Combining Locomotion and Grasping Functionalities in Soft Robots

Alexander Yin, Hung-Ching Lin, Joanna Thelen, Benjamin Mahner, and Tommaso Ranzani

In recent years, the field of soft robotics has grown considerably, demonstrating robots with advanced locomotion capabilities as well as robust grasping and manipulation with respect to their rigid counterparts. The combination of locomotion and grasping capabilities entails a unique set of challenges in soft robotics that have not been fully explored yet, such as the capability to carry a payload without compromising its motion capabilities, and how to adjust changes in the center of mass of the robot. Herein, a soft robotic platform is proposed that demonstrates simultaneous locomotion and grasping. The challenges that such a soft robot would encounter are explored in terms of stability of the robot while supporting a payload and variations in the location of the center of mass. The robot has 13 independently controllable degrees of freedom to study different locomotion and grasping strategies. A passive stiffening methodology is also presented that allows the robot body to statically sustain up to 7.7 times its body weight (BW), and to walk carrying a payload up to 100% times its BW.

The field of soft robotics has grown considerably in the past decade, leading to a paradigm shift on how robots interact with the surrounding environment. Indeed, in the design of soft robotic devices, principles of embodied intelligence and morphological computation can be adopted to develop inherently compliant machines able to tune their stiffness, perform dexterous manipulation, and demonstrate robust locomotion in unstructured environments. Inspired by biological systems, soft-bodied devices provide unique advantages in terms of resilience to dynamic and highly unstructured environments.

Soft-bodied locomotion and grasping are two growing research areas in soft robotics. Previous research in soft robotic grasping has demonstrated systems that were able to perform complex manipulation of delicate and irregular objects or living organisms by simply exploiting their morphology and the mechanical properties of the materials that compose them. There are several different approaches to the design of soft robotic grippers. Some grippers wrap around objects in a method akin to elephant trunks or octopus tentacles. Other grippers enclose an object and sometimes exploit a multifinger approach similar to the human hand. However, most of these platforms are typically connected to a rigid system, either to an industrial manipulator as previously discussed or to a mobile platform. The use for a rigid platform derives from the need to provide stability and stiffness during manipulation and to properly position the soft gripper.

Similar to grasping, multiple different locomotion strategies have been studied with soft robotic platforms. If we focus on ground locomotion, the main strategies are snake-like navigation, peristaltic motion, caterpillar-based locomotion, jumping, growing, and legged locomotion. Among them, legged locomotion provides dexterous and adaptable motion, which gives the ability to move around a variety of unstructured and unknown terrains. Several soft robots with legged locomotion have been demonstrated in the literature using different actuation technologies to move their legs, such as shape memory alloys, dielectric elastomers, and fluidic actuators. Although those robots are able to sustain their own weight, they have not been demonstrated to be able to carry additional payloads as done with their rigid counterparts. A soft robot able to demonstrate inchworm locomotion and grasping was recently proposed in Wang et al. However, this robot is not able to perform both tasks simultaneously, i.e., once it has grasped, it cannot perform locomotion.

The combination of locomotion and manipulation capabilities into a soft robotic platform introduces novel and interesting challenges related to the soft nature of the robot itself. Indeed, the robot needs to be able to withstand the additional payload during the grasping procedure and to shift its center of mass to account for the additional weight. In this article, we took inspiration from nature to address these challenges. One animal that inspired our robot’s design is the ant. Ants lift large objects with their jaws using their neck joints and carry them by distributing the load over their six feet. They adjust the angle of the payload to ensure that their combined center of gravity is still centered over their body. The aim of this article is to create a soft robot that is...
capable of legged locomotion in an environment, picking up a payload, and moving while carrying the payload. As such, the robot demonstrates the aspects of both grasping and locomotion. This article introduces the design and manufacturing of a soft robotic platform with 13 independently controllable degrees of freedom (DoFs) to maximize the flexibility in the control of different motions of the robot. For simplicity, the proposed system is tethered (i.e., each actuator is controlled by an off-board valve connected to a pressure source) and no sensors or embedded control architectures are integrated.

The design of the robot is shown in Figure 1. The robot has four individually actuated legs (i.e., Leg Actuators) and two independently controllable actuators in between them (i.e., Middle Actuators). Those six actuators control the locomotion of the soft robot. The Leg Actuators are designed to bend downward at a 90° angle to elevate the whole body (Figure 1b). The Middle Actuators expand out radially along the length of the robot when pressurized, thus creating an angle between two of the Leg Actuators (Figure 1b,c). The tubing used to pressurize the soft actuators is encased in a silicone structure that acts as a tail for the device. In addition, the tail shifts the center of gravity on the robot to be closer to the back pair of Leg Actuators. The grasping section of the robot (Figure 1a) has seven independently controllable DoFs and comprises total seven actuators. Six of them are independently controllable fingers designed to wrap around an object, whereas the last one is designed to lift the gripper upward. The six wrapping actuators are called the “Arm Actuators,” with the middle two referred to as the “Middle Arms,” whereas the other four wrapping actuators are called the “Outer Arms.” The last actuator is called the “Balloon Actuator,” which serves as a fulcrum to elevate the gripper and thus shift the center of mass of the robot. A piece of cloth runs from below the gripper to the tail of the Base and acts as a lever. When the Balloon Actuator is inflated, it pushes the cloth vertically, causing the gripper arm to elevate, thus shifting the center of mass of the robot. The robot is fabricated using a layer-by-layer manufacturing method that combines planar elastomeric layers fabricated by casting silicone elastomer into 3D printed molds (Form 2, Formlabs, Somerville, MA, USA). A prototype is shown in Figure 1d in the noninflated configuration, whereas, in Figure 1e, the Leg Actuators are pressurized to let the robot stand. Figure 1f shows the side and front views of the robot. Additional details on the fabrication process can be found in the Supporting Information. The motion of the robot structures is achieved by pressurizing its inner chambers with air. Fluidic actuation was chosen for its simplicity and versatility.

The soft and compliant nature of the materials composing the robot makes it challenging to support a payload while walking, as the additional weight causes a substantial deformation of the robot. Although the robot would still be able to move forward even in such a flattened configuration (Movie M_07, Supporting Information), such deformation can limit the locomotion capabilities of the robot while carrying a payload, resulting in losing the advantages given by a legged locomotion strategy. To allow the robot to support the force of an additional payload without compromising its motion range, the Leg Actuators are reinforced with three laser cut acrylic plates, partially enclosed by the soft polymer constituting the robot (Figure 2a). Each plate of acrylic is separated by a 1 mm wide layer of elastomer. These cuts function as flexures and are designed to allow a 45° bend between each plate. Once a 45° angle is reached, the edge of the acrylic plates contact with each other, creating a stable and rigid structure (Figure 2c). This creates a passive stiffening mechanism where the rigidity of the legs increases as they are loaded.

**Figure 1.** Images of the robot: a) top view of the CAD model; b) side view of the CAD model with the legs actuators (red) fully inflated and the gripper lifted up; c) top view of the CAD model with left Middle Actuators (blue) fully actuated; d) picture of the robot uninflated; e) picture of all Leg Actuators fully inflated; and f) side and front views of the robot. Scale bars are 20 mm.
Indeed, as the material in between the plates undergoes compression, the acrylic plates get in contact with each other to generate a rigid structure. The use of rigid components into soft structures has been previously explored in refs. [50–53] to increase force output and accuracy of soft actuators.

An analytical model was developed to predict the deformation that occurs in the Leg Actuator reinforced with three acrylic plates (3-acrylic). This model utilizes Castigliano’s method to analyze the amount of force needed to cause a vertical deformation, $\delta$, of the actuators. We assumed that the Leg Actuators are equivalent to a three-beam setup with each beam at a $45^\circ$ offset from one another, as shown in Figure 2c. This model uses the Young’s modulus $E$ for acrylic, 2.76 GPa,$^{[54]}$ and Shear modulus $G$ of the elastomeric material (Ecoflex 30, Smooth-On, Macungie, PA, USA), 20 kPa.$^{[55]}$ The model assumes that there are two Leg Actuators connected to each other and estimates how much force a pair can withstand. The total deformation $\delta_F$ based on a vertical load force $F$ is given as the sum of the deformations for plates A, B, and C ($\delta_A^F$, $\delta_B^F$, and $\delta_C^F$, respectively) as indicated in Equation (1).

$$\delta_F = \delta_A^F + \delta_B^F + \delta_C^F$$  

(1)

$\delta_f$,$\delta_B^F$, and $\delta_C^F$ are the vertical deformations for the acrylic plates (3-acrylic) respectively.

The plates A, B, and C have lengths $a$, $b$, and $c$, respectively, and each encounters different axial forces ($F_A$, $F_B$, and $F_C$), moments ($M_A$, $M_B$, and $M_C$), and shear forces ($V_A$, $V_B$, and $V_C$). All beams have the same cross-sectional area $A$ and second moment of inertia $I$. Thus, each bar has the following equations

$$\delta_A^F = \int_0^a \left( \frac{P_A (\frac{\partial P_A}{\partial F})}{EA} + \frac{M_A (\frac{\partial M_A}{\partial F})}{EI} + \frac{6V_A (\frac{\partial V_A}{\partial F})}{5GA} \right) \, dx$$  

(2)

$$\delta_B^F = \int_0^b \left( \frac{P_B (\frac{\partial P_B}{\partial F})}{EA} + \frac{M_B (\frac{\partial M_B}{\partial F})}{EI} + \frac{6V_B (\frac{\partial V_B}{\partial F})}{5GA} \right) \, dy$$  

(3)

$$\delta_C^F = \int_0^c \left( \frac{P_C (\frac{\partial P_C}{\partial F})}{EA} + \frac{M_C (\frac{\partial M_C}{\partial F})}{EI} + \frac{6V_C (\frac{\partial V_C}{\partial F})}{5GA} \right) \, dz$$  

(4)

where

Figure 2. Design, modeling, and characterization of the passive stiffening mechanism: a) CAD model of Leg Actuator showing in red the location of the acrylic reinforcement; b) results of the compression tests and estimate from the analytical model; c) free-body diagram of the three-beam model; d) picture of the robot supporting 400 g; and e) pictures of the leg without acrylic reinforcement (left) before and after compression, and the acrylic reinforced leg before and after deformation (right). Scale bars are 20 mm.
\[ P_A = F \]  \[ P_B = (F + R_D) \sin(\theta) \]  \[ P_C = R_D \]  \\
\[ M_A = M_B - R_D \times M_B = M_C - (F + R_D) \sin(\theta) \]  \[ M_C = F_z - M_D \]  \\
\[ V_A = R_D \]  \[ V_B = (R_D - F) \sin(\theta) \]  \[ V_C = -F \]  \\
(5)

As the model assumes symmetry, there is an equivalent reaction force \( R_D \) and moment \( M_D \) at the end of plate C (Figure 2c); \( \theta \) is the angle between each plate. For this model, \( \theta \) is set to 45°. The \( x \), \( y \), and \( z \) correlate to the distance on beams A, B, and C, respectively.

To validate the model, as well as the effectiveness of the proposed passive stiffening mechanism, compression tests were conducted on several different Leg Actuator designs. Pairs of Leg Actuators were fabricated without any acrylic structure and with the three acrylic plates. An Instron machine (Instron 5940 Series, Instron, Norwood, MA, USA) was used for the test. Three different samples of each actuator underwent three compression tests. The legs were pressurized at the same 45 kPa pressure for the test to have them bent at 90° and compressed by 10 mm (Figure 2b). As shown in Figure 2b, in the absence of reinforcement, the legs would be able to hold a force of 0.4 N with a deformation of 10 mm, whereas the 3-acrylic actuator structure was able to withstand a force of 1.2 N with the same vertical deformation, demonstrating a threefold improvement in its load-bearing capabilities. Figure 2e shows the behavior of the robot legs in compression with (right) and without (left) reinforcements, highlighting the stable structure that arises while compressing the acrylic-reinforced leg. The comparison between the model and the experimental results is shown in Figure 2b. The error of the model’s slope in comparison with the linear portion of the compression test is 0.16%. As a result of reinforcing the Leg Actuators, the robot is capable of statically supporting up to 400 g, which corresponds to 770% body weight (BW), as shown in Figure 2d.

Several different gaits can be created by inflating the Leg Actuators and the Middle Actuators in different sequences. The robot uses the Middle Actuators to swing the legs and alter its stance, whereas the Leg Actuators can be used to change the distance between the legs and the ground. This allows the robot to move forward, backward, and turn left and right. An example of the forward locomotion can be seen in Figure 3a. For further details about the robot’s various gaits, please refer to Videos M_01 and M_02, Supporting Information. The inflation of the actuators was obtained by controlling the pressure in each beam.
actuator. This was done using an Arduino board (Arduino Mega, Arduino, Somerville, MA, USA) to individually control the 13 DoFs of the robot with solenoid valves connected to a single pressure surge. A fluid control board (FCB) was developed to consistently control the robot. The FCB enabled control over all 13 DoFs of the robot and the implementation of motion sequences through a user interface (please see Supporting Information for additional information). The gait of the robot was selected as an alternating gait method. This method alternates between moving the right and left side of the robot. Using this gait, the robot was capable of reaching a speed of 6 cm min\(^{-1}\) (0.9 BL min\(^{-1}\)) without supporting a payload. The robot locomotion was tested on increasing payloads up to a maximum of 60 g (100% BL), as shown in Movie M_06, Supporting Information. The locomotion speed of the robot decreased to 0.3 BL min\(^{-1}\) at 50% BW, 0.09 BL min\(^{-1}\) at 75% BW, and 0.06 BL min\(^{-1}\) at 100% BW. The control sequence was maintained constant with the increasing payloads. The decrease in the speed is due to the increased friction of the legs with the ground caused by the added weight, resulting in a reduction in the stride length. We also demonstrated the inchworm locomotion with the robot in a flattened configuration at a speed of 0.23 BL min\(^{-1}\), as shown in Movie M_07, Supporting Information. In this article, we did not focus on optimizing the control sequence to maximize robot speed.

A variety of objects, as shown in Figure 3c, were chosen to demonstrate the robot grasping capabilities. These objects ranged in shape (spherical, cylindrical, and ovoid), size (2.5–6.5 cm), and weight (7–30 g). More details on the objects are given in Supporting Information. The gripper was able to grasp all the chosen objects (Figure 3d). To grasp and pick up an object, the robot first needs to deflect its front two Leg Actuators to align the gripper with the object (Movies M_03 and M_4, Supporting Information). Depending on the size and orientation of the object, the gripper utilized two different grasping methods: large grasp and small grasp, as shown in Figure 3b, left and right, respectively. The large grasp method first actuates the Middle Arms and then the Outer Arms. This pushes the extended polymer on the Middle Arms to be supported by the Outer Arms and is found to be effective to pick up larger objects. The small grasp method first actuates the Outer Arms and then the Middle Arms. This pushes the Outer Arms inward, allowing the gripper to grasp smaller and uniformly shaped objects. After successful grasping of objects, locomotion of the robot was initiated. While carrying a payload (width of 6.5 mm, weight of 5.5 g), the robot was able to move at 3.0 cm min\(^{-1}\), which corresponds to 0.46 BL min\(^{-1}\) (Movies M_04 and M_5, Supporting Information).

This article introduces a soft robotic platform that simultaneously demonstrates locomotion and grasping capabilities. This platform provides important insights on challenges and opportunities in using soft robotic technologies to perform locomotion tasks while carrying a payload. Although soft robots have demonstrated great promise for robot locomotion, they struggle to demonstrate the capability to carry a payload due to the compliance of their body. In this article, we demonstrate a stiffening mechanism that passively adapts the compliance of the leg to the payload carried by the robot, allowing to statically hold up to 770% BW of the robot and at the same time enabling legged locomotion with up to 100% BW payload, thus paving the way to the development of mobile soft robotic platforms able to withstand large payloads. The combination of locomotion and grasping functionalities into a single soft robotic platform allows a better understanding of the challenges and opportunities in terms of ways to allow the robot to support the additional weight, and methodologies to shift the center of mass for demonstrating stable locomotion of the robot after picking up an object. The platform embeds 13 DoFs: six dedicated to the locomotion, six to the grasping, and one to adjust the position of the gripper to shift the center of mass of the robot and guarantee its stability while walking with a payload. The possibility to individually control all the DoFs of the robot with an external system allows flexibility in evaluating different gait strategies and grasping methodologies. We believe that this versatility will enable more extensive studies in the future on soft robot legged locomotion and grasping. In contrast, the use of external valves and pumps reduces the autonomy of the robot in applications such as exploration and sample collection, and future work will focus on increasing the autonomy of the platform. Indeed, recent works have demonstrated promising approaches to increasing autonomy in soft robotic devices exploiting soft logic components\(^{[60]–[69]}\) and chemical energy sources.\(^{[60]}\) As typical in fluidic soft robots, the locomotion speed is limited. In our case, this is mostly due to the absence of optimization in the locomotion control sequence, which is outside the scope of this article. However, two additional factors affect the locomotion speed: the fact that the robot is tethered, and thus the whole line needs to be pressurized before reaching the soft actuators, and the mechanical properties of the elastomer composing the robot.\(^{[61]}\) Recent efforts in integrating embedded fluidic control on-board soft robots are showing promise in increasing the actuation speed and helping to manage the complexity of multi-DoF soft robotic structures, thus moving toward more autonomous soft robots.\(^{[62,63]}\) In addition, to allow the robot to navigate in an environment, sensing integration will be considered in future iterations of the design. For instance, resistive or capacitive soft sensors\(^{[64–66]}\) can be used to monitor the contact forces of the legs with the ground as well as the deformation of its structures during the locomotion process. A camera can also be integrated to implement vision-guided locomotion for inspection or environmental sample collection applications.

**Experimental Section**

The soft robot comprised five individual layers. Layers were designed using a computer-aided design (CAD) program (AutoCAD Fusion, AutoDesk, San Rafael, CA, USA). The mold was fabricated using a 3D printer (Form 2, Formlabs, Somerville, MA, USA). Three different two-component silicone elastomers (Ecocast 30, Dragon Skin 10 SLOW, and Dragon Skin 20, Smooth-On) were mixed with a planetary mixer (ThinK ARE-310, ThinK Corporation, Sotokanda, Chiyoda-ku, Tokyo, Japan), poured into their respective mold, and degassed in a vacuum chamber at \(-100\) kPa. Then, the silicones were cured in a heat oven (Thermo Scientific Heratherm, Thermo Fisher Scientific, Waltham, MA, USA) at 55 °C for 30 min. To combine the layers to create the robot, 10 g of uncured polymer was poured on the bottom layer, whereas it was still in its mold. It was then spun on a spin coater (6800 Spin Coater Series, Special Coating Systems, San Jose, CA, USA) at 1000 rpm for 40 s to create a 50 μm layer of uncured polymer. The next layer was placed on the top and it was all placed into the heat oven at 55 °C for 30 min. The acrylic reinforcement plates (McMaster-Carr,
1.6 mm in thickness) were cut with a laser cutter (Universal Laser System 4.5, Universal Laser Systems Inc., Scottsdale, AZ, USA) and attached to the legs using Sil-Poxy (Smooth-On, Macungie, PA, USA). Sil-Poxy was also used to assemble the robot, to attach a piece of cloth that runs from one end of the robot to the other, and to secure the tubing. More details on the manufacturing process can be found in the Supporting Information.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

Acknowledgements

The authors gratefully acknowledge Professor Douglas Holmes and Professor Sheila Russo for the insightful discussions.

Conflict of Interest

The authors declare no conflict of interest.

Keywords

bioinspired designs, grasping, locomotion, soft robotics

Received: July 25, 2019
Revised: September 29, 2019
Published online: November 4, 2019

References

[1] C. Laschi, B. Mazzolai, M. Cianchetti, Sci. Robot. 2016, 1, eaah3690.
[2] G. M. Whitesides, Angew. Chem. Int. Ed. 2018, 57, 4258.
[3] Y. Mengüç, N. Correll, R. Kramer-Bottiglio, J. Paik, Sci. Robot. 2017, 2, eaar4527.
[4] R. Pfeifer, F. Iida, in Cognition from the Bottom Up: On Biological Inspiration, Body Morphology, and Soft Materials, Springer, Berlin, Heidelberg 2004, pp. 1–26.
[5] R. Pfeifer, G. Gomez, in Creating Brain-Like Intelligence, Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics), Vol. 5436, Springer, Berlin, Heidelberg 2009, pp. 66–83.
[6] M. Manti, V. Cacucioiu, M. Cianchetti, IEEE Robot. Autom. Mag. 2016, 23, 93.
[7] T. Ranzani, C. Gercbioni, M. Cianchettii, A. Menciassi, Bioinspiration Bimimetics 2015, 10, 035008.
[8] C. Laschi, M. Cianchetti, B. Mazzolai, L. Margheri, M. Follador, P. Dario, Adv. Robot. 2012, 26, 709.
[9] D. Drotman, S. Jadhav, P. Dezonia, M. T. Tolley, in Proc. IEEE Int. Conf. on Robotics and Automation, IEEE, Piscataway, NJ 2017, pp. 5532–5538.
[10] M. Calisti, G. Picardi, C. Laschi, J. R. Soc. Interface 2017, 14, 20170101.
[11] K. Jayaram, R. J. Full, Proc. Natl. Acad. Sci. 2016, 113, 0912427107.
[12] D. Trivedi, C. D. Rahn, W. M. Kier, I. D. Walker, Appl. Bionics Biomech. 2008, 5, 99.
[13] D. Rus, M. T. Tolley, Nature 2015, 521, 467.
[14] M. Li, T. Ranzani, S. Sareh, L. D. Seneviratne, P. Dasgupta, H. A. Wundemann, K. Althoefer, Smart Mater. Struct. 2014, 23, 095007.
[15] J. Shintake, S. Rosset, B. Schubert, D. Floreano, H. Shea, Adv. Mater. 2016, 28, 231.
[16] J. Fraš, M. Maciąś, F. Czubaczyński, P. Salek, J. Głowka, in Int. Conf. on Systems, Control and Information Technologies, Springer, Cham 2017, pp. 368–377.
[17] K. C. Galloway, K. P. Becker, B. Phillips, J. Kirby, S. Licht, D. Tchernov, R. J. Wood, D. F. Gruber, Soft Robot. 2016, 3, 23.
[18] J. Shintake, V. Cacucioiu, D. Floreano, H. Shea, Adv. Mater. 2018, 30, 1707035.
[19] T. Ranzani, M. Cianchetti, G. Gerbioni, I. D. Falco, A. Menciassi, IEEE Trans. Robot. 2016, 32, 187.
[20] M. Calisti, M. Giorelli, G. Levy, B. Mazzolai, B. Hochner, C. Laschi, P. Dario, Bioinspiration Biomimetics 2011, 6, 016002.
[21] C. Laschi, M. Cianchetti, B. Mazzolai, L. Margheri, M. Follador, P. Dario, Adv. Robot. 2012, 26, 709.
[22] S. Neppalli, B. Jones, W. McMahan, V. Chitrakaran, I. D. Walker, M. Pritts, M. Csendics, C. D. Rahn, M. Grissom, in IEEE/RSJ Int. Conf. on Intelligent Robots and Systems 2007, IEEE, Piscataway, NJ 2007, p. 2569.
[23] B. Mazzolai, A. Mondini, F. Tramacere, G. Riccomini, A. Sadeghi, G. Giordano, E. Del Dottore, M. Scaccia, M. Zampato, S. Carminati, Adv. Intell. Syst. 2019, 1900041.
[24] F. Iliyski, A. D. Mazzeo, R. F. Shepherd, X. Chen, G. M. Whitesides, Angew. Chem. 2011, 121, 1930.
[25] B. S. Homberg, R. K. Katzschmann, M. R. Dogar, D. Rus, Auton. Robots 2019, 43, 681.
[26] Z. Wang, Y. Torigoe, S. Hirai, IEEE Robot. Autom. Lett. 2017, 2, 1909.
[27] C. Choi, W. Schwarting, J. Delpreto, D. Rus, IEEE Robot. Autom. Lett. 2018, 3, 2370.
[28] W. McMahan, V. Chitrakaran, M. Csendics, D. Dawson, I. D. Walker, B. A. Jones, M. Pritts, D. Dienno, M. Grissom, C. D. Rahn, in Proc. 2006 IEEE Int. Conf. on Robotics and Automation, IEEE, Piscataway, NJ 2006, pp. 2336–2341.
[29] M. Calisti, G. Picardi, C. Laschi, J. R. Soc. Interface 2017, 14, 20170101.
[30] M. Luo, M. Agheli, C. D. Onal, Soft Robot. 2014, 1, 136.
[31] T. Manwell, B. Guo, J. Back, H. Liu, in 2018 IEEE Int. Conf. on Soft Robotics (RoboSoft), IEEE, Piscataway, NJ 2018, pp. 54–59.
[32] S. Seok, C. D. Onal, K. J. Cho, R. J. Wood, D. Rus, S. Kim, IEEE/ASME Trans. Mechatronics 2013, 18, 1485.
[33] H.-T. Lin, G. G. Leisk, B. Trimmer, Bioinspiration Biomimetics 2011, 6, 026007.
[34] M. Tolley, R. F. Shepherd, M. Karpelson, N. W. Bartlett, K. C. Galloway, M. Wehner, R. Nunes, G. M. Whitesides, R. J. Wood, in IEEE Int. Conf. on Intelligent Robots and Systems, IEEE, Piscataway, NJ 2014, pp. 561–566.
[35] E. W. Hawkes, L. H. Blumenschein, J. D. Greer, A. M. Okamura, Sci. Robot. 2017, 2, eaaan3028.
[36] R. F. Shepherd, F. Iliyski, W. Choi, S. A. Morin, A. A. Stokes, A. D. Mazzeo, X. Chen, M. Wang, G. M. Whitesides, Proc. Natl. Acad. Sci. 2011, 108, 20400.
[37] D. E. Koditschek, R. J. Full, M. Buehler, Arthropod Struct. Dev. 2004, 33, 251.
[38] C. Liu, E. Dong, M. Xu, G. Alici, J. Yang, Int. J. Adv. Robot. Syst. 2018, 15, 1729881418798749.
[39] M. Duduta, D. R. Clarke, R. J. Wood, in 2017 IEEE Int. Conf. on Robotics and Automation (ICRA), IEEE, Piscataway, NJ 2017, pp. 4346–4351.
[40] D. Drotman, S. Jadhav, M. Karimi, P. Dezonia, M. T. Tolley, in Proc. IEEE Int. Conf. on Robotics and Automation, IEEE, Piscataway, NJ 2017, pp. 5532–5538.
[41] J. Waynelovich, T. Frey, A. Baljon, P. Salamon, Soft Robot. 2016, 3, 64.
[42] Y. Li, B. Li, J. Ruan, X. Rong, in 2011 IEEE 5th Int. Conf. on Robotics, Automation and Mechatronics (RAM), IEEE, Piscataway, NJ 2011, pp. 166–171.
[43] Y. Pan, F. Gao, in Proc. 2013 Int. Conf. on Advanced Mechatronic Systems, IEEE, Piscataway, NJ 2013, pp. 541–544.

[44] K. C. Galloway, J. E. Clark, M. Yim, D. E. Koditschek, in 2011 IEEE Int. Conf. on Robotics and Automation, IEEE, Piscataway, NJ 2011, pp. 1243–1249.

[45] M. Raibert, K. Blankespoor, G. Nelson, R. Playter, IFAC Proc. Vol. 2008, 41, 10822.

[46] T. Wang, J. Zhang, G. Zhao, Y. Li, J. Hong, M. Y. Wang, in 2018 IEEE/ASME Int. Conf. on Advanced Intelligent Mechatronics (AIM), IEEE, Piscataway, NJ 2018, pp. 1087–1091.

[47] V. Nguyen, B. Lilly, C. Castro, J. Biomech. 2014, 47, 497.

[48] T. Ranzani, S. Russo, N. W. Bartlett, M. Wehner, R. J. Wood, Adv. Mater. 2018, 30, 1802739.

[49] P. Polygerinos, N. Correll, S. A. Morin, B. Mosadegh, C. D. Onal, K. Petersen, M. Cianchetti, M. T. Tolley, R. F. Shepherd, Adv. Eng. Mater. 2017, 19, 1700016.

[50] M. A. Wook Choi, V. Rubtsov, C.-J. Kim, IEEE Trans. Ind. Electron. 2009, 56, 1005.

[51] S. Russo, T. Ranzani, C. J. Walsh, R. J. Wood, Adv. Mater. Technol. 2017, 2, 1700135.

[52] L. Paez, G. Agarwal, J. Paik, Soft Robot. 2016, 3, 109.

[53] Z. Zhakypov, M. Mete, J. Fiorentino, J. Paik, in 2019 2nd IEEE Int. Conf. on Soft Robotics (RoboSoft), IEEE, Piscataway, NJ 2019, pp. 814–820.

[54] Cambridge University Engineering Department, Materials Data Book, Tech. Rep., Cambridge University, Cambridge, UK 2003.

[55] R. Zhao, S. Lin, H. Yuk, X. Zhao, Soft Matter 2018, 14, 2515.

[56] D. J. Preston, P. Rothemund, H. J. Jiang, M. P. Nemitz, J. Rawson, Z. Luo, G. M. Whitesides, Proc. Natl. Acad. Sci. 2019, 201820672.

[57] D. J. Preston, H. J. Jiang, V. Sanchez, P. Rothemund, J. Rawson, M. P. Nemitz, W.-K. Lee, Z. Luo, C. J. Walsh, G. M. Whitesides, Sci. Robot. 2019, 4, eaaw5496.

[58] P. Rothemund, A. Ainla, L. Belding, D. J. Preston, S. Kurihara, Z. Luo, G. M. Whitesides, Sci. Robot. 2018, 3, eaar7986.

[59] S. T. Mahon, A. Buchoux, M. E. Sayed, L. Teng, A. A. Stokes, in 2019 IEEE Int. Conf. on Soft Robotics, IEEE, Seoul 2019, pp. 782–787.

[60] M. Wehner, R. L. Truby, D. J. Fitzgerald, B. Mosadegh, G. M. Whitesides, J. A. Lewis, R. J. Wood, Nature 2016, 536, 451.

[61] J. C. Case, E. L. White, R. Kramer-Bottiglio, Soft Robot. 2015, 2, 80.

[62] S. I. Rich, R. J. Wood, C. Majidi, Nat. Electron. 2018, 1, 102.

[63] M. Wehner, M. T. Tolley, Y. Mengüç, Y.-L. Park, A. Mozeika, Y. Ding, C. D. Onal, R. F. Shepherd, G. M. Whitesides, R. J. Wood, Soft Robot. 2014, 1, 263.

[64] P. Roberts, D. D. Damian, W. Shan, T. Lu, C. Majidi, in Proc. IEEE Int. Conf. on Robotics and Automation, IEEE, Piscataway, NJ 2013, pp. 3529–3534.

[65] S. Russo, T. Ranzani, H. Liu, S. Nefti-Meziani, K. Althoefer, A. Menciassi, Soft Robot. 2015, 2, 146.

[66] T. G. Thuruthel, B. Shih, C. Laschi, M. T. Tolley, Sci. Robot. 2019, 4, eaav1488.