Characterization of fatigue behavior of 3D printed pneumatic fluidic elastomer actuators

ORIGINAL ARTICLE

Characterization of fatigue behavior of 3D printed pneumatic fluidic elastomer actuators

Lorenzo Torzini[1] · Luca Puggelli[1] · Yary Volpe[1] · Lapo Governi[1] · Francesco Buonamici[1]

Abstract

Soft robots have gained significant interest due to their high flexibility and adaptability to various working conditions. Recent advancements in engineering and innovative materials have enabled the design and production of sophisticated soft robotic systems with enhanced capabilities. This study aims to evaluate the fatigue behavior of bellow-type pneumatic soft actuators fabricated through fused filament fabrication (FFF) using thermoplastic polyurethane (TPU), compared to silicone rubber cast actuators. The actuators were equipped with resistive flex sensors to monitor bending motion, and fatigue tests were performed with cycles of inflation and deflation until failure. Results showed that 3D printed TPU actuators could withstand a significant number of cycles before failure, with an average of 6410 cycles at 3 bar pressure, compared to 3439 cycles at 1 bar pressure for the silicone actuators. The study identified a set of fabrication parameters that positively affect the durability of TPU actuators, providing valuable insights for replicating these results. Additionally, the study established a plausible range of utilization for 3D-printed FFF actuators in terms of the number of cycles they can endure, offering critical data for engineers and designers to make informed decisions about the design and application of these actuators in various practical scenarios. The findings demonstrate the potential of FFF for producing durable, long-lasting pneumatic soft actuators.

Keywords Soft actuator · Pneumatic actuator · 3D printing · Fused filament fabrication · Soft material

1 Introduction

Soft robotics is an emerging field characterized by the use of materials and design solutions that grant actuators a high compliance, allowing them to adapt to different working conditions [1]. These robots consist of one or more soft actuators that are able to change their shape and features according to the required task, an aspect that is particularly useful in the case of physical human-robot interaction [2]. Over the past two decades, soft actuators have received significant attention for their new range of capabilities such as wide degrees of freedom and movements unattainable by their rigid counterparts [3]. These advantages are achieved at the cost of smaller forces that are commonly exerted, a reduced accuracy in their movements and positioning, and an increased difficulty in control [4]. In addition, research

in this field has demonstrated the adaptability [5], agility [6] and sensitivity of soft actuators using highly deformable and flexible materials. Often, a combination of more than one material with these characteristics is used to achieve the desired result. Soft actuators can be actuated in many different ways: using shape memory alloys [7], shape morphing polymers [8], electrically using electro-active polymers or dielectric material [9], or fluidically. The latter, called FEAs (fluidic elastomer actuators)—and sometimes referred to as soft pneumatic fluidic actuactors (SPFAs [10])—are a subcategory of soft actuators made of highly deformable materials that uses pressurized fluids to fill chambers to generate a controlled expansion and a programmed movement.[11]. This type of actuator has the advantage of being easily scalable, it can be powered with simple hardware components, and, in general, it can be fabricated with multiple manufacturing methods [12]; thanks to these properties, FEAs have found widespread use in various fields of application, gaining a foothold in agriculture and packaging, for the harvesting and handling of fruits and vegetables [13] thanks to their grasping adaptability to different shapes and textures [14]; they are often used also in pharmaceuticals and health care,

✉ Francesco Buonamici
  francesco.buonamici@unifi.it

1 Department of Industrial Engineering of Florence, University of Florence, Via di S. Marta 3, 50139 Florence, Italy

Springer

for human-robot interaction applications. Moreover, they are capable of handling fragile and delicate components, or soft components that deform when grasped.

Considering the repetitive nature of most typical tasks carried out by FEAs, they are often subject to very high numbers of load-unload cycles; for this reason, interest has grown in studying their fatigue behavior. Many companies are adopting additive manufacturing to reduce the mass of moving components and produce advanced tools for complex operations. Reliable 3D printed actuators in pneumatic systems require accurate estimation of material fatigue limits and performance evolution over time. This information is crucial for maintenance planning and performance monitoring in industrial applications.

This work aims at a characterization of the properties of FEAs, specifically pneumatic ones, in which the working fluid is pressurized air. Main contributions can be identified in the proposal of a methodology allowing for repeatable and accurate measurement of the performance of the bending behavior of pneumatic bellows actuators and the execution of fatigue tests on TPU 3D printed actuators whose manufacturing process was documented and optimized. Results are compared with the performance obtained adopting common casting manufacturing solutions for pneumatic bellow-type actuators. This article is organized as follows. In Section 2, the state of the art related to the manufacturing of pneumatic FEAs is presented with a focus on 3D printing technologies; moreover, literature contributions dealing with the mechanical characterization of such actuators are presented with a specific focus on studies that deal with fatigue. Section 3 addresses the material and methods used in the present study and specifically, it describes the actual fabrication of the actuators as well as the setup used to characterize their behavior. In Section 4, obtained results are presented. Finally, Section 5 presents the conclusions.

2 State of the art

This section provides a brief description of the manufacturing of pneumatic FEAs as well as the description of previous studies which have addressed the investigation of fatigue properties of 3D printed FEAs. Pneumatic FEAs are actuated by changing the pressure of an internal chamber delimited by elastomeric material and inflating or deflating a cavity—or multiple cavities—that are designed to produce the desired kinematic effect. In some instances, vacuum conditions are applied to produce a contraction or to increase the stiffness and opposing forces exerted by a gripper [15]. The resulting movements are often achieved thanks to the combination of multiple materials that react differently to the pressure changes in the fluid; fiber reinforcements are the typical solution applied, in most cases, to control the

deformation of the actuator and constraint it, preventing the ballooning effect observed in positive pressure-driven actuators [16]. This article focuses on bellow-type actuators (Fig. 1), sometimes referred to as PneuNets [11]; these are controlled with a positive pressure differential that causes the enlargement of a series of chambers positioned side by side and intentionally designed to be the elements deforming the most. The interaction between inflated chambers produces a global and controllable deformation of the actuator.

Different bellows shapes and orientations allow for the generation of various movements. Three main categories can be identified considering the type of movement: linear, twisting, and bending actuators. Linear actuators (Fig. 1c) can be obtained with a symmetrical disposition of the bellows on the lateral surfaces of the actuator. Twisting actuators (Fig. 1b, d) are manufactured with different strategies, including the design of multiple internal chambers that differ in size and shape, or through the disposition of fibers in a helicoidal shape on the lateral surfaces of the actuator. Non-extensible fibers define directions along which the extension is constrained; the expansion of the inner chambers can continue only without changing the length of the fiber, hence triggering the desired twisting motion. Finally, bending actuators (Fig. 1a) can be obtained easily by stacking a series of chambers on just one side of the actuator (e.g., [17]) that, when inflated, produce a flexion in the opposite direction. Occasionally, fiber reinforcements are added to better guide the desired deformation or to avoid the deformation of certain parts. More complicated movements can be obtained by mixing such components, obtaining hybrid, three-dimensional, deformations (e.g., the planar-twisting motion depicted in Fig. 1d).
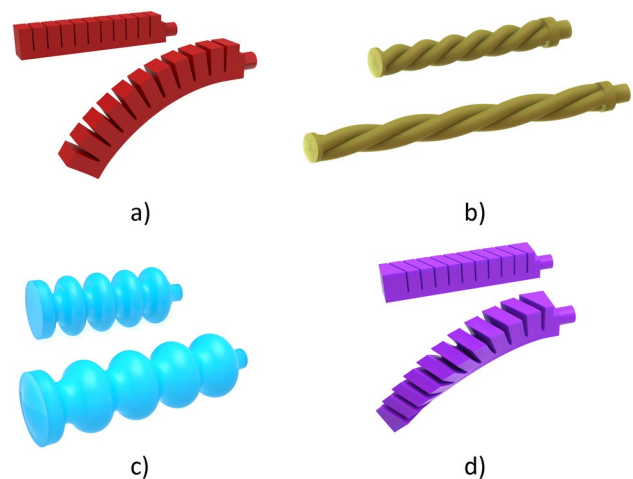

Fig. 1 Pneumatic bellow-type actuator classification according to the type of movement obtained when pressurized. Each image depicts the resting and pressurized forms of the actuator. **a** Planar bending; **b** linear-twisting; **c** purely linear; **d** bending-twisting

This article focuses on planar bending actuators (Fig. 1a) which have a wide range of application; they can mimic human finger movements for grasping and interacting [17], and when multiple actuators are integrated in a single gripper, they can achieve capabilities similar to a human hand. This makes them interesting for human-robot interaction scenarios, where their flexibility ensures safety in cooperative tasks.

2.1 Manufacturing of bellow-type pneumatic FEAs

Silicone rubber is the most common material used for fabricating pneumatic FEAs [18]. Silicones offer a good deformation-to-pressure ratio, biocompatibility certificates for contact with skin and mucous membranes, and high elongation at break. Silicones have a wide range of mechanical properties (e.g., various Shore hardnesses) allowing for the production of customized devices. As previously mentioned, reinforcement fibers are often introduced to alter properties of specific regions; Soft and light textile reinforcements (polyaramide, glass, and carbon fibers) have the perfect characteristics for the application, and they can be arranged based on loads and geometries.

Another important class of materials is 3D printed polymers and particularly thermoplastic polyurethanes (TPUs), commonly fabricated using fused filament fabrication (FFF); this class of materials offers a higher hardness (60–100 Shore A) compared to silicone. Whenever material properties need to be controlled locally throughout the FEA structure, more advanced processes combining multiple materials in the same print (i.e., material jetting processes—MJ) can be used such in [19]. For further reading, [10] provides a detailed review of materials used for FEA production, focusing on silicones, while [20] discusses the application of textiles in soft robotics.

Different techniques are used to manufacture bellow-type FEAs, depending on the shape and material required. The primary fabrication process is casting, especially for platinum-based silicones. This involves pouring two-component liquid silicone into molds where it cures and solidifies. While the process is straightforward, involving typical silicone-casting steps (mixing components, degassing, pouring into an open mold, optional mold degassing, curing, and extraction), complex actuator shapes may require multiple pours and molds. Cavities complicate the process, necessitating cores and features to hold them in place. Multiple solid elements are then joined and sealed with an additional polymer layer [21].

To reduce joint failure due to high pressure, researchers proposed "retractable pin casting" [22]. In this method, actuators are cast in a single mold with removable pins creating air channels, reducing the risk of joint layer rupture. However, channel morphology is limited by the removable pin's shape. An alternative method uses a wax inner core during casting, allowing complex cavity geometries while using a single mold. After curing, the wax core is removed by heating in an oven [23]. This technique is labor-intensive and time-consuming.

3D printing offers a new solution for soft pneumatic actuator fabrication, enabling rapid iterations between design prototypes. The combination of additive manufacturing (AM) and pneumatic actuation presents multiple opportunities [24]. For an overview of different fabrication technologies, refer to [25], which highlights the strengths and features of each technique or [26] a recent and broad review on the application of 3D printing in soft robotics. Generally, AM allows the production of complex geometries, achieving lightweight, high-performance parts with multiple design features (e.g., [27]). With the development of elastomeric printable materials, FFF (fused filament fabrication) can print soft robots by depositing and solidifying molten polymer filaments. Effective design is crucial to exploit AM benefits, considering fabrication limits and required actuator functions. AM does not require specially designed molds and significantly reduces fabrication time compared to casting. Literature shows the possibility of manufacturing highly engineered actuators capable of bidirectional bending motions, which are otherwise unattainable [28]. Gariya et al. [29] present a recent review on the integration of soft sensors on 3D printed actuators with different strategies, enabling a direct control of FEAs.

2.2 Fatigue behavior

Fatigue behavior of FEAs pneumatic actuator is a topic of interest in the context of soft actuators. The materials used to fabricate this class of actuators change its behavior over time due to fatigue phenomena. The type of application typically faced by such devices imposes a high number of duty cycles to the actuators, which create stressful conditions for the functionality of actuators. The study of materials with enhanced capabilities [30], the definition of design practices that try to optimize fatigue resistance [31], the analysis of the limits of soft actuators that are fabricated using advanced manufacturing methods [32] or a specific material [33] are all topics that have been covered by the scientific literature.

Regarding fatigue on elastomeric materials, there are two different approaches for durability analysis: the crack nucleation approach and the crack propagation approach [34]. In the crack nucleation approach, fatigue life is determined by the formation of small cracks, increase of mechanical compliance, or ultimate fracture. The crack propagation approach, on the other hand, is used when the crack size and location are well known. This method is usually applied when the component bears the crack growth before its ultimate failure [35].

The evaluation of the fatigue behavior of pneumatic actuators has been presented in several articles. Libby et al. [36] addresses how fatigue affects the prediction of pneumatic soft actuators using FEA tools, identifying a significant contribution of fatigue to the effective deformation produced by a silicone-cast actuator. This study focuses on the fabrication of FEAs pneumatic actuators and considers AM fabrication of pneumatic planar-bending actuators.

Regarding 3D printed actuators, [25] reviews 3D printed soft robotics and highlights Direct Ink Writing as a promising technology for fabricating soft actuators resilient to fatigue damage, mentioning [37] for producing bending silicone pneumatic actuators capable of over 30,000 bending cycles of 270°. Sparrman et al. [32] examine the fabrication and testing of linear pneumatic actuators using rapid liquid printing (RLP), which deposits silicone material with a syringe-like extruder in a gel support tank, overcoming FFF technology's limitations. This article also evaluates specimens made with material jetting AM techniques (Polyjet by Stratasys), noting that RLP produced higher-quality specimens with consistent performance over 500 cycles, while cast specimens showed significant deviation, and Polyjet specimens failed after an average of 40 cycles. Anver et al. [38] explore the fatigue behavior of FFF-fabricated actuators, claiming that thermoplastic elastomers used in several soft robotic applications showed no significant fatigue-induced damage after over 20,000 cycles. However, the article lacks clear experimental setup details and repeated experiments, limiting its significance. Yap et al. [39] address similar issues with a comparable methodology in materials, technologies, and actuation conditions. Their fatigue analysis showed that 3D-printed soft pneumatic actuators could withstand a significant number of cycles before failure, averaging 606 cycles at 250 kPa and 82 cycles at 400 kPa. Different configurations and design changes were tested, but fatigue analysis results were only provided as aggregate values without detailed geometry information. Keong and Hua [31] use FFF technology to manufacture a bending pneumatic actuator with a Ninjaflex thermoplastic elastomer, employing a custom fold-based wave pattern design. Five different designs tested with inflating cycles at 200 kPa resulted in failure cycles ranging from 1142 to 6473, though these results cannot be directly referenced for the present study due to the differing actuator geometry.

3 Material and methods

Motivated by the analysis of the state of the art, the present study aims at the characterization of the behavior of planar-bending pneumatic actuators featuring a standard bellow-type geometry and manufactured using a low-end FFF printer in a TPU polymer. A generic multipurpose geometry

was chosen, considering that for real applications the shape of the designed actuator is typically extremely specific and customized to the task. The specimens were fabricated using a Prusa i3 M3KS+ FFF 3D printer [40] and NinjaTek TPU [41] material (NinjaFlex 3D Printing Filament, fabricated by Fenner Drives, USA). Ninjatek is a TPU Elastomer characterized by a tensile yield strength of 4MPa, a tensile ultimate strength of 26 MPa, a tensile modulus of 12 MPa and an elongation at break of 660% (yield elongation of 65%). The fabricated actuators have been equipped with bending sensors; cyclic load tests, alternating between inflating and deflating phases, were performed in the study while monitoring the bending behavior and counting the number of cycles before failure.

In order to provide a meaningful point of reference for the evaluation of the actuator characteristics, specimen manufactured using a traditional methodology were fabricated by casting, i.e., the gold standard typically used for soft actuators, as presented in the previous section. A Dragon-Skin 30 silicone by Smooth-On Inc. [42] was used for the manufacturing of traditional actuators (Dragon-Skin 30 Silicone Part A and B, fabricated by Smooth-On Inc., USA). The same geometry, which was devised considering a maximum actuation force of 4 bar for the 3D printed one, was devised in a series of preliminary tests which allowed the achievement of a design that did not leak under pressure, allowing proper connection with standard pneumatic connection hardware, keeping a costant pressure for the entire test duration. Specifically, the design focused on the identification of a valid value for the wall thickness parameter, identified by the letter S in Fig. 2b, which was finally set to 1.6 mm. Moreover, actuators were equipped with a resistive bending sensor, i.e., flex sensor by spectra symbol [43], as proposed in [44], hosted in the lower part of the device. This has introduced additional difficulties to the manufacturing process, as described in the following sections. The actuator was modeled using Dassault Systemes Solidworks 2023 and exported in a STL format for further phases of the study.

3.1 Fabrication

3.1.1 3D Printing

3D printed actuators were fabricated using an FFF technique which, as previously discussed, completely removes the need of inner core to model and generate the internal geometry of the device. FFF is a process that relies on support structures created during the slicing phase to sustain overhanging regions of the parts to be printed; however, due to the specific shape of the actuator designed in the study, a production without any support structures for the inner cavities is achievable with a convenient orientation. Actuators were printed sideways, as shown in Fig. 3; the only overhanging

Fig. 2 Geometry of the bellow-type linear bending actuator used in the study (the width of the actuator, not visible in the section-cut view, is 16 mm). **a** 3D view; **b** section-cut view
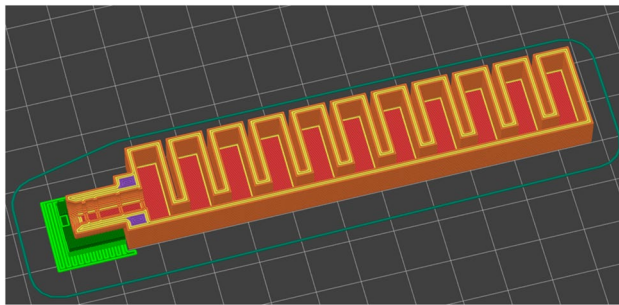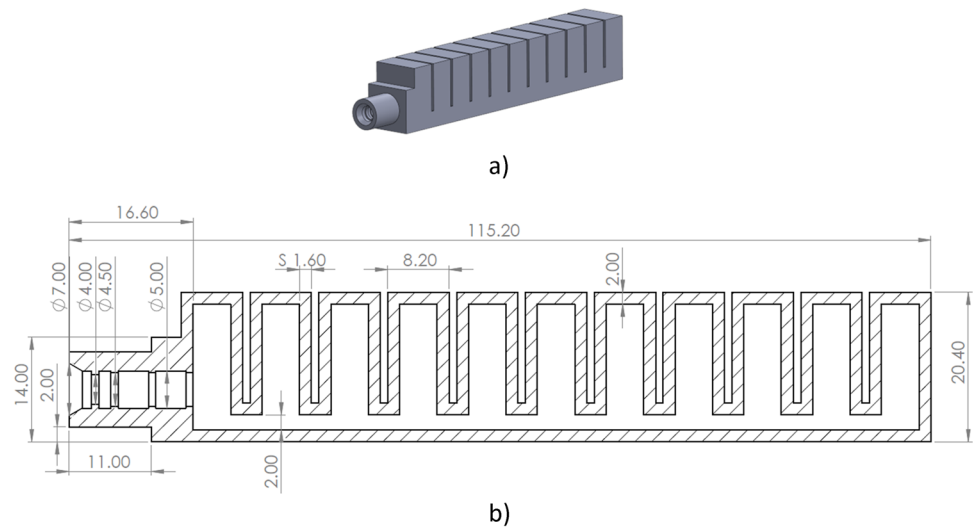

a)

b)

Fig. 3 Slicing of the STL model, green areas identify support material, placed only on the region of the pneumatic connector

Table 1 FFF process parameters

Parameter	Value
Nozzle diameter	0.4 mm
Extrusion temperature	245 °C
Layer height	0.15 mm

structure in this configuration is the top side wall, which is placed exactly horizontal and, as a consequence, it can be printed exploiting the bridging capability of FFF printers. Moreover, this surface is one of the surfaces modeled twice as thick as the thin ones, so the defects and deformations introduced by printing with bridges are abundantly recovered in the following layers, producing a solid and high-quality wall. As previously mentioned, Ninjaflex TPU is the material of choice for the fabrication, selected thanks to a series of preliminary tests performed on materials characterized by similar Shore hardness values. Ninjaflex showed the best printability, specifically with respect to the amount of print defects observed on the final 3D printed models, which are minimized. A Prusa I3 Mk3 FFF printer was used in the experiment. The software used to read the STL and for the slicing phase is the proprietary software of the 3D printer, i.e., PrusaSlicer V2.5.0 (Fig. 3). Most important process parameters are listed in Table 1.

The use of a slightly higher extrusion temperature, with respect to the 225–235 °C range indicated by the producer, allows a reduction of the probability of formation of micro-holes generated by partial melting of the material or inclusion of air pockets within the layers. A higher extrusion temperature, indeed, corresponds to a lower viscosity of the material at the molten state which, in turn, increases the adherence of the material within the layers. This advantage is achieved at the cost of a reduced accuracy in the deposition of the material and the level of detail; both factors, however, do not play a fundamental role for the considered application. The effect of the extruding temperature in the FFF process is a well-studied aspect that directly correlates with the resulting mechanical properties of the printed part [45], but its effect in the range of values considered in this study was judged not significant for the final performances of the actuator.

3.1.2 Silicone casting

A standard silicone casting process was used to build the control group of devices. This process involves pouring polymeric components into molds in their liquid phases and triggers the material solidification process, which—depending on the specific silicone—can happen in different ways. In this study, platinum-based silicones have been used; this class of silicones relies on two components that, after mixing, start the curing process. After a certain period of time, the silicone completes its solidification process and the final part can be extracted from the mold. Dragonskin30 silicone,
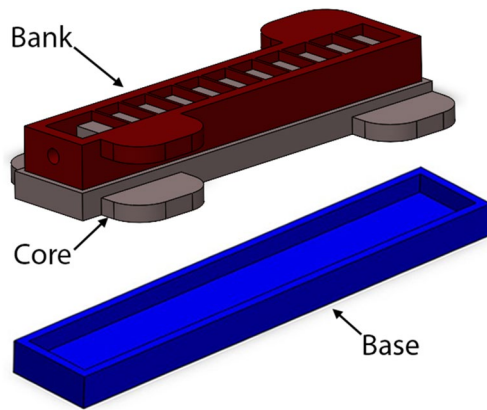
Fig. 4 3D models of the mold components

a two-component silicone with a mixing ratio of 1:1 between the two agents, was used. It has a set time of 45 min and a complete curing time of 16 h. The casting process was applied following the producer's recommendations, casting the material at room temperature (25 °C), applying a release agent on the mold (Ease Release 200) and applying a degassing phase under vacuum post-mixing to remove air bubbles. Custom molds have been fabricated by means of FFF, using PLA material (polylactic acid). The mold geometry is depicted in Fig. 4: the mold is composed of three parts: bank, core, and base. The fabrication process considers the need of introducing two additional elements: the flexion sensor and a piece of rectangular polyethylene textile, included in the bottom part of the actuator to prevent inflation of that area and prevent the extension of the actuator during bending. The following manufacturing phases are applied:

- Assemble core and bank. Pour silicone in base up to the 2.5 mm mark, located in the middle of the mold. Pour silicone in bank mold up to the top.
- After 10 min, apply the layer of polyethylene on the free surface of the silicone on the base mold. The partially polymerized material will glue the textile in place.
- Wait for full solidification (at least 16 h).
- Pour another batch of silicon on the base, completely filling the mold.
- Apply the flexion sensor on top of the base, it will partially sink in the silicone.
- Extract the top part of the actuator from the bank mold and put it on top of the base, upon the liquid silicone that will join the two parts together. Check that the electrical connections of the flexion sensors are free.

3.2 Fatigue test

A durability test has been designed to investigate the number of cycles that an actuator can tolerate before failing. Two

actuation pressure have been chosen, one for each group, corresponding to 1 bar for silicone actuators and 3 bars for TPU ones. These values have been selected considering realistic actuation pressures for both materials, corresponding to similar bending behaviors. A 0.5 Hz frequency was set for both groups, alternating between atmospheric pressure and actuation pressure. For each group, 5 actuators have been fabricated and tested with the chosen setup up to failure. The parameters that are measured during the test are the number of actuation cycles, the actual internal pressure of the actuator and the bending behavior of the device. The total number of cycles withstood by each actuator was identified by the inability to reach the set pressure within a certain time limit. Two solenoid valves are used to control pneumatic inlet (from a compressor) and outlet. The internal pressure is measured by a digital pressure sensor attached in-line with the PVC inlet pipe. The experiment is controlled by a microcontroller (Arduino Uno), which regulates the entire test rig. The flexion resistive sensor integrated in each soft actuator is monitored by the controller, saving the final bending angle achieved at each actuation cycle. Air pressure is regulated manually by an operator using the pressure regulator integrated in the compressor. The setup used in the test is depicted in Fig. 5. The experiment aimed at the evaluation of the fatigue limits of 3D printed actuators. As previously mentioned, the scientific literature offers limited data on this aspect. This research question declines in two specific directions: on one hand, the first goal is the measurement of the number of cycles at failure, and the assessment of the repeatability of such property across different 3D printed actuators. All fatigue-related mechanical properties, unrelated to the analyzed component or the fabrication process considered, are always influenced by the presence of defects within the material. Accordingly, the measurement of the performances under a high number of actuation cycles is an interesting tool to assess the presence of notable defects in 3D printed components. On a second level, the experiment will assess how the bending behavior of pneumatic
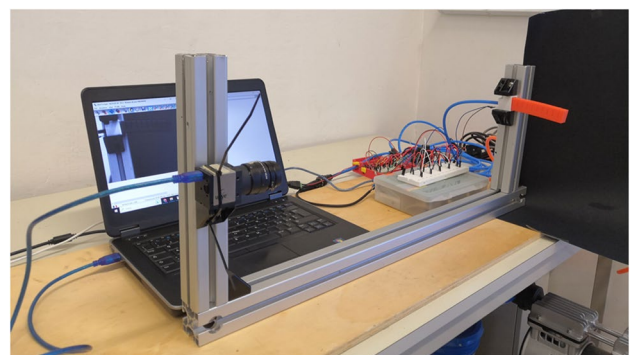

Fig. 5 Experimental setup used for the fatigue tests

Table 2 Number of cycles at failure

	TPU (3D printed)	Silicone (casted)
1	6456	3233
2	6018	3480
3	6350	3769
4	6638	3434
5	6589	3279
Mean	6410	3439
STDDev	247	211

soft actuators is influenced by fatigue, controlling the bend angle during the test.

4 Results

At the pressure of 3 bars, Ninjaflex actuators failed, on average, after 6410 cycles (with a standard deviation of 247 cycles), while silicone actuators, subjected to the pressure of 1 bar, failed, on average, after 3439 cycles (with a standard deviation of 211 cycles); full test results are reported in Table 2. The data is depicted also in Fig. 6. The results of cyclic testing done on 3D printed actuators demonstrated the

efficacy of the design proposed in this work, as the number of cycles reached, on average, at rupture, is significant for the reference field.

An analysis of the failure mechanics was performed on the actuators by means of a visual inspection in order to identify the rupture that has caused a loss in internal pressure, if present, or visible defects that might have affected the performance of the component. Each group showed peculiar features: 3D printed actuators failed principally due to the generation of micro-hole at the base of the humps, particularly in the inner zone between bellows; similar phenomena were observed in other literature studies (e.g., [46] for PLA). Silicone actuators, on the other hand, showed signs of lacerations formed at the base of the humps, particularly on the external-facing walls (measured in the range of 1–2 mm); before the critical rupture, micro-tears were observed. Interestingly, the appearance of micro-tears (measured in the range of 0.2–0.4 mm) did not affect heavily the performance of the actuators before the critical point was reached. Notable examples of such phenomena are presented in Fig. 7.

As previously mentioned, the experimented also allowed to register data on the bending of the actuators during the test. The results shown in Table 3 present values measured by the bending of the sensor over each cycle; the values are acquired by the 5V sensor and digitally converted by

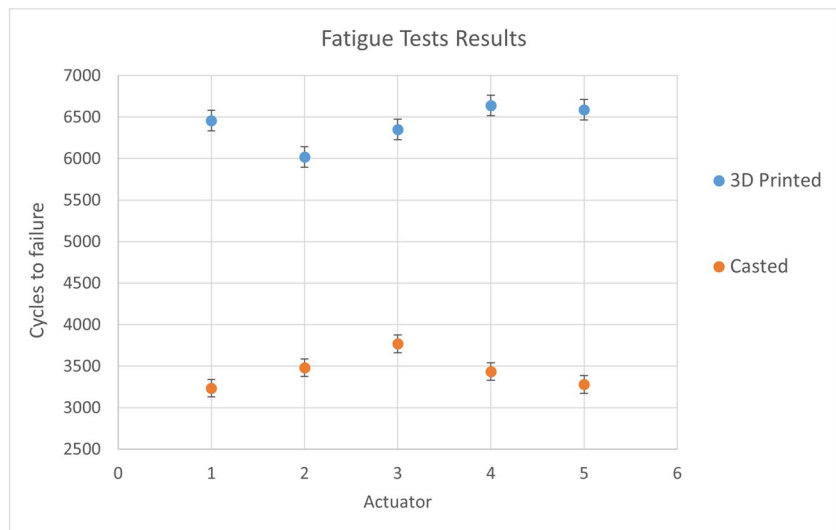**Fig. 6** Number of cycles at failure of 3D printed and cast actuators

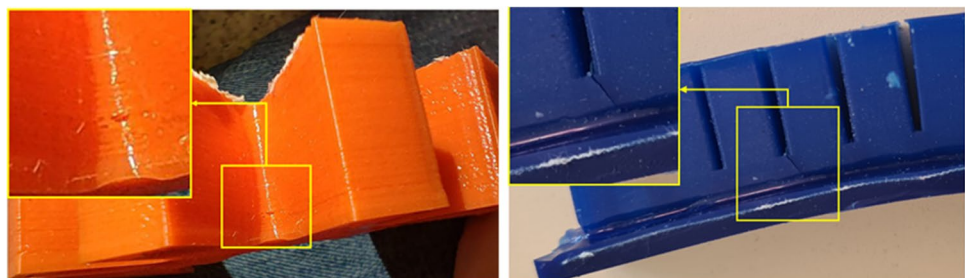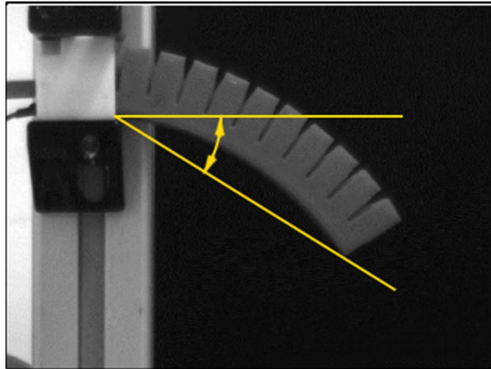**Fig. 7** Fatal failure points for the 3D printed actuators (left) and silicone-cast ones (right)
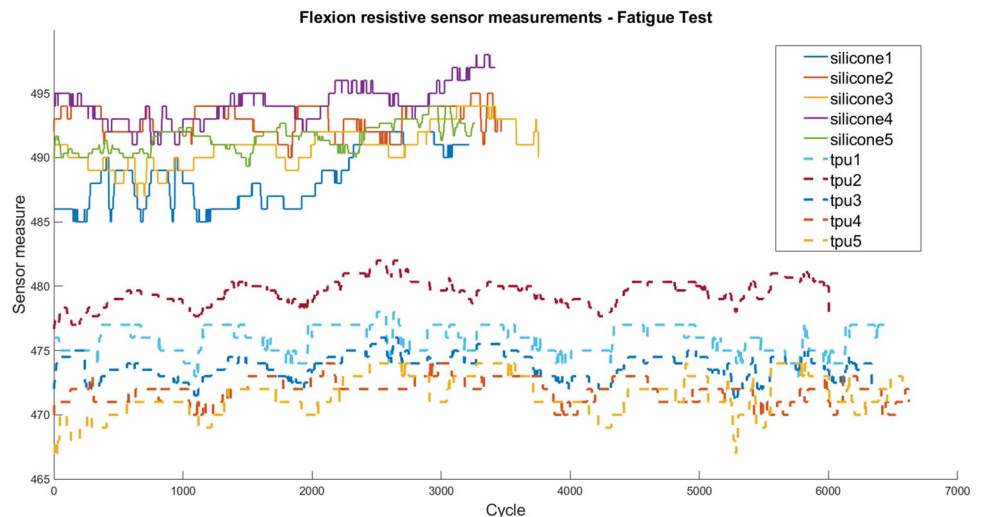
Table 3 Mean values registered by the flexion sensor for each tested actuator

	TPU (3D printed)	Silicone (casted)
1	476	490
2	478	493
3	474	491
4	472	494
5	472	492
Mean	474 (23,3°)	492 (33.2°)

Fig. 8 3D printed actuator pressurized and corresponding bending angle measured

Fig. 9 Flexion sensor measurements across each fatigue test. Continuous lines refer to silicone-cast actuators, dotted lines are 3D printed actuators fabricated in TPU

the Arduino Uno in the 0–1023 range. Preliminary experiments were performed to characterize the behavior of the sensor and map the values read by the sensor corresponding to specific bending angles of soft actuators; a linear relationship between sensor reading and global bending angle of the actuator, computed as shown in Fig. 8 was verified, at least for the range of 0°–120°, which allowed to compute angle data presented in Table 3. Data was collected at the maximum bending position, corresponding to the pressure peak.

Table 3 shows the average bending value of each test, computed across all registered values until failure. The table highlights the regularity of the performances shown by different specimens of the same group. Figure 9 shows acquired measures for both groups across the entire tests. For 3D printed actuators, acquired measures showed a practically constant bending behavior of the actuators throughout the test that is shared by all the specimens. In other words, no significant drift in the relationship between actuation pressure and bending angle exerted by the actuator is observed. A slight drift is observed, on average, for cast specimen fabricated in silicone; Table 4 reports the mean value of the flexion sensor computed for the first and last fifth of the fatigue test for all the silicone specimens, along with the overall mean value. An average drift of 1.7° is observed across all specimens; this observation could be related to the appearance of micro-defects described earlier. To better highlight this drift, a 300-samples moving average signal

Table 4 Mean values measured by the flexion sensor for the first and last fifth of the fatigue test performed on the silicone cast actuators. The last column presents the mean across all specimens

	1	2	3	4	5	Mean
First fifth	488	492	489	493	491	491
Last fifth	491	494	493	497	493	494

was computed for every test; results are depicted in Fig. 10, where the instability of the original signal (caused by possible measurement errors, pressure fluctuations in the system, dynamic effects) is partially filtered out.

5 Conclusions

The study of the state of the art has allowed us to identify a gap in the fatigue performance analysis of this type of actuators, which is incredibly limited. In the case of materials for 3D printing, this analysis is highly dependent on the manufacturing technology and the selected parameters controlling the process. The present study presents its innovative elements in the construction of an experimental setup that allows for repeatable and accurate measurement of the performance of the bending behavior of pneumatic bellows actuators, in the study methodology, which allowed the execution of fatigue tests on TPU 3D printed actuators whose manufacturing process was completely described and optimized, and in the comparison of the results obtained using a 3D printing elastomer with those obtained using more standardized technologies in the field.

The most self-evident finding to emerge from the analysis is the overall significant performance demonstrated by 3D printed actuators in sustaining repeated cycles of pressurization. FFF is generally deemed as a poorly reliable process, prone to introduce defects, inclusions, porosity and voids in the printed parts. While that might be the case in general, results show that with a proper setting of the machine and a valid material choice, fatigue resistance is significant. It is interesting to evaluate obtained results in the light of the literature results described in the previous section; while conducting a comprehensive comparison proves challenging due to variations in experimental conditions, the tested

actuator consistently demonstrated superior performance compared to similar studies. Moreover, the same geometry, tested on traditionally manufactured actuators, showed significantly worse performances in terms of fatigue life before failure. Direct comparisons are difficult even in this case, but silicone cast actuators offer a good point of reference nonetheless.

Another finding that stands out from the results reported earlier is the stability observed in the FFF-printed actuators across the entire campaign of test. TPU actuators produced a stable bending behavior up to their critical point, with minimal fluctuations that are not related to any sign of degradation of the material.

Accordingly, the study proves the feasibility of the application of FFF printed actuators in TPU material (NinjaFlex) for what is typically considered in mechanical applications the low cycle fatigue field. If opportunely designed according to the loads and pressurization required and if they are properly manufactured, FFF soft pneumatic actuators are fit for the task. Concerning the applicability of the presented results, this study identified a set of fabrication parameters that positively affect the fabrication of fatigue-enduring soft actuators made from NinjaFlex TPU. These process parameters and characteristics were validated during the study and could be adopted to replicate the presented results. Moreover, the study established a plausible range of utilization for 3D-printed FFF actuators, specifically regarding the number of cycles the soft actuators can endure. This information is crucial for engineers and designers, as it provides a benchmark for expected performance and longevity, allowing for more informed decisions in the design and application of these actuators in various practical scenarios.

The analysis of failure mechanics revealed dynamics that merit further study, offering potential for significant improvements in soft actuator performance and material

Fig. 10 Moving average computed over 300 samples of the flexion sensor measurements across each fatigue test. Continuous lines refer to silicone-cast actuators, dotted lines are 3D printed actuators fabricated in TPU
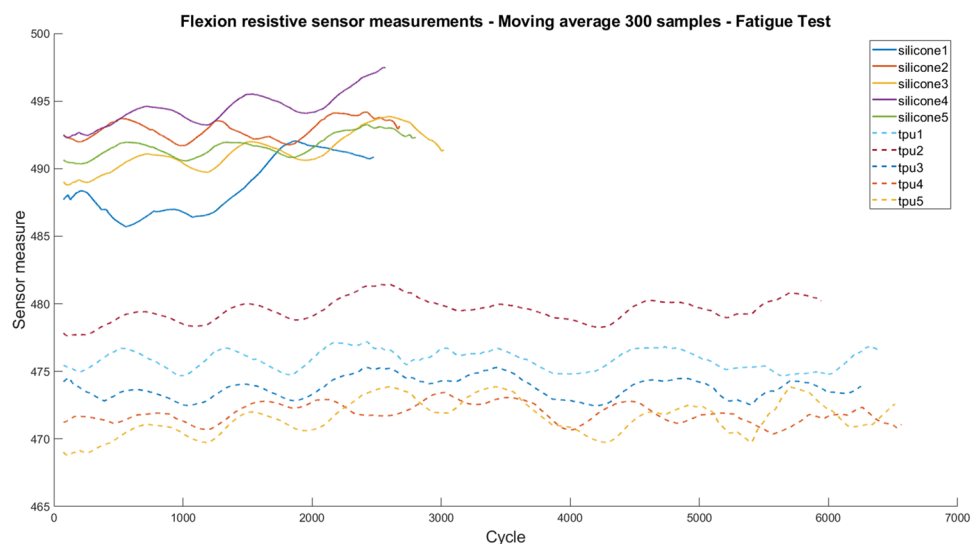
behavior understanding. Future designs could introduce specific features to enhance fatigue life, such as testing different geometries for the connection of bellows to the main body. Fillets and chamfers could distribute internal stresses more evenly, reducing critical stress peaks and limiting crack initiation and propagation. More advanced strategies could involve experimenting with various bellows shapes.

Optimizing the fabrication process or introducing post-processing steps could also increase fatigue life. For 3D-printed FFF components, common defects include partial adhesions between filaments, resulting in voids and air pockets, and occasionally, burnt plastic or external inclusions. These defects can be minimized by adjusting extruding temperature and print speed to ensure continuous material flow and proper solidification, as pursued in this study with promising results.

For cast specimens, air inclusions can be reduced by casting under vacuum. Adding fluidifiers to the silicone mix to lower viscosity can facilitate the casting process and reduce defects, though this study avoided such additions to prevent unpredictable changes in silicone properties. Therefore, efforts focused on applying vacuum during casting and solidification. Enhancing actuator performance could also involve postprocessing surface treatments to waterproof and seal the actuator, benefiting both manufacturing technologies. For FFF, permeation could help seal layers, reducing typical 3D printing discontinuities. This process could involve applying a sealant or coating that penetrates the gaps between the layers, effectively creating a more uniform and robust structure. Both internal and external surfaces could be treated using various tools and techniques, such as dipping, spraying, or brushing with the sealing material. This approach not only addresses the issue of layer adhesion but also improves the overall durability and resistance of the actuator to environmental factors such as moisture and chemicals. Additionally, thermal cycles in post-processing could further consolidate layers. Applying controlled heat treatments to the 3D-printed actuators can enhance the bonding between layers, effectively annealing the material. This process must be carefully designed, considering the specific characteristics of the material and the part's shape and volume distribution. The goal is to apply enough heat to improve the material's microstructure and reduce internal stresses without causing degradation or warping. For instance, gradual heating followed by a controlled cooling process could be explored to achieve the desired effects. Extensive experimentation would be necessary to identify the optimal temperatures and durations for these thermal cycles. This involves a thorough understanding of the material properties and how they change with temperature. Moreover, the impact of thermal treatment on the mechanical properties and longevity of the actuators should be systematically studied. If successful, this post-processing step could lead to actuators with significantly improved performance and lifespan, making them more reliable for various applications.

Another interesting development direction is represented by the study of the effect of FFF parameters. 3D printing software for FFF machines offers access to a vast selection of process parameters, especially for non-industrial systems; the generation of machine code can be tuned introducing constraints and control parameters, changing values, and controlling the trajectory of the end effector. This study considered only main FFF parameters and it exploited previous research in order to identify a suitable set of parameters to be tested; more advanced research could be addressed to test a wider number of parameters, possibly performing a full DOE analysis of the effects.

This study, while providing valuable insights into the fatigue behavior of 3D printed pneumatic actuators, founds its main limitations in the reduced number of tested materials and a particular type of actuator design. Additionally, the study primarily focused on the performance under controlled laboratory conditions, which may not fully replicate real-world applications (e.g., varying loads and different tensional states of the material could significantly impact actuator performance).

The insights gained from this study open up several avenues for future research. One promising direction involves the development of a finite element model (FEM) to simulate the behavior of soft pneumatic actuators under various conditions. Future research will allow a more comprehensive understanding of the actuator's performance, particularly in predicting fatigue life and the impact of different geometric and material parameters. Implementing such a model would potentially allow for the optimization of actuator designs by accurately simulating bending angles and exerted forces under different pressures and configurations. This approach could reduce the need for extensive physical testing, saving time and resources while enhancing the precision of the actuator design process. To unlock such possibilities, significant research efforts should be devoted to the study of a valid material model to be used in FEM simulations, capable of accurately describing the discontinuous characteristics often observed in 3D printed components. By integrating these advanced modeling techniques, future studies could develop more robust and reliable soft pneumatic actuators tailored for specific applications and capable of withstanding extended operational cycles. This would contribute significantly to the advancement of soft robotics, particularly in areas requiring high durability and precise control.

Declarations

References

1. Kim J, Kim JW, Kim HC, Zhai L, Ko HU, Muthoka RM (2019) Review of soft actuator materials. Int J Precis Eng Manuf 20
2. Schmitt F, Piccin O, Barbé L, Bayle B (2018) Soft robots manufacturing: a review. Front Rob AI 5
3. Rus D, Tolley MT (2015) Design, fabrication and control of soft robots. Nature 521
4. Shintake J, Cacucciolo V, Floreano D, Shea H (2018) Soft robotic grippers. Adv Mater 30
5. Galloway KC, Becker KP, Phillips B, Kirby J, Licht S, Tchernov D, Wood RJ, Gruber DF (2016) Soft robotic grippers for biological sampling on deep reefs. Soft Rob 3
6. Marchese AD, Onal CD, Rus D (2014) Autonomous soft robotic fish capable of escape maneuvers using fluidic elastomer actuators. Soft Rob 1
7. Rodrigue H, Wang W, Kim D-R, Ahn S-H (2017) Curved shape memory alloy-based soft actuators and application to soft gripper. Compos Struct 176
8. Zhang Y-F, Zhang N, Hingorani H, Ding N, Wang D, Yuan C, Zhang B, Gu G, Ge Q (2019) Fast-response, stiffness-tunable soft actuator by hybrid multimaterial 3d printing. Adv Funct Mater 29
9. Carpi F, Salaris C, Rossi DD (2007) Folded dielectric elastomer actuators. Smart Mater Struct:16
10. Pagoli A, Chapelle F, Corrales-Ramon JA, Mezouar Y, Lapusta Y (2022) Review of soft fluidic actuators: classification and materials modeling analysis. Smart Mater Struct 31(1). https://doi.org/10.1088/1361-665X/ac383a
11. Ilievski F, Mazzeo AD, Shepherd RF, Chen X, Whitesides GM (2011) Soft robotics for chemists. Angew Chem Int Ed 50:1890–1895
12. Boyraz P, Runge G, Raatz A (2018) An overview of novel actuators for soft robotics. Actuators 7
13. Navas E, Fernández R, Sepúlveda D, Armada M, Gonzalez-de-Santos P (2021) Soft grippers for automatic crop harvesting: a review. Sensors 21
14. Wang Z, Or K, Hirai S (2020) A dual-mode soft gripper for food packaging. Robot Auton Syst 125
15. Joe S, Bernabei F, Beccai L (2022) A review on vacuum-powered fluidic actuators in soft robotics. In: Rehabilitation of the Human Bone-Muscle System. IntechOpen. https://doi.org/10.5772/intechopen.104373 https://www.intechopen.com/chapters/81562
16. Fras, J., & Althoefer, K. (2019). Soft fiber-reinforced pneumatic actuator design and fabrication: towards robust, soft robotic systems. Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics), 11649 LNAI, 103–114. https://doi.org/10.1007/978-3-030-23807-09
17. Faris O, Tawk C, Hussain I (2024) Sopcas finger: a three-dimensional printed soft finger with pneumatic chambers for simultaneous actuation, sensing, and controlled grasping. Rob Rep 2:32–42. https://doi.org/10.1089/ROREP.2023.0019
18. Xavier MS, Tawk CD, Zolfagharian A, Pinskier J, Howard D, Young T, Lai J, Harrison SM, Yong YK, Bodaghi M, Fleming AJ (2022) Soft pneumatic actuators: a review of design, fabrication, modeling, sensing, control and applications. IEEE Access 10:59442–59485. https://doi.org/10.1109/ACCESS.2022.3179589
19. Shorthose, O., He, L., Albini, A., & Maiolino, P. (2021). Design of a multimaterial 3D-printed soft actuator with bi-directional variable stiffness. Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics), 13054 LNAI, 238–248. https://doi.org/10.1007/978-3-030-89177-025/FIGURES/7
20. Fu C, Xia Z, Hurren C, Nilghaz A, Wang X (2022) Textiles in soft robots: current progress and future trends. Biosens Bioelectron 196:113690. https://doi.org/10.1016/J.BIOS.2021.113690
21. Mosadegh B, Polygerinos P, Keplinger C, Wennstedt S, Shepherd RF, Gupta U, Shim J, Bertoldi K, Walsh CJ, Whitesides GM (2014) Pneumatic networks for soft robotics that actuate rapidly. Adv Funct Mater 24
22. Marchese AD, Katzschmann RK, Rus D (2015) A recipe for soft fluidic elastomer robots. Soft Rob 2
23. Jiang, Y., Chen, D., Que, J., Liu, Z., Wang, Z., & Xu, Y. (2017). Soft robotic glove for hand rehabilitation based on a novel fabrication method. 2017 IEEE International Conference on Robotics and Biomimetics, ROBIO 2017, 2018-January, 817–822. https://doi.org/10.1109/ROBIO.2017.8324518
24. Dämmer G, Gablenz S, Hildebrandt A, Major Z (2019) Polyjet-printed bellows actuators: design, structural optimization, and experimental investigation. Front Rob AI 6
25. Wallin TJ, Pikul J, Shepherd RF (2018) 3D printing of soft robotic systems. Nat Rev Mater 3(6):84–100. https://doi.org/10.1038/s41578-018-0002-2
26. Dong, H., Weng, T., Zheng, K., Sun, H., & Chen, B. (2024). Review: application of 3d printing technology in soft robots. https://home.liebertpub.com/3dp. https://doi.org/10.1089/3DP.2023.0127
27. Kuo C-C, Qiu S-X, Lee G-Y, Zhou J, He H-Q (2021) Characterizations of polymer injection molding tools with conformal cooling channels fabricated by direct and indirect rapid tooling technologies. Int J Adv Manuf Technol 117(1–2):343–360. https://doi.org/10.1007/s00170-021-07778-w
28. Peele BN, Wallin TJ, Zhao H, Shepherd RF (2015) 3d printing antagonistic systems of artificial muscle using projection stereolithography. Bioinspir Biomim 10
29. Gariya N, Kumar S, Shaikh A, Prasad B, Nautiyal H (2024) A review on soft pneumatic actuators with integrated or embedded soft sensors. Sensors Actuators A Phys 372:115364. https://doi.org/10.1016/J.SNA.2024.115364
30. Terryn S, Langenbach J, Roels E, Brancart J, Bakkali-Hassani C, Poutrel QA, Georgopoulou A, George Thuruthel T, Safaei A, Ferrentino P, Sebastian T, Norvez S, Iida F, Bosman AW, Tournilhac F, Clemens F, Van Assche G, Vanderborght B (2021) A review on

self-healing polymers for soft robotics. Mater Today 47:187–205. https://doi.org/10.1016/J.MATTOD.2021.01.009

31. Keong BAW, Hua RYC (2018) A novel fold-based design approach toward printable soft robotics using flexible 3d printing materials. Adv Mater Technol 3

32. Sparrman B, Pasquier C, Thomsen C, Darbari S, Rustom R, Laucks J, Shea K, Tibbits S (2021) Printed silicone pneumatic actuators for soft robotics. Addit Manuf 40:101860. https://doi.org/10.1016/J.ADDMA.2021.101860

33. Bui PDH, Prugh B, Padilla AME, Schell C, Keller M, Schultz JA (2023) Endurance tests for a fabric reinforced inflatable soft actuator. Front Mater 10. https://doi.org/10.3389/fmats.2023.1112540

34. Mars WV, Fatemi A (2002) A literature survey on fatigue analysis approaches for rubber. Int J Fatigue 24

35. Tee YL, Loo M, Andriyana A (2018) Recent advances on fatigue of rubber after the literature survey by mars and fatemi in 2002 and 2004. Int J Fatigue 110

36. Libby, J., Somwanshi, A. A., Stancati, F., Tyagi, G., Patel, A., Bhatt, N., Rizzo, J. R., & Atashzar, S. F. (2023). What happens when pneu-net soft robotic actuators get fatigued? 2023 International Symposium on Medical Robotics, ISMR 2023 (2022). https://doi.org/10.1109/ISMR57123.2023.10130227 arXiv:2212.03420

37. Plott J, Shih A (2017) The extrusion-based additive manufacturing of moisture-cured silicone elastomer with minimal void for pneumatic actuators. Addit Manuf 17:1–14. https://doi.org/10.1016/J.ADDMA.2017.06.009

38. Anver, H. M. C. M., Mutlu, R., & Alici, G. (2017). 3d printing of a thin-wall soft and monolithic gripper using fused filament fabrication. In 2017 IEEE International Conference on Advanced Intelligent Mechatronics (AIM) (2017).

39. Yap HK, Ng H, Yeow RC-H (2016) High-force soft printable pneumatics for soft robotic applications. Soft Rob 3

40. Prusa: Prusa i3 M3KS+ (2024). https://www.prusa3d.com/category/original-prusa-i3-mk3s/ Accessed 12/03/2024

41. NinjaTek: NinjaFlex 3D Printer Filament (2024). https://ninjatek.com/shop/ninjaflex/ Accessed 12/03/2024

42. Smooth-On INC (2024). https://www.smooth-on.com/ Accessed 05/04/2024

43. Symbol, S.: Spectra symbol flex sensor (2024). https://www.spectrasymbol.com/resistive-flex-sensors Accessed 05/04/2024

44. Elgeneidy K, Lohse N, Jackson M (2018) Bending angle prediction of soft pneumatic actuators with embedded flex sensors – a data-driven approach. Mechatronics 50

45. Sehhat MH, Mahdianikhotbesara A, Yadegari F (2022) Impact of temperature and material variation on mechanical properties of parts fabricated with fused deposition modeling (fdm) additive manufacturing. Int J Adv Manuf Technol 120:4791–4801. https://doi.org/10.1007/S00170-022-09043-0/FIGURES/17

46. Hassanifard S, Behdinan K (2022) Effects of voids and raster orientations on fatigue life of notched additively manufactured pla components. Int J Adv Manuf Technol 120:6241–6250. https://doi.org/10.1007/S00170-022-09169-1/FIGURES/10