Christian Marzi, Nikola Fischer and Franziska Mathis-Ullrich*

Biocompatible Soft Material Actuator for Compliant Medical Robots

Abstract: Robots from material-based actuators offer high potential for small-scale robots with abilities hardly achievable by classical methods like electric motors. Besides excellent scaling to minimally invasive systems, allowing for omission of metallic components, such robots can be applied in imaging modalities such as MRI or CT. To allow for higher accessibility in this field of research, a facile method for fabrication of such soft actuators was developed. It comprises only two materials: graphene oxide and silicone elastomer. The facile fabrication method does not require specialized equipment. The resulting actuator is biocompatible and controllable by light mediated heat. The bending motion can be controlled by the intensity of applied infrared light and the actuator was experimentally shown to move five times its own weight. Thus, providing capabilities for a medical soft robotic actuator.

Keywords: Actuator, Soft Robot, Light Actuation, Smart Materials, Biocompatible

https://doi.org/10.1515/cdbme-2021-1013

1 Problem

Multifunctional soft materials are rapidly emerging for soft robots due to their various capabilities such as integrated multimodal actuation and sensing. In particular, small-scale soft robotic applications, as often present for medicine, can benefit from such a richness of functionalities embedded in the soft material itself where space is limited and additional attachments deteriorate mechanical properties. For robotic specialists however, the fabrication and handling of such materials can be challenging as they might demand special equipment and facilities as well as biochemical expertise. Especially the field of medical robotics requires non-toxic or biocompatible materials and surfaces as well as accessible applicability for both the fabrication and application.

Multifunctional soft robotic materials that are reconfigurable are frequently fabricated by combining functional materials with soft matter, such as elastomers or hydrogels. Fabrication approaches include heterogeneous blending, post-stabilization of 2D material with soft matter or bilayer integration with a soft base [1]. Stimulus-responsive hydrogels have been widely utilized as actuators in life sciences and intracorporal applications (e.g., targeted drug delivery inside the body [2,3]) due to their high water content and biocompatibility [4]. Elastomers represent a different class of soft matter that may be functionalized for soft robot applications. For example, bilayer integration allows to manufacture robotic skins for protection, actuation and tactile sensing with adjusting material properties via its thickness [1].

Bilayer materials can include graphene and graphene oxide (GO) deployed on a soft polymeric base to form a chemically responsive, electroresponsive, mechanically responsive, thermoresponsive, lightresponsive or magnetoresponsive compound. Thus, various bending actuators with multiple degrees of freedom (DOF) can be synthesized [5]. Liang et al. [6] quantitatively analyse the controllable motion, the dynamic behaviour and high-frequency resonance of graphene and polydiacetylene composites. Increasing the structure's complexity, Selvakumar et al. [7] present a trilayer structure consisting of two self-assembled reduced graphene oxide papers as electrodes with an ionic gel electrolyte in between. Bi et al. [8] propose a microscopic bilayer actuator for micromechatronical systems synthesized of graphene and graphene oxide paper without any polymeric base. Cheng et al. [9] demonstrate a monolayer actuator consisting only of one laser processed GO film for responsive actuation with integrated sensing ability, deployed later in a crawling soft robot. However, many efforts aim towards more simplified fabrication processes, such as a one-step approach, in which a partially reduced graphene oxide-polypyrrole composite film is created [10].

***Corresponding author: Franziska Mathis-Ullrich:** Health Robotics and Automation, Institute for Anthropomatics and Robotics, Karlsruhe Institute of Technology, 76131 Karlsruhe, Germany, franziska.ullrich@kit.edu
Christian Marzi, Nikola Fischer: Health Robotics and Automation, Institute for Anthropomaticsand Robotics, Karlsruhe Institute of Technology, 76131 Karlsruhe,Germany

Here, in a proof-of-concept we intend to focus the seemingly endless possibilities of polymer-based functional materials, composites and process variations on the demands of medical robotic research, aiming for a simplified fabrication process, reducing cost of material and equipment. We eventually aim for a modular thermoresponsive planar soft actuator inspired by [11] that is non-toxic, compatible with common medical imaging modalities (e.g., MRI, CT) and can contribute to more complex soft robotic systems, including surgical continuum robots, microrobots and compliant tools such as grippers.

2 Methods

2.1 Materials

The proposed actuator is a bilayer composite material from a polymeric base and an active layer of graphene oxide. Actuation is achieved by thermal stimulation of the actuator. This results in a bending motion towards the GO layer. For the soft polymeric base, *Silgard* 184 silicone elastomer (Dow Chemical, USA) is used as the material is translucent and can be cured at room temperature. The GO layer is obtained using 4 mg mL^{-1} graphene oxide dispersion in water (Graphenea, Spain). As these two components are the only required constituents for the soft actuator and both are known to be compatible for medical use, the presented method is suitable for general application close to patients. Moreover, if actuated by infrared light, the system is free of magnetic and metallic components and therefore safe for use in presence of or inside a strong magnetic field such as the one necessary for MRI.

2.2 Fabrication

The procedural steps for fabrication of the actuator are illustrated in Figure 1. On a glass surface, 60 µm thick adhesive polypropylene (PP) tape is utilized to frame a 25 mm wide and 100 mm long mask. A thin layer of silicone based release agent (Ease Release 200, KauPo, Germany) is sprayed on the mask to enable subsequent removal of the final assembly. GO dispersion is then filled into the mask using a pipette. Varying amounts of dispersion was deposited to generate GO-layers of varying thickness. Samples with 660 mg (actuator A) and 1100 mg (actuator B) of GO-dispersion are fabricated. The GO dispersion is evenly distributed with a fine brush. For drying and GO layer formation, the sample is then placed in an oven at 80 °C for 40 min. After the heat treatment, a second layer of adhesive

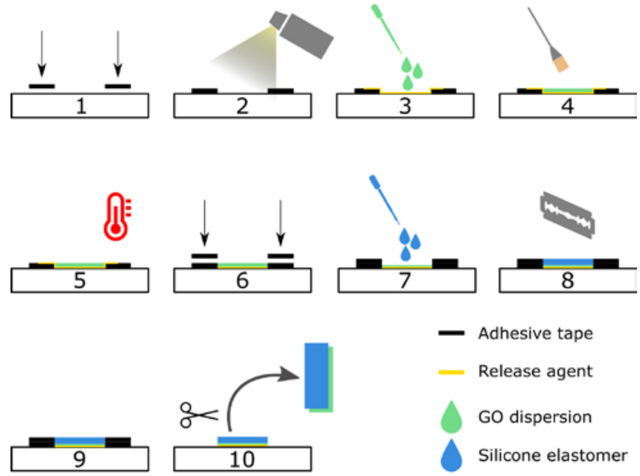

Figure 1: Fabrication steps for a simple bilayer thermoresponsive actuator: A mask is framed on a glass surface (1) and release agent is applied (2). GO dispersion is filled into the mask (3), evenly distributed (4) and heated (5). An additional frame layer is added (6) and a layer of silicone elastomer applied (7) by doctor blading (8). The sample cures at room temperature (9) and can be cut (10).

tape is added onto the first one. This way the total actuator thickness becomes 120 mm. 5.50 g silicone elastomer (blended with curing agent 1:10) is then added, distributed and excess material removed by the method of doctor blading. The created bilayer structure cures for 48 h 25 °C (room temperature) to bond. After completed curing, the mask is removed and the bilayer-structure is cut into 10 mm × 20 mm sample actuators. For each variant (A and B) three samples were cut out for repetitive testing.

2.3 Actuator Characterization

For fabrication, GO dispersion of volume V_{SA} = 0.66 mL or V_{SB} = 1.1 mL respectively is distributed over a surface of A = 25 mm × 100 mm = 2500 mm². With the concentration c = 4 mg mL^{-1} of the GO dispersion and a density of pure GO of ρ = 1.5 mg mm^{-3} the resulting GO layer is estimated to have a thickness of:

$$d_{GO} = \frac{cV_S}{\rho A} \quad (1)$$

Thus, the fabricated composite actuators are characterized by a GO-layer thickness of 0.7 µm (actuator A) and 1.2 µm (actuator B), respectively. The full thickness of both actuators is d_{GO} = 120 µm as it is defined by the height of the mask and doctor blading. Thus, the actuators created and evaluated in the following obtain a relative thickness of the GO-layer of 0.6 % (actuator A) and 1.0 % (actuator B), respectively.

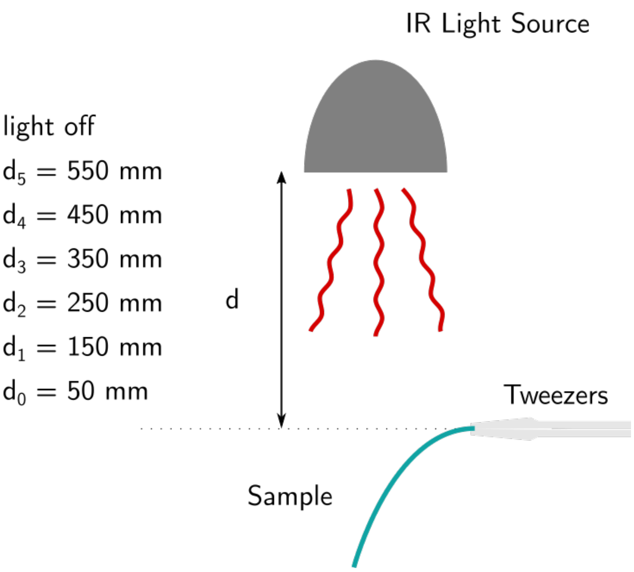

Figure 3: Actuation and data sampling setup. The infrared light source is positioned horizontally above the sample in a distance *d*. The sample is horizontally aligned while hanging downward in idle state. The displayed view is also the tracking camera perspective. The sketch is not to scale, the length of the actuator is 20 mm, *d* was varied from 50 mm to 550 mm.

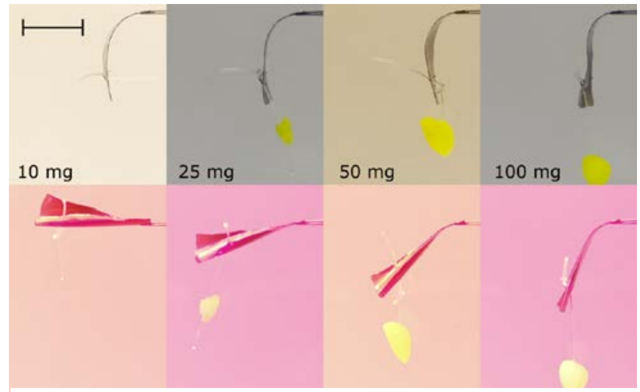

Figure 2: Lifting capabilities of the proposed GO-PDMS soft actuator. Sample weights of 10 mg, 25 mg, 50 mg and 100 mg are attached and the actuator stimulated with maximum intensity. Top images display the idle state of the actuator B, bottom images show full actuation.

Based on the method presented in [11] the sample is actuated by near-infrared light. An infrared light source is used to apply heat to the sample on which the GO layer reacts with contraction and thus bending towards the GO layer. We hypothesize the degree of bending can be controlled by the radiant intensity. This would allow for continuous and controlled actuation and provide foundation for usage as soft robotic actuator.

The setup for actuation and data sampling is illustrated in Figure 2. For characterization, the samples are mounted horizontally in a camera based tracking setup held by tweezers. For comparative measurements, each sample is clamped with the first 2 mm of the tip of the tweezers. The GO layer is facing upwards. A 150 W infrared light source (Philips PAR38) is positioned vertically above the sample. The incident intensity is controlled by moving the light source to 7 different distances *d*: 1) light source switched off, 2) 550 mm, 3) 450 mm, 4) 350 mm, 5) 250 mm, 6) 150 mm, 7) 50 mm distance. The samples were allowed to adapt for 20 s to the changed light stimulus such that static conditions for measuring the terminal deflection at the set intensities were achieved. The sample is filmed during experimentation (Raspberry HQ Camera, 16mm objective lens, Raspberry Pi Foundation, UK). The video stream as well as manually entered data for current light source distance are recorded as ROS2 (www.ros.org) bag files. Figure 3 shows a series of images of the actuation process under increasing intensity of radiation.

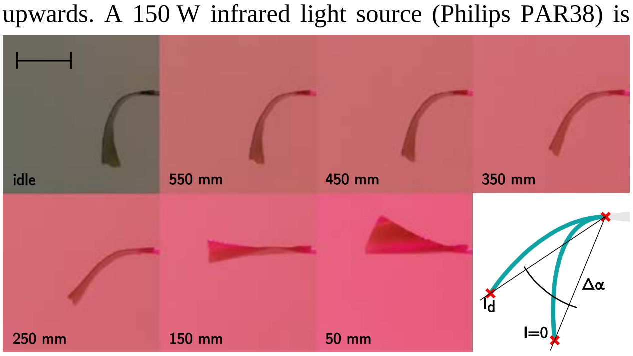

Figure 4: Image series during actuation of the synthesized actuator. Displayed is a 1.2 µm GO layer actuator (type B). The current distances *d* of the light source at each steps are noted. The scale bar represents 10 µm. In the bottom right the measurement scheme is illustrated.

2.4 Application and Evaluation

Subsequently, the presented actuator's loading capabilities are tested (1.2 µm GO layer actuator, type B). Firstly, the actuator is loaded with a filament, which then is incrementally loaded with additional weight. Varying loads of 10 mg, 25 mg, 50 mg and 100 mg are applied. For each iteration the deflection induced by irradiation with the infrared light source at d = 50 mm was measured. The stimulation of loaded actuators carrying different weights is displayed in Figure 4.

After the experiments, video frames for each step of actuation were extracted from the recorded files. The deflection angle of the sample was evaluated with the image manipulation program GIMP (v2.10, www.gimp.org). The angle α from the actuator base (tip of the tweezers) to the center of the actuator's tip was evaluated. As a measure for the magnitude of actuation, the angle difference $\Delta\alpha$ from idle to illuminated state was calculated (see Figure 3). As the mediator for actuation power is the radiant intensity, the distance d_i of the light source was converted into a relative intensity, normalized to the intensity I_{d0} = $I_{d=50\,mm}$. Assuming constant directivity in the solid angle Ω of the actuator positions, and Φ being the radiant flux in this solid angle

$$I_{rel,i} = \frac{I_{d_i}}{I_{d_0}} = \frac{\frac{\Phi}{\Omega d_i^2}}{\frac{\Phi}{\Omega d_0^2}} = \left(\frac{d_0}{d_i}\right)^2 \quad (2)$$

For analysis, mean and standard deviation of the relative deflections of the actuator were calculated over three samples for each type of actuator. The data was processed and plotted in MATLAB (R2021a, MathWorks, USA).

3 Results

The presented actuation experiments demonstrate that the deflection of the created soft actuator can be controlled by near-infrared light intensity, thus proving its potential as a robotic actuator for medical applications. The angle could be controlled by the radiant intensity applied on the material. The process was reversible and the sample could be actuated multiple times. Figure 5 displays the analyzed actuator pose dependency on the applied intensity. The obtained data shows an initial increase of the relative deflection in correlation to the applied intensity and levels off at higher deflection angles for both actuator types A and B.

When challenged with a payload the actuator was able to move up to five times its own weight. When loaded with approximately its own weight the actuator was able to maintain more than 70 % of its range of motion. Figure 6 shows the dependency of maximum bending angle in correlation to the applied payload.

In addition, the presented method for fabrication of actuated materials is facile and fast to learn without profound knowledge or studies of material sciences.

4 Discussion and Conclusion

In the presented work, a facile method for manufacturing and experimental validation of a soft material actuator was presented. A composite actuator was introduced, which allows for a motion range up to 72 °. The actuator offers high potential for utilization in minimally invasive microsurgical applications due to being fabricated from biocompatible materials and the possibility to further miniaturize its active shape. In addition, the loading capabilities of the soft actuator were investigated. Due to it being stimulated by infrared light with omission of metallic components, the soft material actuator may also be used in conjunction with MRI or CT imaging. Its characteristics as a compliant robotic actuator were validated and ought to be suitable for motion control and exertion of forces.

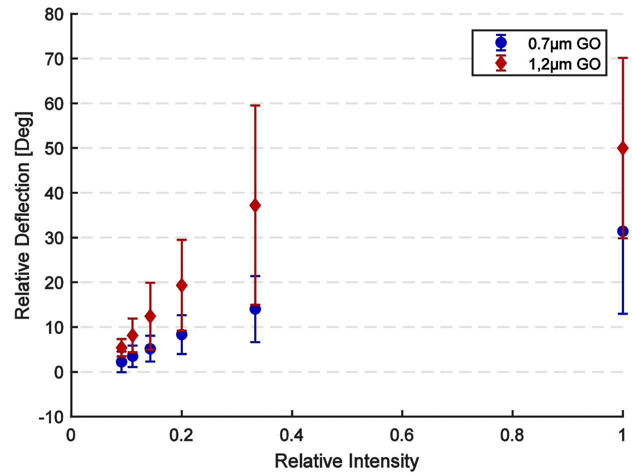

Figure 5: Actuation of GO and PDMS based composite actuators. Displayed are the means and standard deviations over a set of 3 samples for each of two actuator variants A and B.

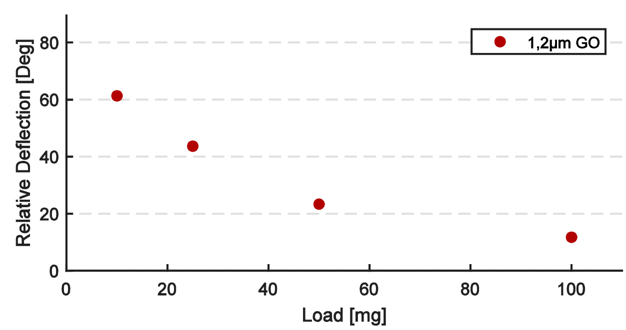

Figure 6: Maximum deflection under payload of the type B actuator 1.2 µm GO layer).

The facile and lightweight design of the soft material actuator allows for adaption of the system with respect to a desired application. For instance, material and motion characteristics can be changed and enhanced by additives, such as carbon nanotubes [11]. As the demonstrated system only exhibits one bending degree of freedom, the next challenges to be approached are the combination to a multi-actuator system, as well as the integration of more complex motion control using near-infrared light.

Author Statement [modify as appropriate]

Conflict of interest: Authors state no conflict of interest.

Acknowledgments

The authors acknowledge Dr. Michiel Petrus for fruitful discussions and technical support.

References

[1] L. Jing,et al., “Recent advances in integration of 2D materials with soft matter for multifunctional robotic materials,”Materials Horizons, vol. 7, no. 1, pp. 54–70, 2020.

[2] S. Fusco,et al., “Chitosan electrodeposition for microroboticdrug delivery,”Advanced healthcare materials, vol. 2, no. 7,pp. 1037–1044, 2013.

[3] H.-W. Huang,et al., “Self-folding hydrogel bilayer for enhanced drug loading, encapsulation, and transport,” in201638th Annual International Conference of the IEEE Engineer-ing in Medicine and Biology Society (EMBC). IEEE, 2016,pp. 2103–2106.

[4] Q. Shi,et al., “Bioactuators based on stimulus-responsivehydrogels and their emerging biomedical applications,” dec2019.

[5] X. Yu,et al., “Graphene-based smart materials,”NatureReviews Materials, vol. 2, no. August, pp. 1–14, 2017.

[6] J. Liang,et al., “Electromechanical actuator with control-lable motion, fast response rate, and high-frequency reso-nance based on graphene and polydiacetylene,”ACS Nano,vol. 6, no. 5, pp. 4508–4519, 2012.

[7] D. Selvakumar,et al., “Reduced graphene oxide paper asbimorphic electrical actuators,”Materials Letters, vol. 191,pp. 182–185, 2017.

[8] H. Bi,et al., “Microscopic bimetallic actuator based on abilayer of graphene and graphene oxide,”Nanoscale, vol. 5,no. 19, pp. 9123–9128, 2013.

[9] H. Cheng,et al., “One Single Graphene Oxide Film for Responsive Actuation,”ACS Nano, vol. 10, no. 10, pp. 9529–9535, 2016.

[10] Y. Jiang,et al., “Spontaneous, Straightforward Fabricationof Partially Reduced Graphene Oxide-Polypyrrole CompositeFilms for Versatile Actuators,”ACS Nano, vol. 10, no. 4, pp.4735–4741, 2016.

[11] W. Wang,et al., “Multistimulus Responsive Actuator withGO and Carbon Nanotube/PDMS Bilayer Structure forFlexible and Smart Devices,”ACS Applied Materials andInterfaces, vol. 10, no. 32, pp. 27 215–27 223, 2018..