Modular Assembly of Soft Machines via Multidirectional Reclosable Fasteners

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Modular soft robots have strong adaptability and versatility in various application contexts. However, the introduction of connection mechanisms will always either reduce the structural compliance or need extra actuation appendages, resulting in the complexity of the structure and system of the robot. To address these issues, herein, a compliant and passive connection strategy is demonstrated, which is accomplished utilizing the reclosable fasteners (RFs), and other varieties including hook-and-loop fasteners, as the connection mechanisms to the soft modules for the rapid assembly of various soft machines. The module is a pneumatic soft actuator with both ends designed with a multifaceted structure to attach the RFs in different orientations, resulting in various assembling patterns, including linear connection, orthogonal connection, and oblique connection. Moreover, an alignment mechanism is also designed to improve the alignment precision between two assembled modules. The versatility of the RF enables soft modules capable of assembling not only between identical modules but also with diverse additional accessories for various application scenarios. Different functional assemblies are demonstrated including soft grippers, soft walking robots, and shape-morphing electrical devices. This approach to the connection mechanisms provides routes to new modular soft robots and devices.

1. Introduction

Soft robots with inherently high compliance and adaptability have implemented and displayed a variety of functions and capabilities, including compliant manipulation,[1–4] bioinspired locomotion,[5–10] and smart shape-morphing devices.[11–15] Most of these soft robots and devices require a combination of multiple materials with different mechanical properties that are sometimes difficult or impractical to fabricate using rapid fabrication techniques, such as soft lithography and 3D printing. Even the robotic structures, especially nonplanar structures, made from homogeneous elastomeric materials, are impractical to be manufactured in a single step, which is always time-consuming and labor intensive. Moreover, once generated, soft structures were fixed and not capable of reversible changes to modify capabilities or functions. Recent advances have introduced the modular design concept into soft robotics, providing a versatile and fast manufacturing method for multifunctional soft robots.[16,17] The key components of the modularized soft robots are the connection mechanisms, which can be mainly divided into two categories according to their effect on the overall stiffness of the robot structure: rigid connections, soft connections, and adhesive connections. Rigid connections, including some mechanical connections,[18–22] and many magnetic connections,[16,23–25] will greatly reduce the softness and compliance of the robot structure and also increase the structural complexities. On the other hand, the soft connections, including electrostatic connections,[26,27] and vacuum-based connection,[28,29] made from soft materials, can maintain the softness of the robot structure. However, these soft connections perform low-alignment precision and require extra actuation appendages resulting in the complexity of systems. In addition, adhesive connections, including glued adhesion,[30–33] hot-melt adhesion,[34,35] and self-healing elastomer,[36–39] are connection methods without introducing any rigid or soft connection counterparts. However, these connections either are irreversible permanent connections or still need extra actuation appendages. Therefore, this study aims to design a passive and reversible soft connection, without the need for any extra actuation appendages, to minimize its effects on both the overall structural compliant of the robot and the complexity of the system.

This study introduces reclosable fasteners (RFs) as the connection mechanisms to the soft modules for the rapid assembly of various soft robots and devices. Reclosable fasteners, and other varieties including hook and loop fasteners, are commonly used for the fabrics to offer closure alternatives to zippers, snaps, and buttons. The soft module is a pneumatic soft actuator with both ends designed with a multifaceted structure to attach the RFs in different orientations, so that modules can be assembled in various patterns, including linear connection, orthogonal connection, and oblique connection. Moreover, to improve the alignment precision between two modules, an alignment
mechanism is also designed without interference with the use of the soft connection. The versatility of the RF allows soft modules to be assembled not only between individual modules but also with diverse additional accessories equipped with the RF. Using this approach, soft grippers and walking robots with multiple configurations were built from identical soft modules, and electrical devices were constructed from soft modules combined with hard structural components.

2. Results and Discussion

2.1. Design and Fabrication of Soft Module

The soft module is a pneumatic soft actuator consisting of an extensible top layer with uniform gaps between the inside walls of each chamber and an inextensible but flexible bottom layer. To explore more assembling patterns, the front end of the actuator is designed as a raised square frustum with RFs, named RF-1 and RF-2, pasted on the top surface and the four bevels, respectively. The rear end is also a raised square frustum of half height with RFs, collectively referred to as the RF-3, pasted on the four bevels next to the front and rear ends of the actuator. It is worth noting that there are no air chambers at the position of the RFs to avoid the change of the position of the RFs caused by the inflation of the air chambers. The RF used in this study is the dual-lock reclosable fastener (SJ-3551, 3M), consisting of polyolefin base with mushroom-shaped caps, due to strong and reliable fastening through the interlocked mushroom-shaped caps; however, other mechanical fasteners also work.

For clear identification, the front end of the module is highlighted in red, the rear end in blue, and the bottom in brown; moreover, the RFs in different positions are marked with different colors, as shown in Figure 1A. Figure 1B shows the schematic of the sectional view of the two neutral planes of the module along the length direction. C) The three categories of connections based on the relative assembly positions of two modules, including the linear connection (i), orthogonal connection (ii), and oblique connection (iii). Inserted partial enlarged views show the schematics of the interlocked mushroom-shaped caps of the bonded RFs and the positioning mechanism to improve the assembling accuracy, respectively. D) The schematic and the actual diagrams (top view) of the three mentioned connection patterns, including one linear connection (i), three orthogonal connections (ii), and two oblique connections (iii). Scale bars: 30 mm.
module along the longitudinal direction. The dimensions of the chambers are determined so that two inside walls are thinner than other exterior walls. An increase in the internal pressure will inflate the chamber by preferentially expanding the inside walls and minimizing the strain that occurs on the other exterior walls. Therefore, the expanding inside walls of the adjacent inflated chambers push against each other, resulting in an overall pure bending deformation toward the bottom layer of the module. In addition, a thin layer made of relatively viscous polymer (Ecoflex20, Smooth-On) is attached to the bottom of the module to increase the friction. The module is made of elastomer (Dragon Skin 30, Smooth-On) and its overall dimension is determined as $54 \times 17 \times 19$ mm (length $\times$ width $\times$ height). The detailed dimensions and the fabrication process of the module are described in Figure S1 and S2, Supporting Information.

2.2. Assembling Patterns Between Two Modules

The diversity of positions of RFs enables a rich variety of assembling patterns between modules. According to the relative positions of the two connected modules after assembly, the assembling patterns of a single pair of RFs used in this study are generally divided into three categories. The first one is the linear connection, where the two modules are assembled in a straight line through bonding RF-1 and RF-2 on each module. The second one is the orthogonal connection, where the two modules are assembled at a right angle through bonding RF-2 and RF-2, RF-2 and RF-3, or RF-3 and RF-3 on each module, respectively. The third one is the oblique connection that can be formed by bonding RF-1 and RF-2 or RF-1 and RF-3 on each module. An inherent disadvantage of the connection method via RF is the low assembling accuracy because the assembly can be achieved even with a certain alignment error. To improve the assembling accuracy, a strategy is introduced by placing a pin structure to the center of each RF. One end of the pin is designed with a cap to be embedded in the surface of the actuator for a firm fix. When assembling, the two pins of the two RFs are aligned using an additional sleeve structure. The pin and sleeve structure are designed to be small enough not to interfere with the bonding between the RFs (Figure S3, Supporting Information). Figure 1D shows both the schematic and the actual diagrams of the three mentioned connection patterns, including one linear connection, three orthogonal connections, and two oblique connections. Moreover, any module in the following assemblies can be individually controlled by a customized control system (Figure S4, Supporting Information).

2.3. Strength of RF Connection

The pull-force measurements were conducted to determine the axial strength of the RF connections against tensile load. The axial strength of the connections depends on both the bonding force between the RFs and the adhesion between the RF and the soft module. The first experiment was conducted to determine the bonding force between the bonded RFs. Two squared RFs of area $25 \text{mm}^2$ are firmly glued to two rigid fixtures where one is fixed to the ground and one is attached to a load cell (SMT1-5 N, Interface). The initial distance between the two fixtures is adjusted to ensure that two RFs are completely bonded together. The upper fixture is then moved upward slowly using a universal tensile machine (AGS-X Series, Shimadzu), and the pull-force is generated by the bonded RF until their separation is recorded, where a maximum force is about $0.36 \text{N mm}^{-2}$ at a separated displacement of around 2 mm (Figure 2A). The second experiment was conducted to determine the adhesive force between the RF and the actuator. A specimen is fabricated by pasting a squared RF of area $25 \text{mm}^2$ to the cured polymer surface using the same method for pasting the RFs to the module. The heads of the RF are firmly glued to a fixed base, and the polymer side is directly attached to the same load cell. Then, the load cell is slowly moved upward using the machine, and the pull-force generated between the RF and polymer surface until their separation is recorded, where a maximum force is about $0.46 \text{N mm}^{-2}$ at a separated displacement of around 2 mm (Figure 2A). One can see that the maximum adhesive force between the RF and the actuator surface is greater than the maximum bonding force between the RFs, that is, the RF connection can provide a maximum axial connecting force of $0.36 \text{N mm}^{-2}$ and the repeated use of the RFs will not cause damage to the adhesion between the RF and the module.

A bending measurement was further conducted to determine the force that the assembled two modules can withstand in the direction perpendicular to the axial direction. Two modules were linearly assembled and the two ends were firmly fixed using a jig with a support span of 54 mm (i.e., the length of one module). The bonded RF connectors were placed in the middle, and then the load cell is pressed on it during downward motion through the universal testing machine. As a control test, a module with twice the original length was fabricated and then subjected to the same measurement. An obvious separation between the bonded RF connectors can be detected when the displacement reaches about 6 mm, and the measured forces of the load cell for both measurements are shown in Figure 2B. One can see that the measured forces increase approximately linearly with the displacement, and the result shows that the assembled modules and the pure module structure can withstand a force of 0.40 and 0.63 N mm$^{-1}$, respectively, that is, the strength of the assembled modules can reach a ratio 63% of that of the pure module structure.

2.4. Performance Evaluation of the Soft Module

The bending deformation of the module was measured at different applied pressures. The module was hung vertically by fixing its one end and actuated using pressures ranging from 10 to 160 kPa in increments of 10 kPa. Figure 2C shows both experimental and molding results for the bending angle of the module at different applied pressures (Figure S5, Supporting Information). The results show that the bending angle goes up along with an increase in the applied pressure and an applied pressure of 160 kPa causes the module to contact end to end to reach a maximum bending angle of around 251°. The following experiment was conducted to measure the bending force of the modular at a zero bending angle. The module with the fixed rear end was placed horizontally and the front end is directly against
The vertically placed same load cell. The bending force generated by the tip of the module is measured at different applied pressures, and results show that the bending force at a zero bending angle increases approximately linearly with applied pressure.

2.5. Assembly of Soft Robotic Grippers with Different Configurations

The modules are first applied to the design of grippers to demonstrate the proposed module with immediate potential for use. Considering the variety of shapes and sizes of objects being grasped, grippers with two and four fingers are constructed separately, wherein the fingers are constituted by one and two modules, respectively. The grippers with a total of four different configurations are described in Figure 3A. The first gripper (namely gripper-1) is a planar two-fingered gripper formed by directly bonding the two rear ends of two modules via RF-5 to a base having RFs installed to the lower surface. The second gripper (namely gripper-2) is similar to the first one, except that each finger contains two modules assembled end to end via the linear connection. The third gripper (namely gripper-3) is a four-fingered gripper, which is formed by assembling four modules in one plane using orthogonal connections. The fourth gripper (namely gripper-4) is similar to the third one, except that each finger contains two modules assembled end to end via the linear connection. All the four grippers were constructed by repeatedly using the same set of modules, and their overall dimensions are shown in Figure S6, Supporting Information.

To evaluate the grasping force, all the four grippers were bonded to the same base fixed to the same universal tensile machine to measure the force generated by the gripper on fixed spherical objects with different diameters from caging the objects to their separation. The spherical objects were designed with a diameter ranging from 10 mm to the maximum size that can be caged by the gripper. All the constituent modules were actuated simultaneously using an applied pressure of 100 kPa regardless of the target objects. The vertical maximum pulling forces generated by the grippers with the mentioned four configurations on the fixed objects were measured. Figure 3B,C shows the measured forces of the two-fingered grippers and four-fingered grippers, respectively. One can see that there is an optimal point to achieve the maximum pulling force for the gripper in each configuration. The maximum pulling forces for the diameters of the spherical objects obtained by the grippers from gripper-1 to gripper-4 is ≈1.4 N for 50 mm, 1.0 N for 60 mm,
2.0 N for 50 mm, and 1.6 N for 60 mm, respectively. The results also showed that the greater the number of fingers, the greater the pulling force generated by the gripper. Moreover, the grippers with longer fingers produced less pulling force but were able to grasp larger objects. The performance of the grippers was also evaluated by gripping different objects with different shapes and weights (Figure 3D). This demonstration shows that rapid assembly and disassembly enable the grippers with different configurations to be easily constructed according to the grasping objects with different characteristics. One can see that there is some separation on the inside of the fingers between the two assembled modules, that is because the area of the RF-1 and RF-4 for the linear connection is much smaller than the cross-sectional area of the module and a heavy load can then cause a certain rotation between the two modules relative to the center of the bonded RFs. The situation can be improved by increasing the area ratio between the RF and the cross-sectional area of the module.

2.6. Assembly of Soft Walking Robots with Different Gaits

To further explore the diversity of applications, soft modules are assembled to form different walking robots with distinct gaits. A bipedal robot with a length of 106 mm is first constructed by simply assembling two modules end to end via the linear connection (Figure 4A, and S7, Supporting Information). The robot can realize an undulated deformation by alternately actuating the front and rear constituent modules, resulting in bidirectional linear motion. The direction of movement depends on which module is actuated first, that is, if the module on the left is driven first, it will move to the right; otherwise, it will move in the opposite direction (Movie S1, Supporting Information). Figure 4B shows a forward stride to the right on the ground at an applied pressure of 60 kPa with the distance of 17 mm in 2 s, that is, the speed of the robot is about 8.5 mm s⁻¹, that is, 16% body length per stride.

Quadruped robots, composed of five modules named as four legs and one body, with two different configurations, were
further constructed. The first one with a length of 133 mm is constructed using four oblique connections (Figure 4C, and S7, Supporting Information). By actuating the constituent modules with different sequences at 60 kPa, two different gaits of undulation and crawling can be achieved. The undulating motion was achieved by sequentially pressurizing two rear legs, body, and two front legs and then depressurizing them in the same sequence (Figure 4D). At the last step, the two rear legs and the body contact the surface to generate more friction than the front legs, thus creating a forward resultant force to produce a forward movement when depressurizing the two front legs. Figure 4D shows a forward stride of undulating motion to the right with the distance of 19 mm in 3 s. The speed is about 6.3 mm s⁻¹, that is, 14.1% body length per stride. This robot can also perform a crawling gait by first pressurizing the body to lift the spine of the robot and then sequentially pressurizing and depressurizing one rear leg, one front leg opposite to it, the other rear leg, and the other front leg to complete a stride (Figure 4E). Figure 4E shows a forward stride of crawling motion to the right with the distance of 5 mm in 2 s. The speed is about 2.5 mm s⁻¹, that is, 3.6% body length per stride. Using the pressurizing and depressurizing sequence of the legs for the crawling motion, the robot can also perform swim motion on the water surface. Figure 4F shows a forward stride of swimming motion to the right with the distance of 34 mm in 2.8 s. The speed is about 12.1 mm s⁻¹, that is, 25.3% body length per stride. The second quadruped robot with a length of 88 mm is constructed using four orthogonal connections (Figure 4G, and S7, Supporting Information). Figure 5H shows that the robot can perform an inchworm-inspired motion to the right on a tree branch. One stride of the motion was accomplished by the following sequences of depressurizing the two rear legs, pressurizing the two front legs to grab the branch, then pressurizing the body to pull the robot forward, then pressurizing the two rear legs, and then depressurizing the two rear legs to complete a stride. Figure 5H shows the robot on a tree branch.
legs to grab the branch to anchor the robot from sliding backward, and then depressurizing the two front legs and body to push the robot forward. The robot can perform one stride at 90 kPa with a forward distance of 13 mm in 6 s, that is, the speed of the robot is around $2.2 \text{ mm s}^{-1}$, that is, 14.81% body length per stride. In addition, all the actuation patterns with the corresponding motions are summarized in Figure S8 and Movie S2, Supporting Information.

To construct more versatile structures, a hexapod robot is constructed by assembling the front ends of the six modules via orthogonal connections (Figure 5A, and S7, Supporting Information). The robot stands on three legs and all four possible orientations for each leg touching the ground are divided into two cases of bottom down and bottom up. The hexapod robot can perform both a flipping stride and a rotational stride. The forward flipping stride with a forward distance of around...
55 mm can be achieved by actuating one rear bottom-down leg at 140 kPa (Figure 5B,C). The rotational stride with a rotational angle of 35° can be achieved by sequentially pressurizing one bottom-down leg followed by one bottom-up leg at 140 kPa and then simultaneously depressurizing these two legs (Figure 5D,E). The rotation direction of the robot is the same.
as the direction of actuating the two legs in turn. Figure 5E shows the six standing forms of the robot. The yellow triangle indicates that the corresponding bottom-down modules can be used for flip motion. The squares indicate the corresponding modules for the rotational motion where the module marked by the blue square is first actuated followed by the one marked by the red square. In any of the standing forms, the robot can achieve both flipping and rotating motions in specific directions. The flipping motion enables the robot efficiently to move forward in the restricted direction, and the rotational motion enables the robot to adjust its orientation to achieve different forward movement directions to avoid insurmountable obstacles. Figure 5G shows that the robot can cross a 5 mm-high obstacle using the flipping motion, where modules indicated in different colors represent the modules to be actuated by the next flipping motion. Moreover, combining the two types of motion enables the robot to maneuver in complex environments. The locomotion performance of the robot is evaluated through its controllable motions to avoid obstacles and go through a right-angled narrow passage (Figure 5H,I, Movie S3, Supporting Information), where red and yellow dots indicate the positions reached by the robot using flipping motion and rotating motion, respectively.

2.7. Assembly of Electrical Devices

Except for the assembly between modules, the versatility of the RF also allows the soft modules to be assembled with diverse additional accessories equipped with the RF to build a wider range of functional devices and machines. Using this extension, electrical conductivity was introduced into the soft modules whose functions were achieved using the deformation of the modules. To demonstrate this concept, a three-light switch circuit was constructed by introducing conducting components to a cruciform assembly. The cruciform assembly was formed by four soft modules, namely from M-1 to M-4, via orthogonal connections. The electrical conductivity was achieved by firmly gluing RF to one side of the conductive copper sheet and then temporarily bonding the copper sheet to the modules via RFs. The copper sheets are bonded to the front end of the modules corresponding to the breakpoints from 1 to 6 indicated in the circuit diagram to construct the three-light switch circuit (Figure 6A, Movie S4, Supporting Information). The insets show the distribution of bonded copper sheets including two copper sheets soldered by a resistor. Figure 6B shows the photograph sequence of different modules that are bent under pressurization to make contact with each other to implement different circuit paths. The red, white, and yellow LEDs are turned on by actuating M-1 and M-3 to contact the breakpoints of 1 and 4, M-1 and M-2 to contact the breakpoints of 2 and 4, and M-2 and M-3 to contact the breakpoints of 3 and 4, respectively. Moreover, the brightness of the LED can be adjusted, for example, by introducing a resistor to dim the brightness of the red LED accomplished by actuating M-1, M-3, and M-4 to contact the breakpoints of 1 and 5 and 4 and 6. In addition, according to the design of the switch circuit, more complex and functional circuits can be achieved using more modules and introducing more breakpoints.

The actuation of the modules also enables the assembled 2D structures to fold into 3D structures. To demonstrate this concept, a four-sided signaling device is assembled, capable of folding and indicating different information using different LED colors (Figure 6C, and S9, Supporting Information). Each side of the device is a hinge-like structure involving two modules, where one is for the folding and the other one for signal conversion of each side separately. The upper-right inset of Figure 6C shows the assembled mechanism for folding and unfolding a single side of the device based on one module. The rear end of the module is bonded to the bottom of the hinge-like structure, and the front end is bonded by a slider structure to fold and unfold one side of the device through a slider and rail mechanism. A pressure of 110 kPa enables a maximum bending angle of the hinge-like structure of 90° to be achieved in around 1.4 s. Figure 6D shows the folding sequence of the four-sided signaling device from a 2D to a 3D configuration. The bottom-right inset of Figure 6C shows the module for lighting different LED lights with the schematic diagram of the circuit shown in the bottom-left inset. The rear end of the module is bonded to the bottom of the device, and the front end is bonded by a zigzag copper sheet as the breakpoint 4. After folding one side of the device, different pressures of 17, 19, and 27 kPa enable the module to generate a bending deformation of 22°, 26°, and 35° to allow the zigzag copper sheet (breakpoint 4) to contact the breakpoints 1, 2, and 3, resulting in the lighting of LEDs of red, yellow, and green, respectively. By controlling the four modules used for the circuit, the indicating LED lights on the four sides of the device can be controlled individually, so that the indicating lights on each side can be the same or different (Figure 6E, Movie S5, Supporting Information).

3. Conclusion

In summary, this study introduced the RF to the pneumatic soft actuator to form the modules for rapid assembling of various soft machines. Both the front and rear ends of the module are designed with a multifaceted structure, so that the RFs can be attached with different orientations, which enables multiple connection patterns between two modules, including linear, oblique, and orthogonal connections used in this study. At the same time, an alignment mechanism was introduced to improve the alignment precision between two assembled modules. Moreover, the versatility of the RF also allows the soft module to be assembled with diverse additional accessories equipped with the RF to build a variety of functional devices and machines. Assemblies using identical modules are demonstrated by constructing soft grippers and walking robots with multiple configurations. In addition, assemblies between modules and diverse additional accessories are demonstrated by building different shape-morphing electrical devices. It is worth mentioning that the proposed soft modules are not limited to the mentioned connection patterns and demonstrated assemblies and could be used to form a wider range of soft robots and devices.

Through the modular assembly, the manufacturing time and required materials of soft robots and devices are significantly reduced. The total number of modules required to build all the prototypes in this study is 42. However, by reutilizing the
proposed modules, only eight modules were needed to manufacture all samples. This reduced the time and cost necessary to manufacture the samples by 4.25 times, and the modules can be reutilized in future soft machines. This also facilitates repairing of damaged modules and thus allows to keep using functional modules rather than replacing the entire structure.

Compared with the previously reported connection methods of the soft modules, the RF-based connection approach in this study offers several promising advantages. First, the easy availability of the material allows RF to be used as a low-cost and versatile assembling method. Second, the RF-based connection made from flexible materials is a kind of soft connection, which will not reduce but maintain the softness and compliance of the robot structure. The third one is the simplicity of design. The force provided by an RF-based connector depends on the size of the connector area, so connectors of different areas can be customized to meet the required force. In addition, the size of the RF can be freely customized, so RF-based connections can be designed over a wide range of dimensions. At the same time, small-sized RFs enable multiple RF-based connectors to be mounted on one single soft actuator at different positions and orientations to achieve a variety of possible connection patterns. Future works will focus on optimizing the design of RF-based connections and developing assembling methods to construct large-scale soft robotic structures to accomplish diverse functions.

4. Experimental Section

Please see the Supporting Information for details of the experiments.

Supporting Information

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

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Keywords

connection mechanisms, detachable bonding mechanisms, modular robots, reconfigurations, soft robots

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[1] E. Brown, N. Rodenberg, J. Amend, A. Mozeika, E. Steltz, M. R. Zakin, H. Lipson, H. M. Jaeger, Proc. Natl. Acad. Sci. 2010, 107, 18309.
[2] R. Deimel, O. Brock, Int. J. Rob. Res. 2016, 35, 161.
[3] W. Wang, S. H. Ahn, Soft Robot. 2017, 4, 379.
[4] W. Wang, C. Y. Yu, P. A. Abrego Serrano, S.-H. Ahn, Soft Robot. 2020, 7, 283.
[5] E. W. Hawkes, L. H. Blumenschein, J. D. Greer, A. M. Okamura, Sci. Robot. 2017, 2, eaan3028.
[6] B. Kang, Y. Lee, T. Piao, Z. Ding, W. D. Wang, Mater. Horizons 2021, 8, 939.
[7] R. K. Katzschmann, J. DelPreto, R. MacCurdy, D. Rus, Sci. Robot. 2018, 3, eaar3449.
[8] B. Gorissen, D. Melancon, N. Vasios, M. Torbati, K. Bertoldi, Sci. Robot. 2020, 5, eabb1967.
[9] B. F. Haynes, W. Chen, Y. Feng, D. S. Dimitrov, G. Kelso, S. C. Harrison, T. B. Kepler, N. S. Longo, D. E. Russ, H. W. Sun, P. E. Lipsky, S. Kupriyanov, Science 2015, 349, 161.
[10] J. Hwang, W. D. Wang, Adv. Mater. Technol. 2022, https://doi.org/10.1002/admt.202101153.
[11] M. Boyvat, J.-S. Koh, R. J. Wood, Sci. Robot. 2017, 2, eaam1544.
[12] N. Kellaris, V. Gopaluni Venkata, G. M. Smith, S. K. Mitchell, C. Keplinger, Sci. Robot. 2018, 3, eaa3276.
[13] W. Wang, C. Li, H. Rodrigue, F. Yuan, M.-W. Han, M. Cho, S.-H. Ahn, Adv. Funct. Mater. 2017, 1604214, 1604214.
[14] I. D. Sirbu, G. Moretti, G. Bortolotti, M. Bolognini, S. Diré, L. Fambri, Sci. Robot. 2021, 6, eaa5796.
[15] S. C. Hofferberth, M. Y. Saeed, L. Tomholt, M. C. Fernandes, C. J. Payne, K. Price, G. R. Marx, J. J. Esch, D. W. Brown, J. Brown, P. E. Hammer, R. W. Bianco, J. C. Weaver, E. R. Edelman, P. J. Nido, Sci. Transl. Med. 2020, 12, eaay4006.
[16] W. Wang, N.-G. Kim, H. Rodrigue, S.-H. Ahn, Mater. Horiz. 2017, 4, 367.
[17] C. Zhang, P. Zhu, Y. Lin, Z. Jiao, J. Zou, Adv. Intell. Syst. 2020, 2, 1900166.
[18] S. Kurumaya, B. T. Phillips, K. P. Becker, M. H. Rosen, D. F. Gruber, K. C. Galloway, K. Suzumori, Robert J. Wood, Adv. Mater. Horizons 2018, 5, eaar3449.
[19] A. D. Horchler, A. Kandhari, K. A. Daltorio, K. C. Moses, J. C. Ryan, K. A. Stultz, E. N. Kanu, K. B. Andersen, J. A. Kershaw, R. J. Bachmann, H. J. Chiel, R. D. Quinn, Soft Robot. 2015, 2, 135.
[20] M. A. Robertson, J. Paik, Sci. Robot. 2017, 2, eaa6357.
[21] W. Wang, Macromol. Eng. 2020, 305, 1900568.
[22] J. Y. Lee, W. B. Kim, W. Y. Choi, K. J. Cho, IEEE Robot. Autom. Mag. 2016, 23, 30.
[23] S. W. Kwok, S. A. Morin, B. Mosadegh, J. H. So, R. F. Shepherd, R. V. Martinez, B. Smith, F. C. Simeone, A. A. Stokes, G. M. Whitesides, Adv. Funct. Mater. 2014, 24, 2180.
[24] A. Vergara, Y. Lau, R.-F. Mendoza-Garcia, J. C. Zagal, M. Bryant, K. Mostov, R. Keller, J. Bongard, V. Zykov, H. Lipson, M. Yim, W. Shen, B. Salemi, D. Rus, M. Moll, H. Lipson, V. Zykov, M. Efstatios, A. Bryant, H. Lipson, K. Stoy, D. Brandt, D. Christensen, R. Arkin, B. Gumbiner, M. Leptin, B. Grunewald, M. Turing, P. Watson, R. Shepherd, et al. PLoS One, 2017, 12, e0169179.
[25] J. Zou, Y. Lin, C. Ji, H. Yang, Soft Robot. 2018, 5, 164.
[26] J. Germann, M. Dommer, R. Pericet-Camara, D. Floreano, Adv. Robot. 2012, 26, 785.
[27] H. J. Kim, L. Paquin, C. W. Barney, S. So, B. Chen, Z. Sue, A. J. Crosby, R. C. Hayward, Adv. Mater. 2020, 32, 2000600.
[28] Z. Jiao, C. Zhang, W. Wang, M. Pan, H. Yang, J. Zou, Adv. Sci. 2019, 6, 1901371.
[29] M. E. Sayed, J. O. Roberts, R. M. McKenzie, S. Aracri, A. Buchoux, A. A. Stokes, Soft Robot. 2021, 8, 319.
[30] S. A. Morin, Y. Shevchenko, J. Lessing, S. W. Kwok, R. F. Shepherd, A. A. Stokes, G. M. Whitesides, Adv. Mater. 2014, 26, 5991.
[31] S. A. Morin, S. W. Kwok, J. Lessing, J. Ting, R. F. Shepherd, A. A. Stokes, G. M. Whitesides, Adv. Funct. Mater. 2014, 24, 5541.
[32] B. H. Lee, N. Oh, H. Rodrigue, IEEE Robot. Autom. Mag. 2020, 27, 65.
[33] E. Perez-guagnelli, J. Jones, D. D. Damian, Cyborg Bionic Syst. 2022, 2022, 9786864.
[34] Z. Ye, G. Z. Lum, S. Song, S. Rich, M. Sitti, Adv. Mater. 2016, 28, 5088.
[35] R. Coulson, C. J. Stabile, K. T. Turner, C. Majidi, Soft Robot. 2021, https://doi.org/10.1089/soro.2020.0088.
[36] E. F. Gomez, S. V. Wanasinghe, A. E. Flynn, O. J. Dodo, J. L. Sparks, L. A. Baldwin, C. E. Tabor, M. F. Durstock, D. Konkolewicz, C. J. Thrasher, ACS Appl. Mater. Interfaces 2021, 13, 28870.
[37] S. Terryn, J. Brancart, D. Lefeber, G. Van Assche, B. Vanderborght, Sci. Robot. 2017, 2, eaan4268.
[38] E. Roels, S. Terryn, F. Iida, A. W. Bosman, S. Norvez, F. Clemens, G. Van Assche, B. Vanderborght, J. Brancart, Adv. Mater. 2022, 34, 1.
[39] J. Lou, Z. Liu, L. Yang, Y. Guo, D. Lei, Z. You, Adv. Funct. Mater. 2021, 31, 1.