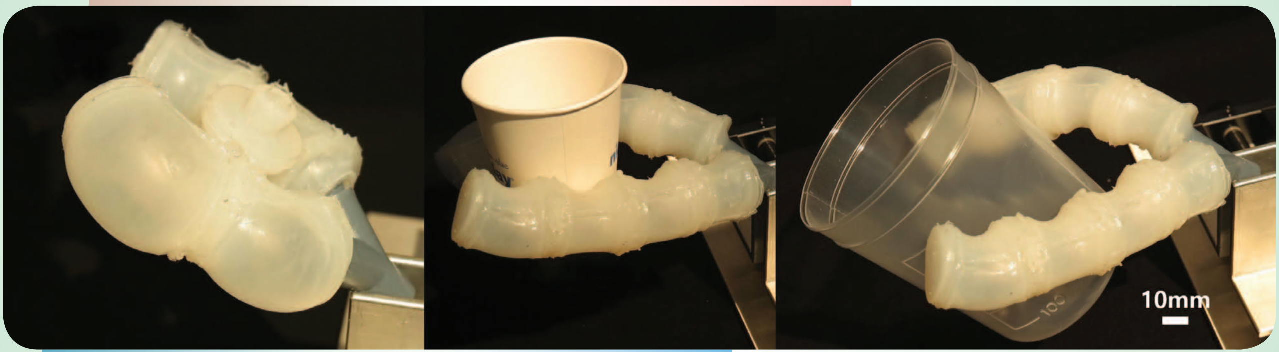
Soft Robotic Blocks



Introducing SoBL, a Fast-Build Modularized Design Block

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This article presents a new, modularized design concept based on a bottom-up approach to assembly. This concept enables the structures and motions of soft robots to be rapidly revised to create new designs that can accomplish different tasks. We designed three basic types of pneumatically actuated soft modules, called *soft robotic blocks (SoBL)*, that implement a single motion each (translation, bending, or twisting), which, when assembled, create structures capable of various motions. We introduce three types of connection mechanisms—screw thread, push fitting, and bistable junction—that can be used with any of the modules and that are designed to make for easy assembly and disassembly. Units were fabricated by multimaterial three-dimensional (3-D) printing or silicone molding.

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Performance tests of the assembled modules and tensile tests of the connectors were conducted. A gripper robot and a crawler robot were rapidly prototyped from the modules. We envision end users creatively assembling and reassembling our modules to easily and rapidly prototype soft robots. We expect this design concept to prove highly useful for rapidly prototyping a wide variety of soft robots and for simplified repair and maintenance of these robots.

Soft Robot Challenges and Advances

Contemporary soft robots are made of soft materials, such as elastomeric polymers with enormously high degrees of freedom, allowing them to continuously and softly change their shape with simple actuation [1], [2]. With suitably designed structures and motions, these advantages enable researchers to create a wide variety of soft robotic applications, such as adaptive soft grippers [3]–[5], shape-changing interfaces [6], postinjury and postsurgical rehabilitation robots [7]–[9], and exploration robots [10]–[12].

Soft robots made from elastomeric polymers are generally fabricated as a single structure by the molding method [13]. This can be considered a top-down approach, in

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which all components are custom designed to fit a robot's overall purpose and function [14]. While rigid robots are normally designed as an assembly of off-the-shelf parts and component mechanisms, soft robots made with polymers require unique designs that are customized to the desired motion and structure of the robot. Generally, soft robot parts are irreplaceable, whereas rigid robot parts can be replaced when needed.

Researchers attempted to overcome the limitations and difficulties of conventional molding and casting methods by implementing a modular design approach. Whitesides' group proposed building soft structures by bonding small elastomeric bricks and tiles [15]–[17]. These bricks and tiles were stacked and bonded to each other to build air chambers and soft structures. However, the modules cannot be disassembled after they are bonded. Rus et al. proposed modularized fluidic soft bending actuators [13], [18], which are small bending actuators that can be connected to each other to build soft robotic applications. However, these modules' connectors cannot be concealed once assembled, and the connection process is not simple enough to be accomplished in a few seconds.

In this article, we present a new type of modularized soft robot made of soft blocks that can be as easily assembled and disassembled like LEGO blocks. Each of these SoBL units consists of a deformable chamber containing a pneumatic channel, an input connector, and an output connector (Figure 1). The chamber can deform in bending, translating, and twisting modes, depending on its design. The input and output connectors are male and female connectors that can be easily connected and disconnected. By connecting SoBL units of various deformation types, new soft robot designs can be rapidly prototyped and revised as needed to handle different objects and environments (Figure 2). The modular design makes it particularly easy to rapidly prototype soft robots with large and complex structures that are difficult to produce by molding. The modular design also enables easier maintenance and simplified repairs.

SoBL units can enable a bottom-up approach to soft robot design, allowing end users to creatively and freely build various shapes of soft robots from modules with differing functions. Furthermore, the end user can quickly and easily reconfigure a prototyped robot or even dismantle it and build a completely new one from the same units, just like playing with LEGO blocks. To achieve this vision, SoBL units need to be easy to assemble and disassemble, and various types of units need to be developed.

We developed three types of units, each of which can generate one of three basic motions (bending, translating, and twisting) and are easy to connect and disconnect. Three types of connectors were also developed and tested: two rigid connectors using screw threads and push fitting and a bistable soft connector with soft materials. These connectors can hold actuating pressure without leakage, are easily assembled and disassembled, and can endure significant deformation and external stress. We also designed noninflatable units that do not generate motion.

Design of Units

Each SoBL unit has a single air chamber and a connector (Figure 1). There are two kinds of units: an inflatable motion-generating unit and a noninflatable unit. When air pressure is applied to a motion-generating unit, its inflatable section enlarges and creates a particular motion. The noninflatable units do not generate motion but instead allow users to construct pneumatic networks to distribute air pressure and connect with multiple units. Both types of units are assembled via their connectors to build structures.

Three types of connectors were also developed and tested: two rigid connectors using screw threads and push fitting and a bistable soft connector with soft materials.

Motion-Generating Units

We investigated three kinds of standardized motion-generating units: a bending unit for pitch motion, a translating unit for linear motion, and a twisting unit for a rolling motion. These units can be combined to achieve complex motions.

Figure 1(a)–(d) shows two kinds of bending units. They differ in terms of how constraint is applied to the units to make the bending motion. We call one of the units a *cooperating bending unit* [Figure 1(a) and (b)] and the other an *independent bending unit* [Figure 1(c) and (d)]. When a single cooperating bending unit is pressurized, its inflatable air chamber enlarges like a balloon, and no bending occurs. However, when a number of such units are connected serially, the resulting structure is able to bend, because the inflated chambers push each other while the bottom of each unit is constrained by junctions.

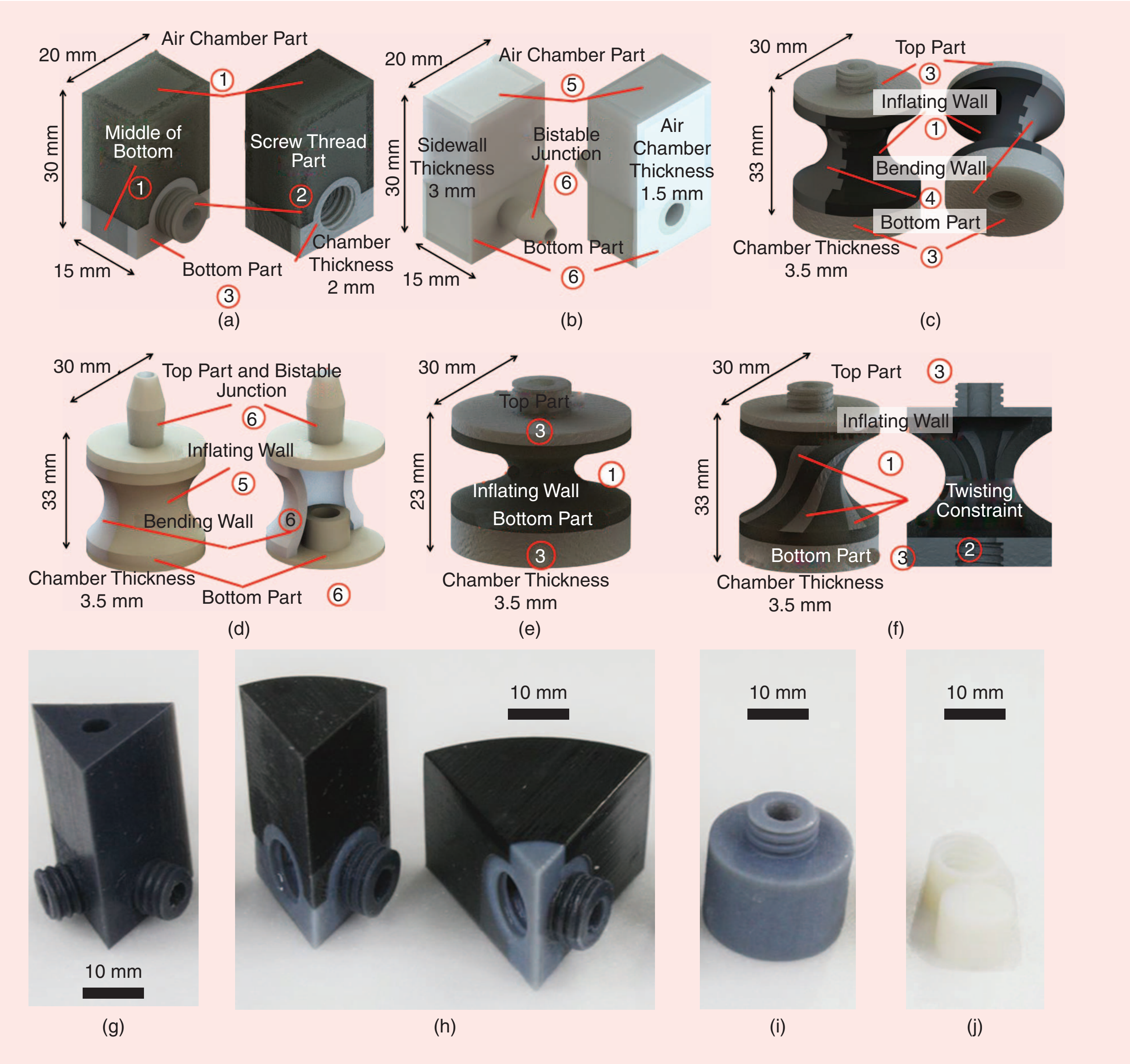

Figure 1. The details of motion-generating units. (a) and (b) Front and rear views of the cooperating bending unit. (c) and (d) Top and bottom views of the independent bending unit. (e) Translating unit. (f) Side and cross-sectional views of twisting units. (g)–(j) Noninflatable units and angled units. (g) A three-way air distribution unit. (h) Two angled units. (i) A connecting cap. (j) A sealing cap. Schematics for the multimaterial 3-D-printed units are shown at the left sides of (a)–(f). (b) and (d) show units made of elastomer. The circled numbers refer to materials used at the indicated parts of units: 1, TangoBlack+; 2, FLX9895-DM; 3, RGD8530-DM; 4, FLX9870-DM; 5, Ecoflex 0030; 6, Dragon Skin 30. Materials 1–4 are from Stratasys Ltd., and materials 5 and 6 are from Smooth-On, Inc.

In contrast, the independent bending units have two inflatable walls that are parallel to their cylindrical axis. One of these walls is made with softer material than the other, so when a single unit is inflated, the softer wall stretches more than the stiffer wall. Therefore, this type of unit can bend individually.

These two types can be combined in many different ways to create soft robots with differing abilities. Cooperating bending units are appropriate when force transmission is needed, because pressure applied to the units can be transmitted to force without unnecessary inflations. Independent bending units are equivalent to a typical joint that bends its body when inflated, and, therefore, they are appropriate for generating motion of a desired shape.

A translation unit is shown in Figure 1(e). The middle part of the unit is made of a soft material, and the top and bottom of the unit are made with a stiffer material to enable connectors to be built. When air pressure is applied, the middle of the unit inflates linearly and produces a translating motion.

For a rolling motion, we created a twisting unit that has a design similar to that of the translation unit [Figure 1(f)].

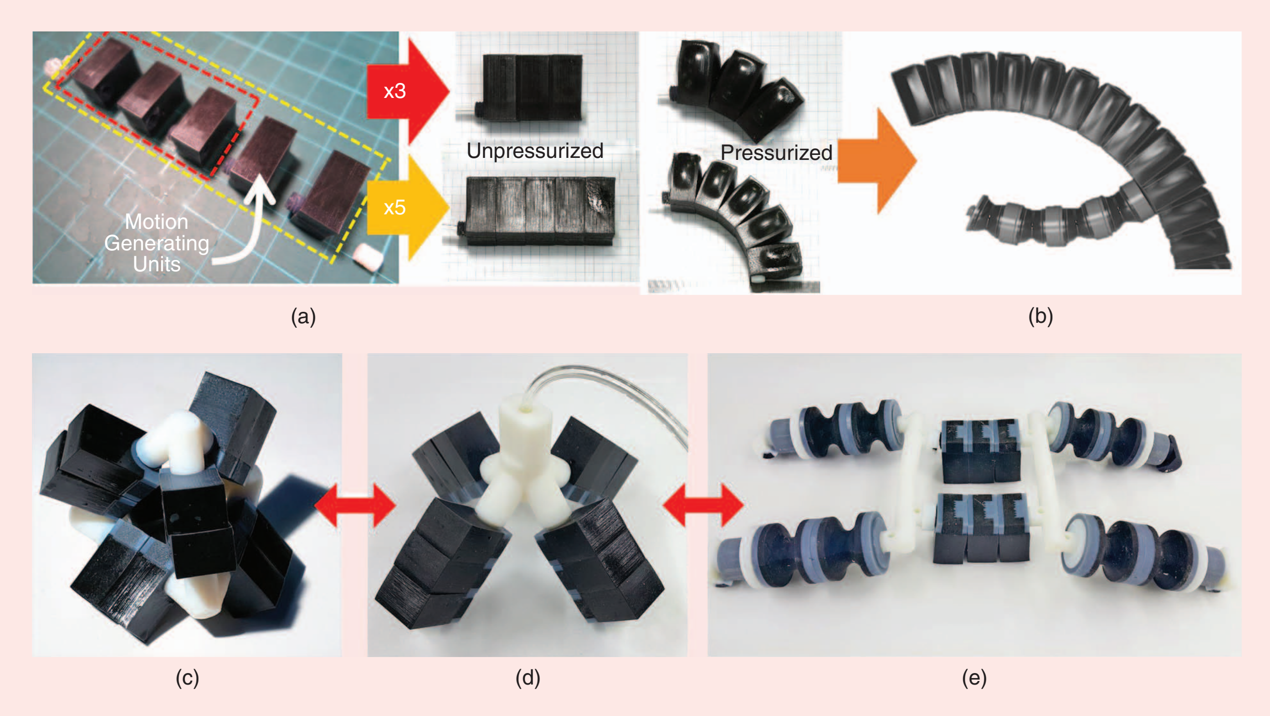

Figure 2. The SoBL modularized design concept allows rapid prototyping, structure reconfiguration, and easy repairs. (a) Sets of modules are configured into (b) bending actuators (image generated by 3-D rendering). (c) A complex triangular pyramid structure is reconfigured into (d) a gripper and (e) a crawler.

However, the twisting unit is spirally constrained at its middle to produce twisting motions.

Noninflatable Units

The design called for many different types of noninflatable units, designed and fabricated according to users' needs and target objects. Figure 1(g)–(j) shows a few examples of noninflatable units.

One basic noninflatable unit is the bent unit. Using 3-D printing, we fabricated such units with a 60° bend. When these bent units were connected to units with a predesigned angle, no motion was generated. Another basic noninflatable unit is the hub unit. Multiple units can be connected to a hub unit, thereby allowing air pressure to be distributed to all connected units at the same time.

Connecting Mechanisms

Various active and passive methods for connection have been researched for rigid modular robots (e.g., mechanical connections, magnets, and vacuum [19], [20]). For soft modular robots, however, only a few connection mechanisms have been reported (e.g., using an embedded magnet [21] or an electroadhesion pad [22]).

We designed a connecting junction at the front and rear of each unit to permit units to be assembled into structures. The connecting junctions had the following requirements: 1) They need to be easily assembled and disassembled and reusable after disassembly, 2) they need to be tight enough to endure applied air pressure and to prevent leakage of actuating fluid, and 3) they need to retain enough flexibility for adaptiveness as soft robots. We designed three connectors satisfying those requirements: two rigid connectors using screw threads or push fitting and one bistable soft connector.

In the screw-thread connector design [Figure 3(a)], a male screw thread is positioned at the front of a unit and a female one at the rear. The screw-thread design was robust enough to endure 450 kPa of air pressure, which was enough to puncture the units' air chamber.

A push-fitting design was proposed to improve the ease of assembling units [Figure 3(b)]. The push-fitting design made assembly much simpler and easier than screwing in units. The screw thread on the male connector was replaced with a small bump that acts as an O-ring. The screw thread on the female connector was replaced with a concave-shaped O-ring in the middle of the hole. Two different diameters of female holes were tested, one the same size as the male plug (a 10 mm diameter) and one with a diameter 0.2 mm smaller than the male plug.

The push-fitting design made assembly much simpler and easier than screwing in units.

The third proposed design, a bistable connector, was intended to make the junction more flexible (Figure 3). The female part of this connector has two stable states, as shown in Figure 3(c)–(g). When the female part is in a pulled-out state [Figure 3(d)] and a male part is pushed into it, the female part

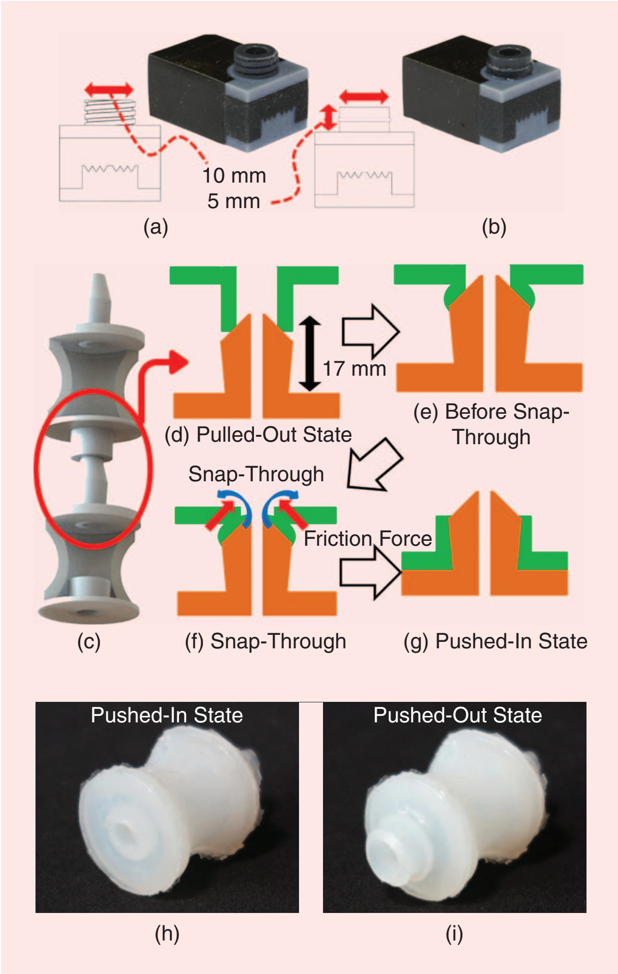

Figure 3. The schematics and photographs of a cooperating bending unit with (a) a screw-thread connector and (b) a push-fitting connector. (c)–(g) A schematic diagram of a bistable connector. (h) The pushed-in state and (i) pulled-out state of the bistable connector.

The final products of the molding and casting process were more robust and endured higher air pressure than the units created via multimaterial 3-D printing.

rolls up to a critical point [Figure 3(e)]. When the female part passes this critical point, it rapidly snaps through to the pushed-in state and drags the male part inside by surface friction [Figure 3(f) and (g)]. This bistable mechanism helps to overcome the large difference of diameter between the male and female parts. To improve ease of assembly and performance, the diameter of the male part was changed through the longitudinal direction. The top of the male part was given a smaller diameter than the female part, and the bottom of the male part a larger diameter. Changing the diameter of the male part makes it easier to insert a male part into a female part and allows the connector to endure more tensile load.

Screw-thread and push-fitting connectors need to be rigid enough to ensure strong assemblies. This rigidity is helpful for force transmission and form maintenance. However, the rigidity also provides a disadvantage since it hinders both the flexibility and the robustness of the screw-thread and push-fitting connectors. There is a trade-off between force transmission and softness. Table 1 shows quantitative and qualitative evaluations of these three connecting mechanisms.

Fabrication

The units were fabricated with either multimaterial 3-D printing or a molding process (Figure 4).

Multimaterial 3-D Printing

Motion-generating units were fabricated with an Objet 260 Connex multimaterial printer (Stratasys, Ltd.). This printer allows entire units to be printed at once, even though each unit has three parts with varying physical properties. Because the parts of the unit do not need to be separately printed, no additional fabrication process, such as bonding, was needed after the units were printed.

Three kinds of material were used to print the motion-generating units. For the softest parts of units, such as the air chambers, TangoBlack+ material was selected (Shore A hardness, ~ 26-28, Stratasys, Ltd.). FLX9895-DM material (Shore A hardness, ~ 92-95, Stratasys, Ltd.) was chosen for medium-stiffness parts. For example, the male parts of screw-thread and push-fitting connectors were made of this material, because they needed to be hard enough to allow tight assembly yet flexible enough to ensure softness and adaptiveness for the whole, assembled soft robot. The stiffest parts of the units were printed with RGD8530-DM (Shore D hardness, ~ 76.1-81.7, Stratasys, Ltd.) [23]. However, current 3-D printer materials have lower tear strength compared to the silicone-based polymer used in the molding and casting process. Therefore, bistable connectors fabricated by multimaterial 3-D printing were easily torn.

The 3-D printing process for five cooperating bending units and two sealing caps took about 2 h. After printing, support material for the units and sealing caps was removed with a waterjet.

Molding and Casting

3-D-printed molds and commercially available soft elastomers were used to fabricate units via the molding process, which is similar to soft lithography. Each part of a single unit was created from an elastomer whose physical properties were carefully matched to the performance needs of that part, especially in regard to modulus, hardness, and elongation at break. Ecoflex 0030 (Smooth-On, Inc.) was used for the air chamber, which must support inflation and motion generation. Polydimethylsiloxane and Dragon Skin 30 (Smooth-On, Inc.) were used for parts that need constrained inflation and elongation.

The final products of the molding and casting process were more robust and endured higher air pressure than the

Table 1. The characteristics of connectors.

	Screw Thread	Push Fitting (9.8 mm)	Push Fitting (10 mm)	Bistable Junction
Fabrication	3-D printing/molding	3-D printing	3-D printing	Molding
Type	Rigid	Rigid	Rigid	Soft (adjustable)
Force transmission	++*	+	–	–
Robustness to impact	+	–	– –	++
Ease of assembly	+	–	++	+
Tensile pressure (kPa)	462.77 (293.67)**	330.12 (263.67)	188.23 (137.89)	172.99
Strain (kPa)	0.28 (0.33)	0.16 (0.13)	0.11 (0.1)	1.21

*+: better qualitative performance; –: worse performance.
**Under 100 kPa of actuating pressure

units created via multimaterial 3-D printing. On the other hand, multimaterial 3-D printing was only a one-step process, but molding and casting required additional steps, such as curing each elastomer and adhering separately fabricated parts. It took approximately 8 h to build a single module via the molding and casting process.

Experiments

The performance of the motion-generating units and connectors was tested. The bending angle, length of translation, and twisting angle were measured at varying levels of applied air pressure. The pulling forces exerted on the connecting junctions and their maximum hold pressures were tested.

Experimental Procedure for Connectors

To isolate the performance of connectors from influences exerted by the design of the units, square-shaped test samples of connecting junctions were fabricated [Figure 5(a)]. The maximum holding pressure without leakage and the tensile strength were examined.

The air chambers of the tensile test samples were surrounded by a rigid shell and the female and male connectors connected to each other. This design allowed us to measure the maximum air pressure exerted on the connectors without inflation.

The female parts of the samples were connected to the load cell of a tensile test machine, and the male parts of the samples were fixed with a vise [Figure 5(b) and (c)]. The female samples were pulled at a speed of 1 mm/min as tensile force, and the pulled length was recorded. The measured tensile force data were converted to pressure.

Experimental Procedure for Motion-Generating Units

We first tested the performance of a single cooperating bending unit and a single independent bending unit, one of which was

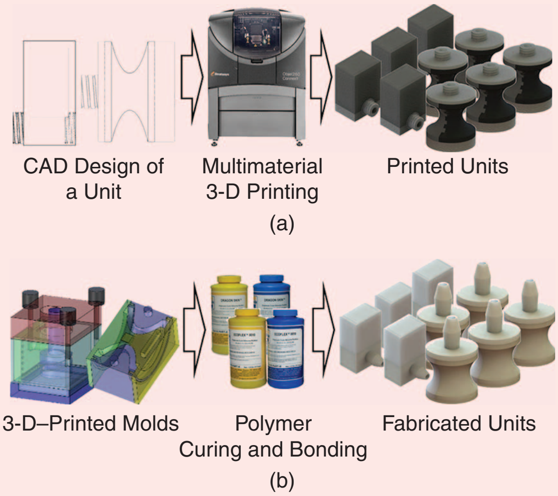

Figure 4. The schematic diagrams of fabrication methods: (a) multimaterial 3-D printing and (b) molding and casting with silicone-based polymers. (3-D printer image courtesy of Stratasys, Ltd. Polymer bottle image courtesy of Smooth-On, Inc.)

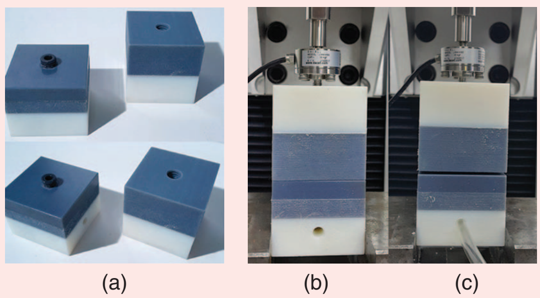

Figure 5. (a) A tensile test sample of screw-thread connectors. (b) Tensile tests without actuation and (c) under 100 kPa. The screw-thread and push-fitting connectors were 10 mm in diameter and 5 mm high. The bistable connector was 17 mm high, and its diameter varied according to height, from 6 mm at the bottom to 11 mm at the middle.

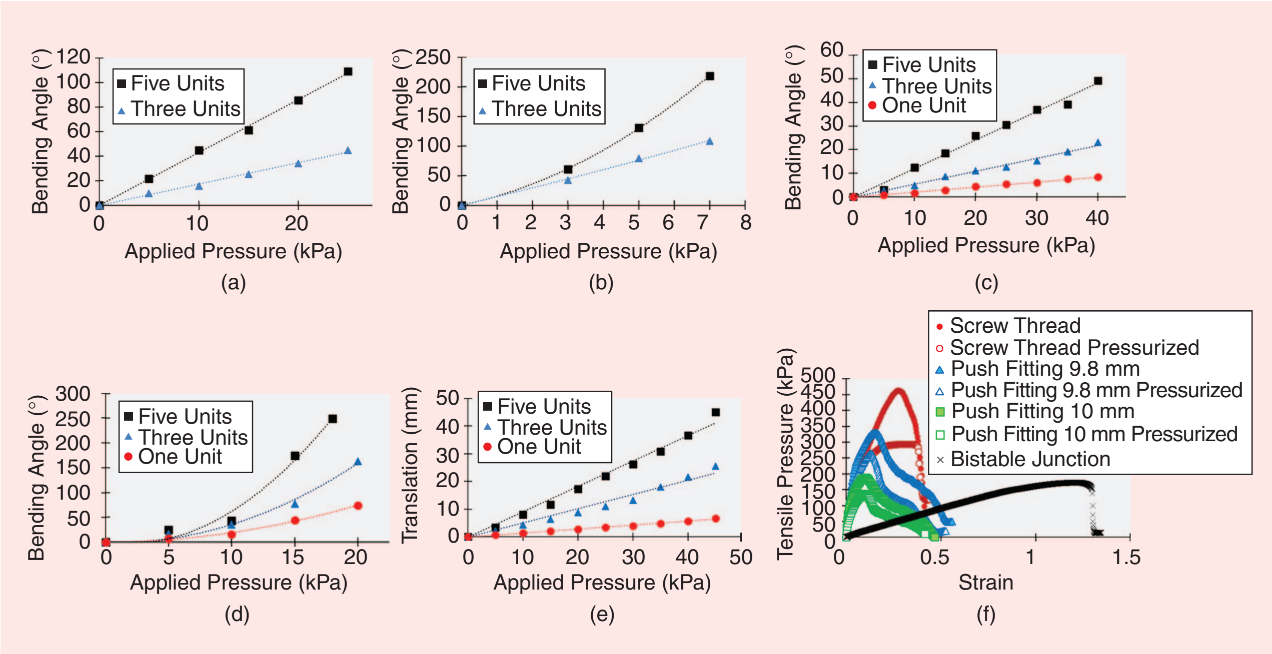

Figure 6. The bending angles and translation for each type of unit and both fabrication processes. (a), (c), and (e) Results for 3-D-printed units. (b) and (d) Results for units fabricated by the molding and casting process. (a) and (b) Results for bending actuators made with cooperating bending units. (c) and (d) Results for bending actuators made with independent bending units. (e) Results for an actuator made with translating units. (f) A graph of the tensile test results for different types of connectors.

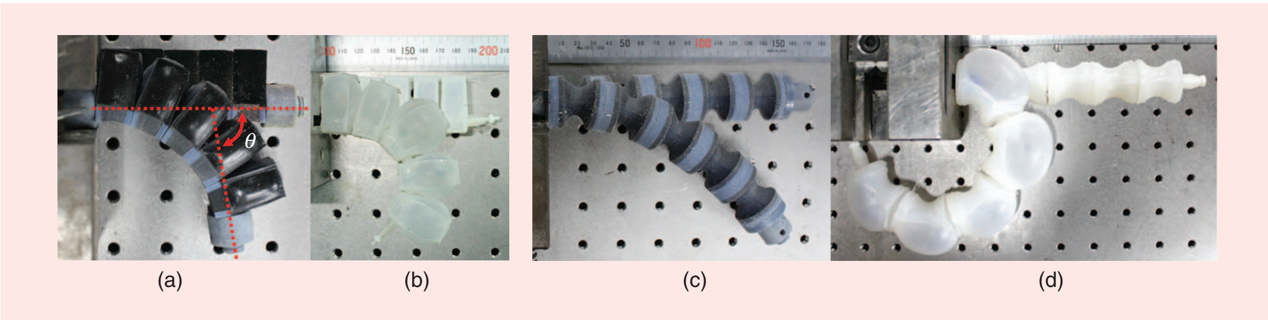

Figure 7. (a) and (b) The actuators with cooperating bending units and, (c) and (d), the independent bending units. (a) and (c) The 3-D-printed actuators. (b) and (c) The molded silcone actuators. The bending angle θ is defined as the angle between the units at both ends [indicated by red dashed lines in (a)].

created by each of the two fabrication methods. We then tested the performance of actuators created by assembling three or five cooperating bending units or independent bending units, again using units created by each of the fabrication processes (see Figure 6). From these experiments, we hoped to discover whether the units generate adequate motion under 50 kPa of air pressure.

The bending angles, length of translation, and twisting angles were measured, as shown in Figures 7–10. Single units and assembled three- and five-unit actuators were sequentially inflated from 0 to 25 or 60 kPa. Applied air pressure was controlled by a simple feedback control system with solenoid valves (VUVG solenoid valve, Festo AG & Co. KG) and solid-state pressure sensors. The control system [Figure 10(b)] was set up with LabVIEW and myRio (National Instrument Corporation). The structural performance was measured after each inflation. Following inflation to the target pressure, about 10 s were allowed to elapse after the actuator reached a steady state, and then either the angle or length was measured.

Experimental Results

Performance of Connectors

The test results for the three design candidates for connectors appear in Table 1. The 3-D-printed test samples endured 450 kPa of actuating pressure, which was much higher than the working pressure of the units. Figure 6(f) shows the results of tensile tests of each kind of connector.

During the experiments, the male part of the push-fitting and bistable connectors was pulled off and disengaged without fracture. However, the male part of the screw-thread

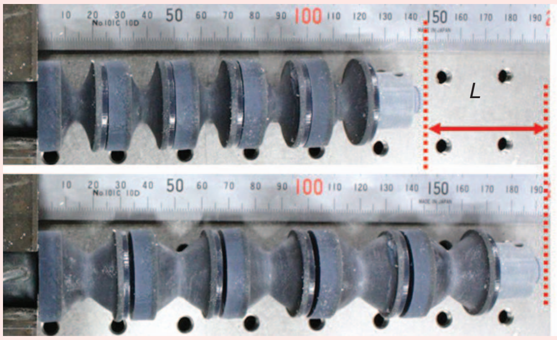

Figure 8. A translating actuator made with 3-D-printed translation units. The length of translation *L* is indicated by red dashed lines.

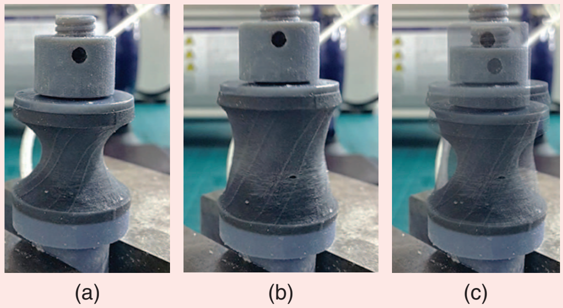

Figure 9. The twisting unit made with a 3-D printer. (a) Unpressurized state. (b) Actuated at 50 kPa of air pressure. (c) A combined image of unpressurized and actuated states.

connector was fractured rather than pulled off from its female part. There was a trade-off between ease of assembly and maximum disengagement pressure. On the other hand, the polymer-molded bistable connector held much more strain than the 3-D-printed connectors because of its material properties. From these experimental results, we determined that the screw-thread connector is appropriate for multimaterial 3-D-printed units and the bistable connector is appropriate for molded silicone units.

Performance of Motion-Generating Units

Displacement Characteristics of Units

Figure 6 shows the experimental results for bending actuators and translating actuators. A single 3-D-printed cooperating bending unit could hold up to about 35 kPa of air pressure, and a single mold-cast unit could hold up to 7 kPa. At 25 kPa, five-unit actuators made with 3-D-printed cooperating bending units could bend 109.5°, and three-unit actuators made with 3-D-printed units could bend 45.1° [Figure 6(a)]. At 7 kPa, five-unit actuators made with molded units could bend 218.6° [Figure 6(b)].

A single 3-D-printed independent bending unit could hold up to 60 kPa, whereas a single molded unit was usually punctured at about 25–30 kPa. A single 3-D-printed unit could bend 12.6° at 60 kPa and 8.5° at 40 kPa. The maximum bending angle of actuators with three or five 3-D-printed units was 23.1° and 49.2°, respectively, at 40 kPa [Figure 6(c)]. In contrast, the bending angle of actuators with five molded units was 249.5° at 20 kPa [Figure 6(d)].

Figures 6(e) and 8 show experimental results for 3-D-printed translating units. A single unit and assembled actuators with three and five units were tested. The actuator with five 3-D-printed units could elongate 45.0 mm at 45 kPa of air pressure [Figure 6(e)].

Unfortunately, the twisting units displayed poor performance. Figure 9 shows the unpressurized and the actuated state of the unit. The unit twisted only about 3° at 50 kPa of air pressure. In addition, as the twisting unit actuated, its translational motion was coupled with a twisting motion. Therefore, improving twisting performance and decoupling translating and twisting motions are goals for future research.

For the most part, the bending angles of the actuators made with 3-D-printed units were proportional to the applied pressure [Figure 6(a), (c), and (e)]. However, polymer-molded units show a gradually increasing slope [Figure 6(b) and (d)]. These results are related to the phenomenon of rubber balloon inflation [24]. This behavior could be analyzed by the finite-element method, but this remains to be studied.

Force Characteristics of Units

As shown in Figure 10(a), a load cell was mounted on an optical table, and the tip of the bending actuators was measured. Force profiles for two bending actuators, one made with five cooperating bending units and the other with five independent bending units, are shown in Figure 10(c). The bending actuator made with 3-D-printed cooperating bending units could exert 1,214.5 mN at 30 kPa. This was about 2.8 times higher than the force profiles for bending actuators made with independent bending units, which could exert 421.8 mN at 60 kPa.

> **This construction process is a bit like stacking LEGO bricks to make a shape, an activity that exemplifies bottom-up structuring.**

Attempts to measure the pushing force of five-unit translating actuators were not successful because buckling occurred when the air pressure reached around 15 kPa. Therefore, peak force was measured by applying pressure to the actuators from 0 to the target value, rather than attempting to apply a stationary pushing force. The actuators exerted 2,550 mN when air pressure was applied from 0 to 10 kPa and 3,639 mN when pressure was applied from 0 to 20 kPa.

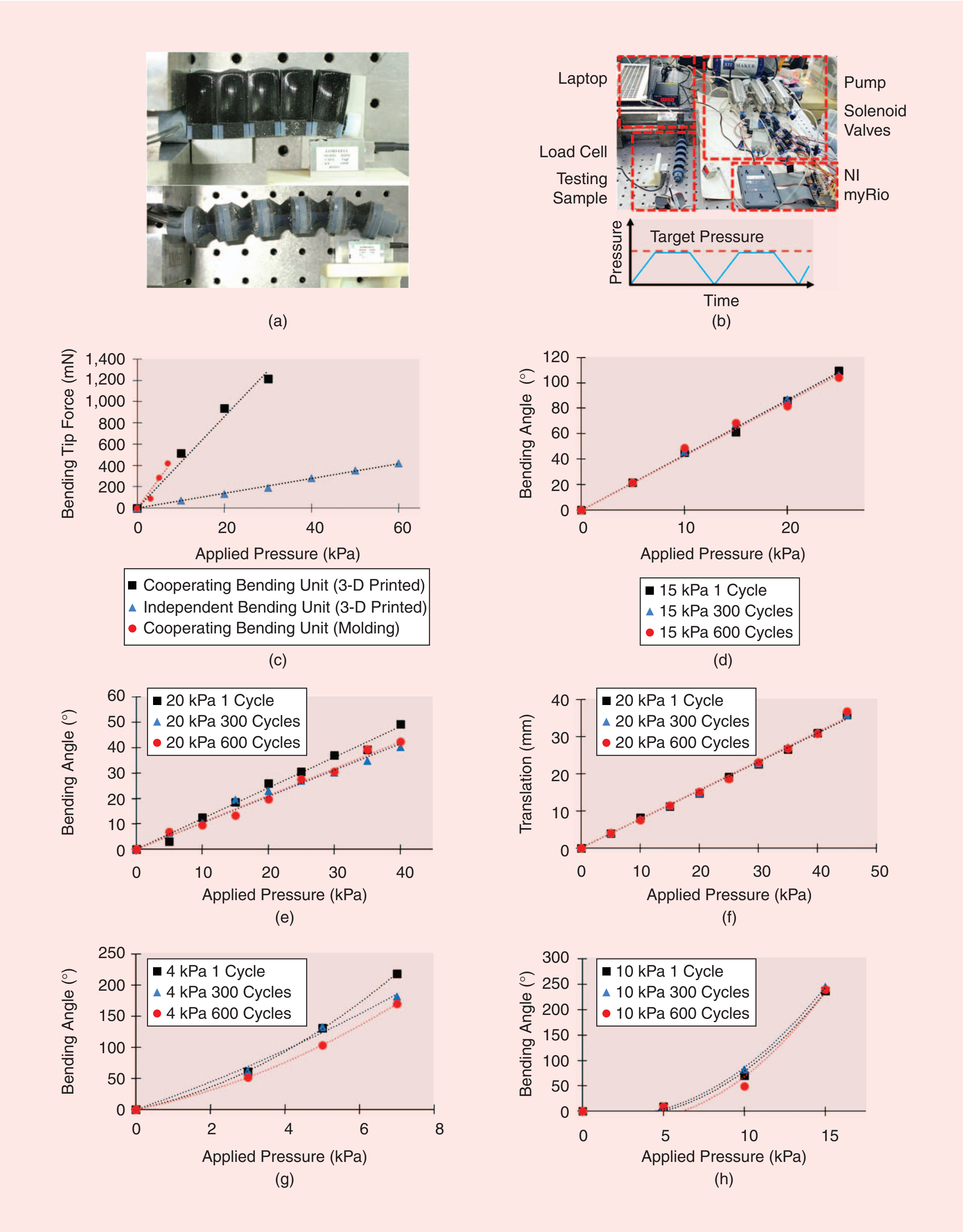

Figure 10. (a) The bending tip force measuring experiments. (b) The experimental setup with a simple feedback control system. (c) The bending tip force profile for actuators made with five 3-D-printed cooperating bending units, five 3-D-printed independent bending units, and five polymer-molded cooperating bending units. (d)–(f) show the fatigue test results for actuators made with five 3-D-printed cooperating bending units, with five 3-D-printed independent bending units, and with five 3-D-printed translating units, respectively. (g) and (h) show the fatigue test results for actuators made with five polymer-molded cooperating bending units and with five independent bending units, respectively.

Actuators made with polymer-molded units were also tested. For actuators made with five polymer-molded independent bending units, the force was almost 49 mN at from 5 to 15 kPa of air pressure. This is because the units were connected with soft and flexible bistable junction connectors. However, actuators made with five polymer-molded cooperating bending units exerted a maximum of 418.6 mN force at 7 kPa of air pressure. This difference occurred because cooperating bending units have greater structural constraints than independent bending units. In the future, we will optimize the design of the polymer-molded bistable connectors, which we hope will improve the force characteristics of units assembled with bistable connectors.

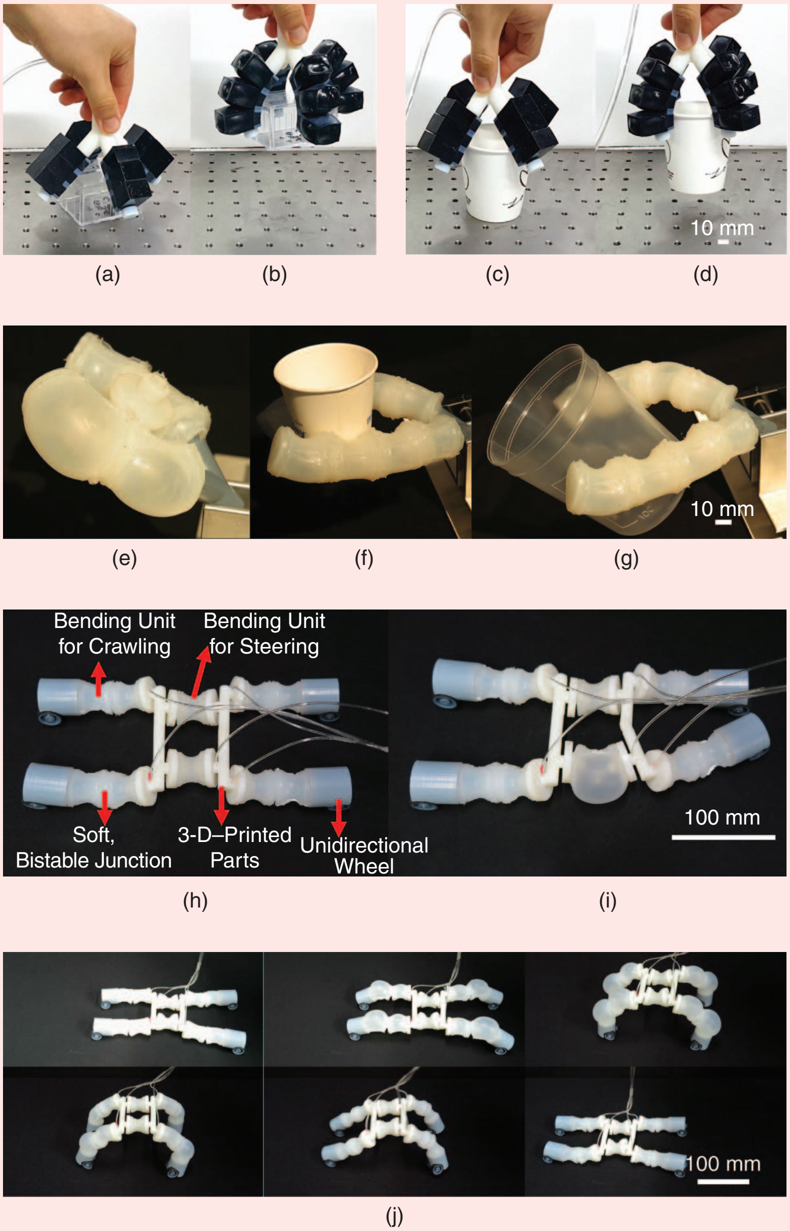

Figure 11. Rapidly prototyped structures and applications using various shapes of units. (a)–(d) A gripper built with 3-D-printed cooperating bending units and rigid connectors. (b) and (d) This gripper could grasp a 33.2-g square box and a 3.7-g paper cup at 20 kPa of air pressure. (e) Four-unit and, (e) and (f), eight-unit grippers built with independent bending units with bistable connectors for grasping different sizes of objects. (h) A crawler prototyped with soft modules. (i) The crawler turns by inflating the module in the center of the robot. (j) The robot crawls forward by simply inflating its legs (the crawler's speed was 603 mm/min, or 2.3 body lengths/min).

Reliability and Fatigue Characteristics of Units

The reliability and fatigue of bending and translating actuators assembled with different kind of units were tested. The experimental setup was prepared with a feedback control system [Figure 10(b)]. During the fatigue tests, pressure was applied up to a target value for one cycle, held for about 1 s, then ventilated [Figure 10(b)].

Reliability testing was performed first. The highest applied pressure, which was used in displacement performance tests, was set as the target pressure for each type of bending and translating actuator. Bending actuators and translating actuators made with five 3-D-printed units were fatigue tested with this target pressure for 500 cycles, and they failed at around 350–500 cycles. However, thanks to our modularized design concept, the failed actuators could be quickly repaired by changing only their failed units.

To avoid the failure of units during fatigue-test cycles, fatigue tests were performed with target pressures at around half of the highest pressures. Figure 10(d)–(h) shows the results of fatigue tests for actuators made with five 3-D-printed cooperating bending units, with five 3-D-printed independent bending units, with five 3-D-printed translating units, with five polymer-molded cooperating bending units, and with five polymer-molded independent bending units, respectively. As the graphs show, the deformation characteristics of 3-D-printed actuators and polymer-molded independent bending units were almost the same at the first cycle and after 300 and 600 cycles of pressurizing and ventilations, respectively.

Rapid Prototyping of Soft Robots

We constructed robots by assembling various combinations of units to enable different features and functions. This construction process is a bit like stacking LEGO bricks to make a shape, an activity that exemplifies bottom-up structuring. Because each of our modules has its own functions, constructing a robot from them is likewise a bottom-up process.

We implemented a complex geometrical configuration and then disassembled it and used the units to create two completely different applications, a gripper and a crawler [Figure 2(c)–(e)]. All the applications were considered to have the appropriate morphology for their tasks.

Figure 11 shows three kinds of soft robots built from the units proposed in this article (see also the video that accompanies this article in IEEE *Xplore*). The triangular pyramid in Figure 2(c)–(e) was fabricated with noninflatable units and nine 3-D-printed cooperating bending units. We disassembled this structure and reassembled its units into a four-fingered gripper. Because the cooperating bending units had the advantage of force transmission and could bend at an affordable angle, the gripper could grasp a 33.2-g rectangular box and 3.7-g paper cup [Figure 11(b) and (d)] at 20 kPa of air pressure. We also built grippers from molded independent bending units with bistable connectors [Figure 11(e)–(g)]. We prototyped a two-fingered, four-unit gripper first and then added four more units to build a bigger gripper. These grippers were more adaptable, so they could safely grasp light and fragile objects. However, they could not hold as much weight as the gripper made with cooperating bending units and rigid connectors. These grippers were controlled by a simple on-off control.

The crawler shown in Figure 11(h) and (i) was rapidly prototyped using independent bending units to allow large motions and bistable connectors for robustness to impact. The crawler was designed to turn by inflating modules at the center of its body. We assembled a unidirectional wheel (using clutch bearings) at the end of each leg so the crawler could move forward. The crawler was actuated by the same control system we used in the experiments. Air hoses were connected to the front legs, rear legs, and left and right steering units separately. Air pressure was sequentially applied to the front legs and rear legs to create a forward crawling motion [Figure 11(i)]. The body length of the crawler was 266 mm. The speed of the crawler was 603 mm/min, which was about 2.3 body lengths/min. Figure 11(j) shows a single crawling sequence for the robot. The speed of the crawler depended on the flow rate of the actuation system. The modular robots will inherently be outperformed by single-bodied soft robots built as a unit due to the connectors used to assemble them, but the distinct feature of modularity will empower the users to create new robots and change the designs easily.

SoBL units could be distributed along with cheap and simple actuators, such as hand pumps, to make inexpensive educational robotics kits and allow rapid prototyping.

Conclusions

In this article, we suggested a new modularized design concept for soft robotics consisting of standardized motion-generating units, connectors, and noninflatable units. We explored two fabrication methods for building the units. No additional procedures were needed to finish the units following fabrication. We tested the performance of the inflatable part of the units and the connectors.

We were able to rapidly build pneumatically actuated modular soft actuators for bending and translating from our standardized motion-generating units, producing soft robots of varying shapes and abilities. Prototyping, testing, design modifications, and maintenance were made easy by the simple snap-together, modularized concept of the units.

These units can be configured into countless different types of structures. We plan to expand the repertoire of the SoBL design concept by investigating units that will add new functionality, such as a unit with multiple air chambers and channels, a unit that can switch flow direction or switch to on-off states, and a sensing unit. These new units could allow the SoBL concept to provide a complete construction platform for soft robotics, giving researchers and end users the freedom to build creative new soft robots by simply combining units. In the future, SoBL units could be distributed along with cheap and simple actuators, such as hand pumps, to make inexpensive educational robotics kits and allow rapid prototyping. In addition, SoBL units could be distributed with sensing and actuating modules according to user demand.

We hope that SoBL, the bottom-up modularized design concept that we have introduced in this article, will stimulate further investigation in the field of soft robotics by enabling researchers to rapidly, inexpensively, and creatively build prototypes.

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