservoir filled with a light-activated resin, a so-called photopolymer. The polymer can be cross-linked and hardened by irradiation with UV light from a projector or laser. Afterwards, the build platform is moved one step higher, and the next layer can be hardened in the same way [7]. This method allows printing details with high resolution [10], but no parallel printing of different materials [11]. In addition, the choice of materials is limited to a few photoactive materials [5], which have significantly poorer mechanical properties compared to conventional cast materials [7]. Selective laser sintering (SLS), which is very similar to SLA, is also used occasionally in soft robotics, but for the generation of geometry-based compliant systems from relatively stiff materials [12].

Another process that uses photopolymers is polyjetting. In this process, a photopolymer is applied layer by layer by an inkjet print head and then cured with a UV lamp [10]. The choice of materials is limited in the same way as with SLA [6], but the printing of multiple materials is possible [13].

Another group of materials can be printed by means of FDM. Here, material is extruded layer by layer from a print head. The material is a thermoplastic melted in the print head, which hardens after extrusion due to cooling [11]. The choice of material is limited to thermoplastic elastomers (TPE) such as thermoplastic urethane (TPU). FDM, like polyjetting, allows simple multi-material printing, but the resolution is lower and there is a higher porosity of the printed part, which can be a problem for fluidic actuators [14]. Another limitation is the significantly higher Shore hardness of thermoplastic elastomers compared to commonly used silicones [5].

For additive manufacturing of silicone, which is the most popular material for soft robots, mostly Direct-Ink-Writing (DIW) processes are used. In a DIW process, a mostly paste-like material is extruded through a nozzle to build up the part layer by layer. A heated bed and a hot air gun can be used to support cross-linking. In addition to silicone, other materials such as hydrogels can also be printed using the DIW process. As with polyjetting, also multi-material printing is possible. The geometric stability and resolution remain far behind commercial polyjet systems [5], [15], [16].

2 DIRECT-INK-WRITING OF RUBBER

The 3D printing system used in this work is a novel method for printing rubber-based (here: EPDM), silicate and/or carbon black filled and curable rubber materials, which was first presented in [17, 18, 19]. It is based on Direct-Ink-Writing (DIW) and is used here for the first time for the fabrication of soft robots. The fabrication method is based on a modified conventional FDM 3D-printer. The extruder is exchanged by an endless piston pump system for highly viscous media and pastes. This allows the printing of rubber with, compared to conventionally processed rubber, low viscosity. Materials with a viscosity of up to $1 \times 10^5\ \mathrm{Pa \cdot s}$ can be printed. A nozzle diameter of $0.4\ \mathrm{mm}$ is used in this work.

In contrast to silicone or polyjet printing, the rubber is not vulcanized during the printing process. Instead, the component is printed as a green compact on a safety glass plate and then transferred to an autoclave for vulcanizing in a second fabrication step. This increases the manufacturing effort and reduces the achievable dimensional accuracy, as deformations can occur during printing and vulcanizing. The biggest limitation at present is the geometric stability of the printed part. When printing high narrow structures, these become increasingly unstable and overall, there is an increasing rounding of the edges with increasing height. While overhangs should be avoided at best, the printing of infill structures is possible. These should be as rectangular as possible, since deformations can occur due to relaxation of the polymer chains in honeycomb and zigzag structures. A vertical tapering of the component to be printed can increase the geometric stability. For parts with a vertical taper, higher geometric stability can be achieved during printing. The use of rigid support structures during fabrication is possible with a second FDM printhead. However, for these rigid support structures the choice of materials is very limited because they must be able to withstand the vulcanization process, which involves high temperatures and pressures.

3 GRIPPER DESIGN

In order to investigate the potential of the manufacturing process, tendon actuated and pneumatically actuated fingers for a three-finger gripper are designed and manufactured in the following. The geometric dimensions of the gripper are chosen to be comparable to those of a human hand. This allows the gripper to grip various everyday objects, which is a common application for soft robot grippers. For simplicity, only fully soft fingers without rigid support structures are considered in this work.

An important design limitation of soft robots is bending caused by gravity. Soft materials like silicone or rubber usually have a density of $1\,\mathrm{g/cm^3}$ or above and a Young's modulus in the range of $10^4 \dots 10^9\,\mathrm{Pa}$ and therewith a very low specific stiffness. This limits the maximum size of soft robots when using solid material, if large bending caused by gravity cannot be accepted. One way to overcome this issue is to use infill structures that allow for very light designs. With conventional manufacturing processes, however, these infill structures can usually only be fabricated with extremely great, effort, e.g. with lost-wax-casting. With additive manufacturing techniques infill structures can be fabricated very easily. For conventional FDM 3D printing, infill structures are already widely used, mainly to save material.

Another design limitation is, that for soft robotic applications often anisotropic behavior is desirable. For a soft finger, for example, low stiffness in the direction of bending is important in order to achieve low actuator forces. At the same time, high stiffness in the direction orthogonal to this is desirable to keep the deflection due to gravity low. Furthermore, when gripping delicate objects, a low stiffness at the contact surfaces is important in order not to damage the objects to be gripped.

Finally, pneumatically operated soft robots require the integration of different types of pressure chambers. These are so far mostly fabricated using lamination casting. However, this multi-stage process is time-consuming, and the bonding of the different parts is prone to errors. Moreover, it is often not possible to achieve the same strength as with one-step production.

In the following, a 3D printed design for a tendon-actuated and for a pneumatically-actuated soft robot are presented. These are the two most used actuation methods for soft material robots. The fabrication of pneumatically-actuated soft material robots is particularly challeng-

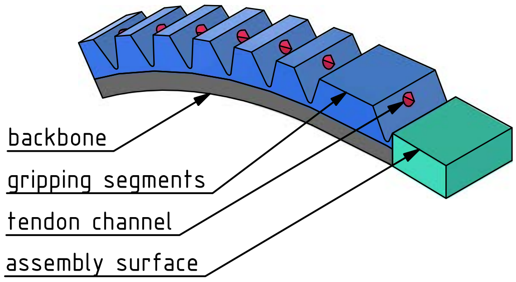


Figure 1: Design of the tendon-actuated finger.

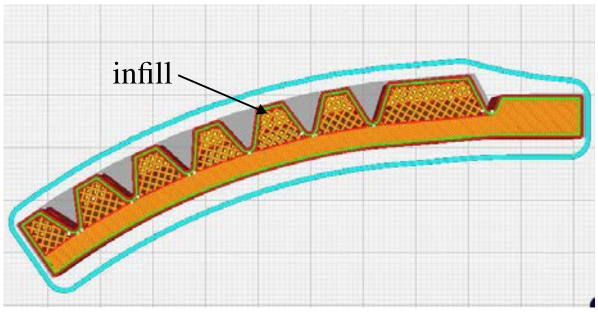


Figure 2: Infill of the tendon-actuated finger.

ing because the soft material robot must be airtight and the wall stiffnesses of the integrated pressure chambers are of great importance for the actuation.

3.1 Tendon-actuated soft finger

The design of the tendon-actuated soft robot gripper is based on the soft three finger gripper presented in [20]. One finger is shown schematically in fig. 1. Each of the three fingers consists out of a beam-shaped backbone and seven trapezoidal truncated gripping segments with integrated tendon guide. The bending of the finger is achieved by tendon actuation, the restoring into straight configuration by the inherent stiffness of the backbone. The tendon is guided in polyurethane tubes to reduce rope friction. Each of the three fingers can be actuated separately with a servomotor. To achieve a quick restoring to the straight configuration, the finger is slightly precurved against the direction of bending during actuation. This significantly increases the restoring force, especially near the straight configuration. For weight reduction, the finger is printed with $65\,\%$ infill of type ”grid” of the CURA slicer. Additionally, the infill structure is used to achieve anisotropic behavior of the finger. The infill structure is chosen such that the gripping segments have a lower stiffness against in plane (vertical) pressure than against out of plane (lateral) pressure. This allows improved gripping of delicate objects. The infill structure is shown in fig. 2. The finger is printed lying on its side.

Additionally, for comparison purposes, a conventionally manufactured version of the gripper is fabricated using silicone molding. A 3D-printed mold is used for this. The infill structure is omitted, as it cannot be produced with the fabrication process used.

3.2 Pneumatically-actuated soft finger

The pneumatically-actuated soft finger is designed as a pneu-net. The design of the finger is shown in fig. 3. The pneumatic finger is beam-shaped with integrated pressure chambers which are supplied by a fluid channel. When the pressure chambers are pressurized, they expand laterally. This leads to a bending of the finger. The individual pressure chambers are separated by structures with $65\,\%$ infill of type ”grid”. This leads to a reduced stiffness which supports

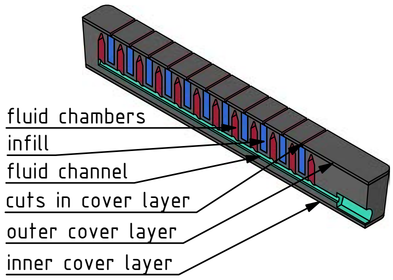


Figure 3: Design of the pneumatically-actuated finger.

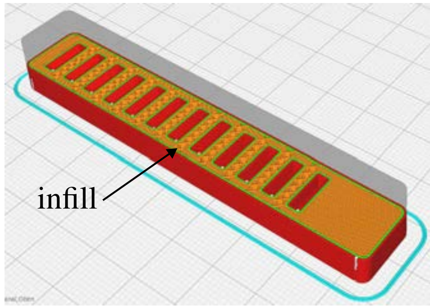


Figure 4: Infill of the pneumatically-actuated finger.

easy bending. The infill structure is shown in fig. 4. The inner side of the finger consists of a comparatively thick inner cover layer. This is comparatively stiff in the longitudinal direction and therefore hardly stretches at all. This is important for achieving the bending. The outer cover layer is only needed for easier fabrication and hinders the bending. Therefore, after the vulcanization this layer is cut over the infill structures. The position of the cuts is indicated in fig. 3. A silicone casted version was also made for this finger for comparison.

4 EXPERIMENTAL EVALUATION

For the experimental evaluation, in a first step the different fingers are printed. The dimensional accuracy of the print is then examined. Next, the gripping performance of the tendon-actuated gripper is examined in detail and compared to the performance of a gripper with conventionally manufactured silicone fingers. The outer geometry of the silicone and rubber fingers is identical, but the silicone fingers are made of solid material, while the rubber fingers contain a support structure inside. The required actuation forces and the resulting holding forces are investigated. Finally, the functionality of the pneumatically actuated soft finger is briefly tested.

4.1 Dimensional accuracy

Overall, the rubber 3D printing process presented is able to achieve good geometric stability even with slight overhangs and no upward taper. This can be seen in fig. 5 for the tendon-actuated finger and in fig. 6 for the pneumatically-actuated finger. Slight material build-up can be seen on the underside of the printed parts. This can be explained by the fact that the parts are vulcanized in a separate production step after printing. Until then, the material is very viscous, but still slightly flowable. Larger cavities should be printed with support structures, especially if these cavities lead to thin load bearing structures. This can be seen, for example, in the tendon guide. Here, the tubes must be inserted during printing, otherwise the layers above would sink in. Nevertheless, it can be seen that the material clearly sinks in at the tendon guide. This can be explained by insufficient support due to a too thin surface layer and too little infill. Cavities with support structures, e.g. in the form of infill, can be printed without any problems, as can

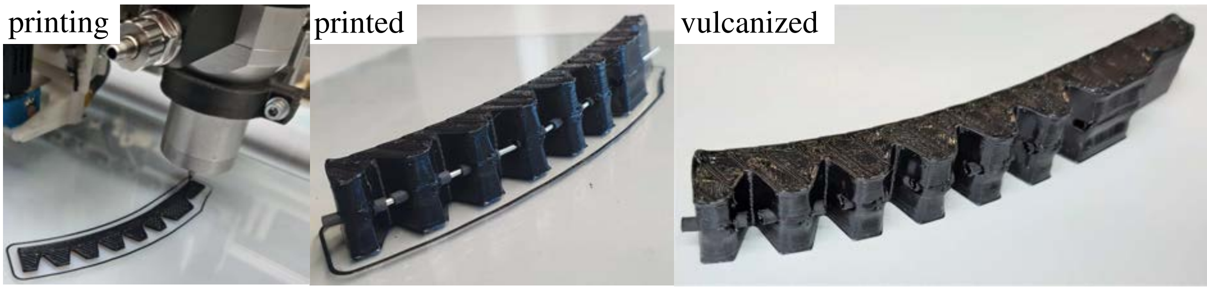


Figure 5: Tendon-actuated EPDM-based soft robot finger during printing, printed and vulcanized.

Figure 6: Pneumatically-actuated EPDM-based soft finger.

be seen in both finger designs. However, with careful design, larger cavities can be printed without infill if the overlying layers are adequately supported. This can be seen, for example, in the comparatively large chambers of the pneumatically actuated finger, which do not cause the material to sink and are not visible from the outside.

The dimensional accuracy of key dimensions of the tendon-actuated soft robot is compared between the 3D printed rubber finger and the silicone casted finger. The fingers and their dimensions are shown in fig. 7. Figure 8 shows the obtained dimensional accuracy. For each of the seven segments, the height h, the contact length l_{contact}, and the width w are examined for three fingers each. Additionally, the total length l_{total} of the finger is considered. In addition to the mean deviation, the standard deviation is also shown. It can be seen, that with the 3D-printing process a comparable accuracy to the silicone casting can be achieved. The mean dimensional deviation in terms of amount is less than $10\,\%$ for all dimensions. The maximum deviation occurs at the length l_{contact} of the contact surface for both manufacturing processes. This is mainly due to a rounding of the edges during direct printing of the rubber finger and printing of the mold for the silicone finger. For both fabrication processes, the standard deviation is very low, which shows that the fabrication is very reproducible.

4.2 Performance of the tendon-actuated gripper

For the evaluation of the fingers, three of the tendon-actuated rubber and silicone fingers are combined to a three-finger gripper each. The grippers are shown in fig. 9. Overall, with the tendon-actuated gripper out of rubber a good performance could be achieved. In fig. 11 it is shown, that differently shaped objects can be gripped with this gripper. Due to the use of infill

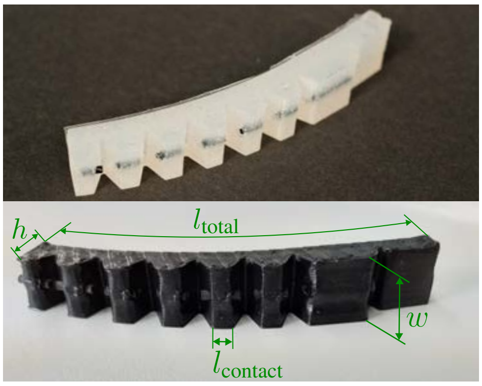


Figure 7: Finger dimensions.

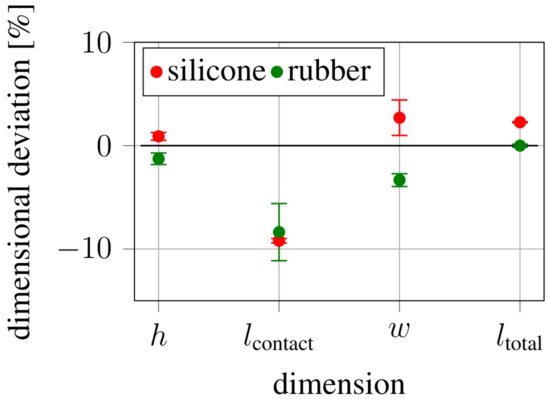
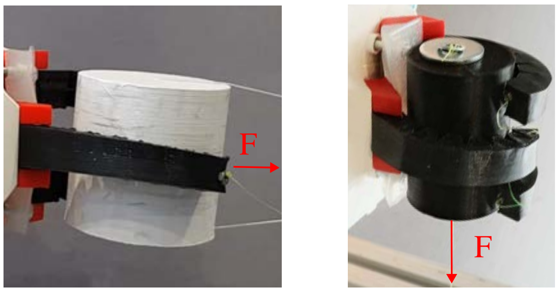


Figure 8: Dimensional accuracy of the fabrication.

(a) Rubber gripper. (b) Silicone gripper.

Figure 9: Assembled grippers.



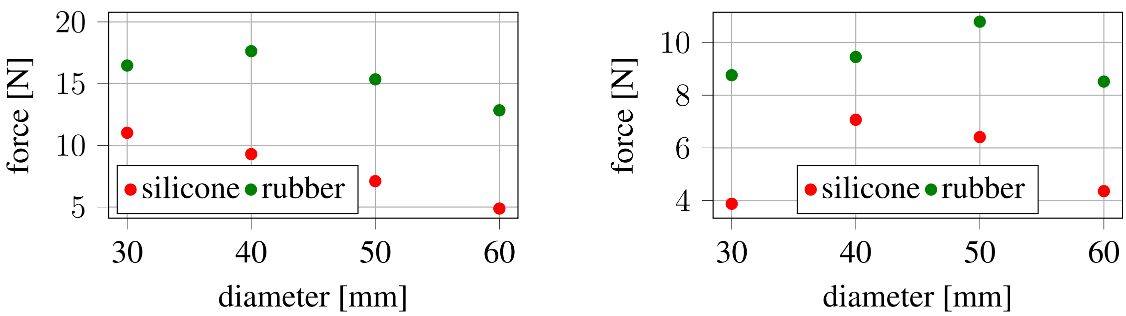
(a) Horizontal direction. (b) Vertical direction.

Figure 10: Experimental setup for determination of holding forces.

structures, the rubber finger has a weight of $12\,\mathrm{g}$, which is $28\,\%$ lower than the weight of the silicone finger. The infill structure leads to a lower stiffness in vertical than in lateral direction of the printed tendon-actuated finger. However, in the fully assembled finger this effect is hardly noticeable, because the tubes used as tendon guide lead to an additional stiffening. Therefore, the diameter of the tendon guide should be reduced in future designs.

In a second step, the holding forces for cylindrical objects of different diameter in horizontal and vertical direction are examined. Thereby, the holding forces of the rubber and the silicone fingers are compared. The different objects are slowly pulled out with a constant velocity of $1\,\mathrm{mm/s}$ while the pulling force is measured. In fig. 10 the experimental setup is shown. The experimental results are shown in fig. 12. The experiment is repeated three times for each combination of gripper and diameter. The plots show the mean value. On average, the pulling force in horizontal and vertical direction is twice as high for the rubber gripper than for the silicone gripper. This can be explained by the higher coefficient of friction of rubber compared to silicone, the slightly higher bending stiffness of the rubber fingers, and the contact points of

Figure 11: Gripping of differently shaped objects with the rubber fingers.



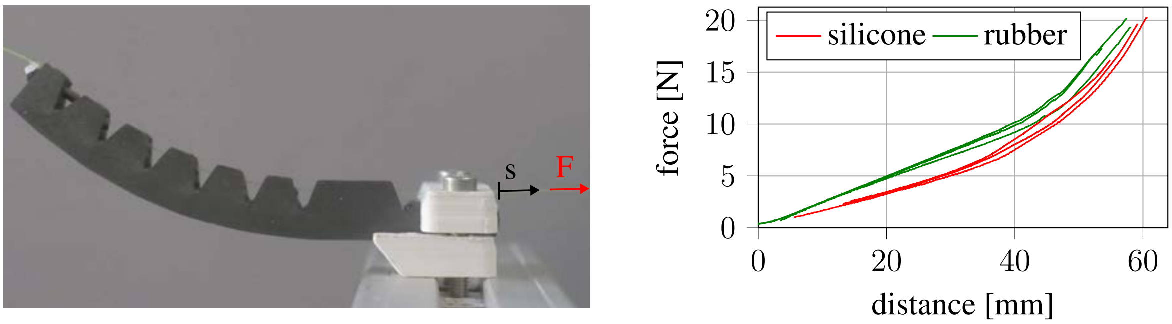
(a) Horizontal direction.

(b) Vertical direction.

Figure 12: Holding forces for round objects with different diameters and pulling directions.

the gripping segments, which are softer for the rubber gripper due to the use of infill. This effect is particularly strong for large diameters in vertical direction.

Finally, the required tendon forces for bending one finger are examined. In fig. 13a the experimental setup is shown. The finger is clamped at its assembly surface and the tendon length s is increased until the finger reaches its maximum curvature. Thereby, the tendon force is measured. The curvature of the finger is directly related to the tendon length. The tendon force depends on the stiffness and the geometry of the finger. In fig. 13b the tendon force is plotted over the tendon length for the silicone and for the rubber gripper. Three repetitions of the experiment are shown. It can be seen, that overall the silicone and the rubber finger have a very similar stiffness. Thereby, the stiffness of the silicone finger is slightly lower than the stiffness of the rubber finger for small curvatures and slightly higher for large curvatures. Furthermore, it can be seen that the relationship between tendon force and tendon length is linear over a wider range for the rubber finger than for the silicone finger. This is advantageous for the control of the finger.



(a) Experimental setup.

(b) Experimental results.

Figure 13: Required tendon forces for bending the finger.

4.3 Note on the pneumatically-actuated finger

In fig. 14 the pneumatic finger fabricated out of rubber is compared to a silicone version fabricated with silicone casting. The finger is shown in straight configuration, in bend configuration without the cuts in the cover layer indicated in fig. 3 and in bend configuration with the cuts. The bending performance of the rubber and the silicone version of the finger is very similar. To achieve full bending a pressure of 3 bar is applied to the gripper. Higher pressures could not be tested so far to avoid destruction of the finger. Both fingers are fully airtight. The achievable maximum bending of the fingers is relatively low. However, this can probably be changed with an improved design of the fingers. Overall, it can be shown that an airtight pneumatically actuated rubber-based soft robot with a complex pressure chamber structure can be manufactured in one part using the 3D printing process presented.

Figure 14: Bending performance of the pneumatically actuated finger compared to the silicone casted version.

5 CONCLUSIONS

In this contribution, the additive manufacturing of rubber for soft robot grippers was presented. Thereby, the integration of functional infill structures was shown. For the examination of the advantages and disadvantages of this new fabrication process, tendon-actuated and a pneumatically-actuated fingers for gripping applications were fabricated and compared to similar fingers fabricated using silicone casting. For additive manufacturing, a Direct-Ink-Writing (DIW) process was used. With this fabrication process a comparable dimensional accuracy as with silicone casting could be achieved, while allowing the integration of more complex infill structures. With the tendon-actuated rubber gripper, on average, twice as high holding forces in horizontal and vertical direction could be achieved as with a comparable silicone gripper. This especially improves the gripping of larger objects. Overall, the applicability of the presented rubber 3D printing technique for soft robots with integrated functional structures was shown. This demonstrates the potential of using a whole new class of materials in the additive manufacturing of new and innovative soft robotic systems. Further research should now focus on using this technique to design and manufacture more complex functional structures that utilize the unique properties of rubber materials.

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