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Soft LEGO: Bottom-up Design Platform for Soft Robotics

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***Abstract*— This paper introduces soft LEGO for bottom-up design platform of soft robotics that can be used for various purposes, ranging from research and fast prototyping of soft robots to toys and entertainment. We integrated the interlocking mechanism of LEGO into a modular soft robot. With this design, soft robots could be built by a simple and play-like assembling process. Three kinds of components were proposed to make soft robotics compatible with LEGO: pneumatically inflatable soft brick, flexible bending brick, and channel brick. The soft brick has an air chamber and can generate motions when inflated. The bending brick has flexure and is bendable for generating motion when the assembled soft bricks are pneumatically actuated. The air channel brick has an air channel inside and works as an interface between air hoses and soft LEGO bricks. Detailed design parameters of the soft brick were optimized based on the Taguchi method with finite-element analysis to improve robustness. Design of the bending brick was selected based on experimental results to enhance the robustness of the flexure. Thanks to the multi-material 3-dimensional printer, the soft LEGO bricks could be fabricated with a single printing process. To see the feasibility of soft LEGO as a bottom-up design platform, a simple toy robot for children and a gripper that had a hybrid mechanism of hard and soft materials were built and tested. We hope this soft LEGO could lower the hurdle of soft robotics for children, researchers from other fields, and the public interest in robotics.**

I. Introduction

Soft robotics has shown the potential to overcome limitations of traditional rigid material-based robots [1]–[3]. Soft robots inherit flexibility and adaptiveness to the environment from their soft materials that enable them to move like biological systems. On the basis of these features, there have been many efforts to utilize soft robots for various applications, such as gripping objects [4]–[7], manipulations [8], [9], rehabilitation [10]–[14], explorations [15]–[17], and human-computer interactions [18], [19].

Compared to hard material-based mechanical systems that are typically built by assembling standard mechanical components, most soft material-based robots have been fabricated with molding and casting methods. For the first step, molds have to be prepared for pouring and curing processes of elastomers. In a vast number of cases, additional bonding steps are necessary after curing elastomers. This bonding process is necessary to create intended motions by placing different materials at proper positions and to seal air channels and chambers.

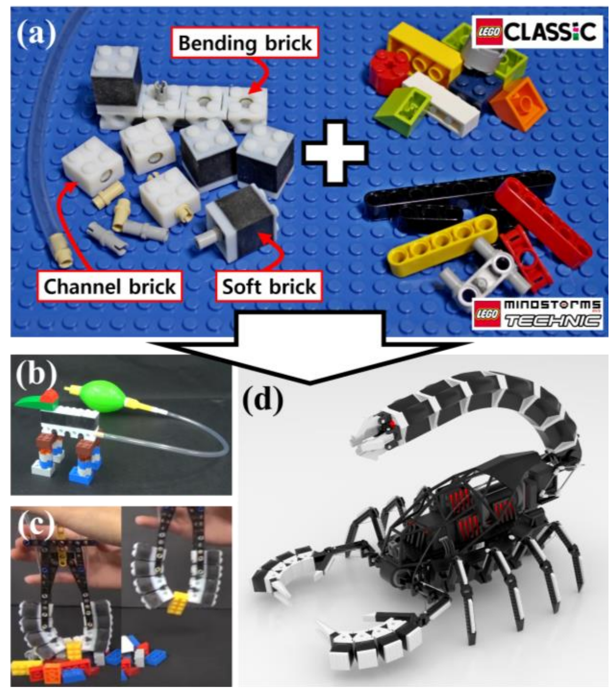

Figure 1. Soft LEGO that can be seamlessly assembled with typical LEGO bricks. (a) Soft LEGO set has flexible bending bricks, pneumatically inflatable soft bricks, and air channel bricks. (b) A simple toy robot was assembled with soft LEGO and LEGO Classic. (c) Soft gripper was assembled with soft LEGO and LEGO Technic. (d) Concept design of a scorpion-inspired robot built with soft LEGO and typical LEGO bricks.

Recently, soft robotics has received attention of researchers from various fields and public interest in robotics [20]. Much potential for applications in toys, education, and entertainment exists for soft robotics. However, the molding- and casting-based fabrication processes are major hurdles to making this technology available to people who want to build a soft robot but are not familiar with the field. In addition, the molding process is a relatively time-consuming process, and prototyping various designs of soft robots with the molding method requires time and labor. On the other hand, soft robots built with the elastomer molding methods have demonstrated difficulties of maintenance, such as modifying and repairing formed structures. To overcome these disadvantages, one of the previous efforts was to modularize soft robotic systems.

Professor Whitesides' groups at Harvard University introduced small elastomeric bricks [21] and elastomeric tiles

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[22]. They modularized soft robots into a small element level, which could be used to build pneumatically actuated soft robotic systems by stacking and bonding those elements. On the other hand, there have been efforts to modularize soft robots at the actuator level. Many researchers tried to build manipulators and grippers by connecting these actuator-level modularized soft robotic components [23]–[25].

In our previous research [26], modularized soft blocks, named SoBL, were introduced. Users could build soft robotic systems by assembling these standardized soft blocks. With these soft blocks, assembled systems could be dismantled and reassembled into different shapes and configurations. However, there has been no additional block except the SoBL blocks presented in the previous paper. To make more complex and diverse structures, a greater variety of block shapes is required.

In this paper, we introduce soft LEGO (Fig. 1) that can be assembled with common LEGO bricks to build soft robots. LEGO is a popular construction toy for all ages worldwide. The popularity of LEGO is based on its interlocking mechanism. The interlocking mechanism of LEGO is simple and easy enough for kids to play, versatile for building various structures, and durable for assembling and dismantling bricks a number of times. We integrated our previous research, which was about modularizing soft robots with soft blocks, with the interlocking mechanism of LEGO Classic bricks as well as pin joint connection of LEGO Technics.

Soft LEGO allows us to easily apply the soft robotics to traditional LEGO that can make any structure. Therefore, soft LEGO can be used for various purposes as a bottom-up design platform (Fig. 1). The soft LEGO bricks may help people who are unfamiliar with soft robotics to build soft robots by an assembling process as simple as playing with LEGO bricks. It may free people from concerns about fabrication processes of elastomer-based soft robots. In addition, robots that are hybrid with soft material- and hard material-based mechanical systems could be seamlessly constructed with the soft LEGO.

In the next section, detailed designs of soft LEGO bricks will be introduced. We used the Taguchi method to decide proper design parameters of the soft brick based on a finite-element analysis. Performances, such as bending angles and tip forces, were tested. Test results will be shown in a following section. We built demonstrations by assembling the soft LEGO with typical LEGO bricks. These demonstrations show how soft LEGO could be used for educational purposes and for a bottom-up design platform that shows synergy of soft material-based and rigid material-based mechanisms.

II. Design and Fabrication

Typical LEGO bricks have a thin shell design and are made of acrylic plastic. However, if we make thin shell bricks with a soft material, the flexibility of the material will weaken the interlocking force. In addition, sealing the actuating fluid, such as air, while maintaining the versatility and simplicity of the interlocking mechanism of LEGO is a challenge.

We suggested three main bricks for Soft LEGO: a pneumatically inflatable soft brick, a flexible bending brick, and an air channel brick. The soft brick has an embodied air chamber and can be inflated with air pressure to generate motion. The bending brick has soft flexures and can be passively bent. They are designed to use soft materials to have softness and are robustly connected to one another and typical LEGO bricks to prevent air leakage. The channel brick is as stiff as regular LEGO bricks, but it has an air channel inside. Therefore, users can build their own air channel by connecting the channel bricks. Dimensions of the soft brick, the bending brick, and the channel brick were decided for seamless assembly with typical LEGO Classic and LEGO Technic bricks. All bricks were fabricated with a multi-material 3-dimensional printer to obtain soft material and hard material parts.

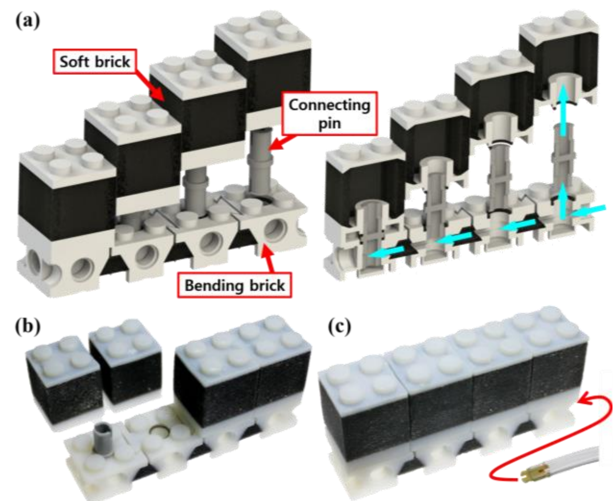

Figure 2. The soft bending actuator assembled with four soft bricks and the bending brick. (a) Computer-aided design (CAD) rendered model and cross-sectional view of the assembling process of the soft bending actuator. Arrows indicate flow of air. (b) State during the assembling. (c) Fully assembled soft bending actuator and an air hose for pneumatic actuation.

A. *Soft LEGO Bending Actuator and Connecting Pin*

The two kinds of Soft LEGO bricks, the soft brick and the bending brick, can be assembled to build the soft bending actuator (Fig. 2). The soft bricks plug into the bending brick. They are basically connected by the interlocking mechanism of LEGO. In addition, they are also joined by connecting pins from LEGO Technic (CONNECTOR PEG, design ID: 3673, LEGO Group). The connecting pin can be plugged into the hole on the bending brick. The pin works as an air channel between the soft brick and bending brick (Fig. 2 (b)). When the assembled soft bricks are inflated and pushed against each other to make the bending motion, the connecting pins keep the soft bricks on the bending bricks. Interlocking force between the soft brick and the bending brick was on average 22.57 N for the normal direction. Two by two LEGO Classic bricks had an interlocking force of 6.02 N, while it was 8.28 N for linkage brick and CONNECTOR PEG of LEGO Technic in our tests.

Off-the-shelf flexible polyvinyl chloride (PVC) air hose with 6 mm outer diameter was used to connect the assembled bending actuator to a pneumatic source. At the end of the air hose, a connecting bush was inserted (Fig. 2 (c)). With this connecting bush, the air hose can directly plug into the air hole on the bending brick. The flow direction of air is indicated as blue arrows on the cross-section view in Fig. 2 (a).

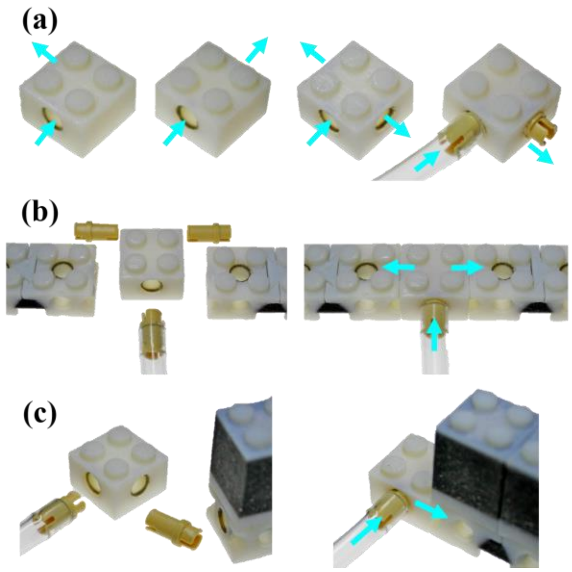

Figure 3. Air channel bricks and connecting examples. (a) Air channel bricks with different directions. Arrows indicate the direction of airflow. The far-right photo shows the air hose from a pneumatic source connected to the air channel brick. (b) An example how the air channel brick connects two bending bricks to a single air hose. (c) An example of usage of the right-angle channel brick.

Detailed designs of the bending brick and the soft brick will follow.

B. Air Channel Bricks

We suggested air channel bricks, as shown in Fig. 3. These channel bricks can change connecting directions of the air hose to the bending bricks. The channel bricks can connect to each other by the connecting bush (1 1/2 M CONNECTING BUSH), which is also used for connection between the air hose and the bending brick. O-ring shaped air sealing components were printed at the surroundings of holes for the connecting bush. Thanks to the air channel bricks, there is no need to worry about the connecting direction of an air hose. Moreover, by connecting these bricks, air channels can be embedded into any assembled LEGO structure. Therefore, users have more design freedom in terms of air channel.

C. Design of Bending Brick

The bending brick consists of two parts. One is the hard material-based interlocking part, and the other is the flexure. An air channel is embedded inside of the bending brick to pneumatically connect the assembled soft bricks. While most of pneumatically actuated soft bending actuators have inextensible layers at their bottom [27], the bending brick also has a role as an inextensible layer to generate the bending motion.

While the single soft brick is actuated with air pressure, the inflatable air chamber of the single soft brick will be expanded to the circumferential direction and there will be no bending motion. Meanwhile, when the soft bricks are assembled into the bending brick and actuated, the soft bricks push neighbor bricks as they are inflated, and the bending motion can be generated. However, this pushing motion caused by the torque weakens the interlocking mechanism of the LEGO. Therefore, we employed connecting pins to keep the soft bricks on the bending brick even if they pushed against each other to generate the bending motion.

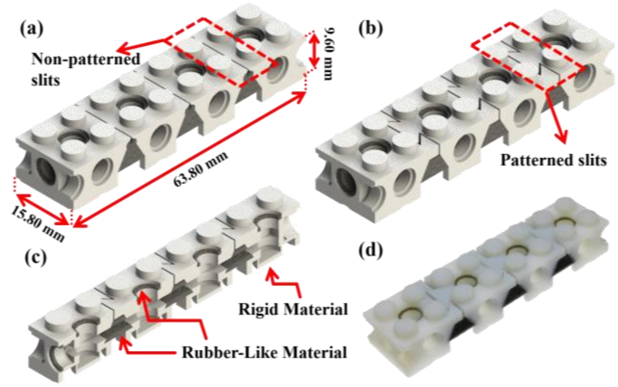

Figure 4. CAD-rendered models and photo of the bending bricks. (a) The bending brick with nonpatterned slits. (b) The bending brick with patterned slits. (c) A cross-sectional view of the bending brick with patterned slits. (d) A photo of the bending brick with patterned slits.

The bending brick has flexures in order to generate the bending motion, as in Fig. 4. A soft material (TangoBlack+, Stratasys Ltd.) is used for these flexures. Detailed design of the flexure will be explained in the following subsection. Other parts are made of a relatively stiff material (VeroWhite, Stratasys Ltd.) to ensure a robust connection between bricks and pins.

Height and width of the bending brick are 9.60 mm and 15.80 mm, respectively. The length for two by eight sized brick is 63.80 mm (Fig. 4). The dimension is the same as that of the two by eight LEGO Classic brick. The bending bricks can be seamlessly assembled with LEGO Classic bricks as the soft brick. In addition, there are pinholes on both flanks of the bending bricks and an end face of the brick. Thanks to these pinholes, users can also seamlessly assemble the bending bricks with link bricks from LEGO Technic with "1 1/2 M CONNECTING BUSH" (Design ID: 32002 by LEGO Group).

D. Flexure Design of Bending Bricks

Especially for the flexure, two designs were suggested. The bending actuator with the first flexure design is shown in Fig. 5 (a). The neutral axis of the bending, which is indicated as a red dashed line in Fig. 5 (a), is placed in the middle of the flexure. Therefore, the upper part of the flexure suffers tensile stress. A crack started at the top of the flexure by this tensile stress, and the flexure was easily torn apart. To solve this issue, the design of the bending actuator was revised, as shown in Fig. 5 (b).

Compared to the first design, the upper stiff part of the bending brick is patterned and the height of the flexure is reduced. When the bending motion starts, the slit between patterns comes close until the patterns contact each other. When the patterns contact, contact points constrain the stretching motion of the upper part of the bending brick and the contact points work as the center of rotation. Compared to the first design, this center of rotation is placed above the flexure. Therefore, the flexure mainly suffers compression rather than tension, as shown with red arrows in Fig. 5 (b). As a result, the bending bricks with patterned slits increase

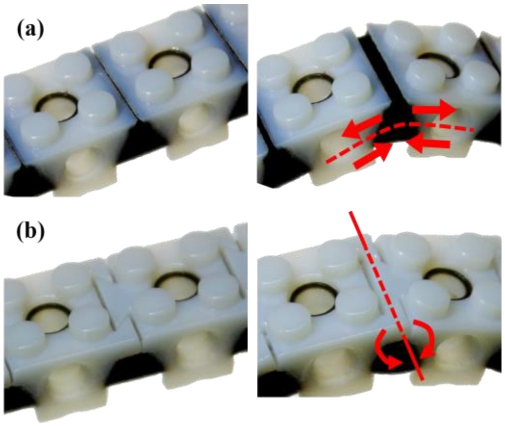

Figure 5. Close views of the nonpatterned and patterned flexure design. (a) Neutral state and bent state of the nonpatterned bending brick. A dashed line in (a) indicates a neutral axis of bending of the flexure, and arrows mean tension and compression applied to the flexure. (b) Neutral and bent states of the patterned bending brick with 0.3 mm slits. A dashed line in (b) indicates the axis of rotation. Arrows mean compression applied to the flexure by the rotation.

durability, and can endure more bending and fatigue than the first design.

E. Design of Soft Brick

The middle section of the brick is an inflatable air chamber and is made of the soft material TangoBlack+ (Fig. 6 (a) and (b)). Therefore, the brick can be inflated with positive pneumatic pressure. Meanwhile, top and bottom sections are made of a relatively stiff ABS-like material called VeroWhite. These parts enable the bricks to seamlessly and firmly assemble with each other and with conventional LEGO bricks.

At the center of the bottom of the soft brick, there is a hole for air flow (Fig. 6 (c)). On a rim of the entrance of this hole, there is an O-ring, which is also printed with the soft material (TangoBlack+). Thanks to the O-rings, if the bushes and bricks are assembled properly, there is no air leakage during the experiments. The connecting pin is inserted into the hole and serves as the air channel between the air chamber of the soft brick and the bending brick.

The dimensions of the brick are identical to those of the basic two-by-two square type LEGO Classic brick. The height of the soft bricks was 19.20 mm, which was the same as that of the double stack of LEGO Classic bricks. Width and length of the soft brick were identical to LEGO Classic bricks at 15.80 mm. Therefore, the soft bricks itself could seamlessly assemble with typical LEGO bricks even without the soft bending bricks.

F. Design Optimization of Soft Brick Using the Taguchi Method

Detailed design parameters of the soft brick were determined through Taguchi optimization method [28], [29]. Target design parameters are shown in Fig. 7 (a). Each design parameter has three levels; therefore, the L9 (3^4) orthogonal array was used as Table I.

Experimental results for orthogonal array were obtained through finite-element analysis (FEA). Dog bone specimen tensile test (ASTM D412), planar tension test, and volumetric tests were performed to identify material properties of

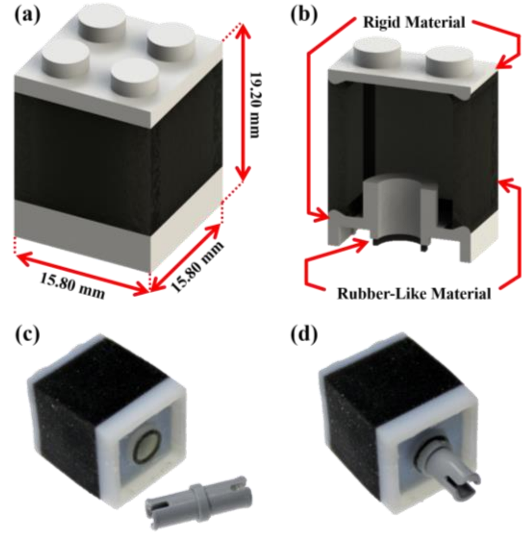

Figure 6. CAD model and photos of the soft brick. (a) The dimensions of the soft brick are identical to those of LEGO Classic bricks. (b) A cross-sectional view of the brick. (c) and (d) How the connecting pin was inserted into the soft brick.

TangoBlack+ material for FEA. The analysis was performed with a commercial FEA package (Abaqus/Standard 3DEXPERIENCE R2016x, Dassault Systems). Quarter symmetric models of the soft brick were used during the finite-element analysis (Fig. 7). The models were pressurized up to 60 kPa, as was done in the experiments shown in section III.

Maximum von Mises stresses, with an average of 75 % at three different sections on the soft brick, were selected as smaller-is-better signal-to-noise (S/N) ratio factors for the Taguchi method. These three sections were where failure empirically happened, and FEA results also indicated vulnerable points. S/N ratios #1 in Table I are averages of the S/N ratios from the stresses of three sections. On the other hand, maximum expansion displacement of the inflatable air chamber was selected as a larger-is-better S/N ratio factor.

S/N ratios, which were evaluated from simulated results, are shown in Table I. The response graphs are plotted in Fig. 7. As shown in Fig. 8 (a), fillet #1 and wall thickness were figured as sensitive design parameters in terms of stress. In terms of expansion, wall thickness was the most sensitive design parameter (Fig. 8 (b)).

The S/N ratio of stress is related to durability of the soft brick, and the S/N ratio about the expansion is related to performance. Based on the Taguchi method, parameters with maximum S/N ratio were selected to maximize the robustness of the design. Design parameter for fillet #2 and #3 had maximum S/N ratios with third level parameters in terms of stress (Fig. 8 (a)). However, the third level of these two design parameters did not maximize the S/N ratio in terms of expansion (Fig. 8 (b)), and was less sensitive to the expansion. Therefore, parameters for fillet #2 and #3 were selected as the third level at 1 mm for both to emphasize durability. On the other hand, wall thickness had opposite responses to expansion and stress. Therefore, design parameter for wall thickness was selected as the second level at 2 mm for balance between durability and performance.

From the first Taguchi orthogonal matrix experiment, the design parameters for fillet #2 and #3 as well as the wall thickness were set as 1 mm, 1 mm, and 2 mm, respectively. Additional experiments were performed to select the design parameter of fillet #1. Based on the second level of the parameter at 0.5 mm, we tested adjacent high and low values, which were 0.25 mm and 0.75 mm. As a result, 0.75 mm was selected for fillet #1. The final design had -3.57 for S/N ratio #1 and 13.74 for S/N ratio #2.

To verify improvement of the final design, two different designs were experimentally tested, of which one was the final design. The comparison design had the same wall thickness as the final design but no fillet. We tested four samples for each design. Each sample was inflated individually until it was punctured. While the basic design without fillets could inflate up to 78.8 kPa of pneumatic pressure, the bricks with optimized design could inflate up to 88.4 kPa. Therefore, the optimized design had an improved puncture resistance of 12.2 % more than that of the nonoptimized design. Meanwhile, the puncture that occurred in the real soft brick was the same as the maximum von Mises stress that occurred in the simulation.

G. *Fabrication*

All bricks were fabricated with the multi-material 3-D printer. Soft LEGO bricks have design features, such as the air channel, flexures, air chamber, and pinholes, in a compact form. Therefore, it was a challenge to use traditional molding and the casting method for soft robotics. Thanks to the multi-material 3-D printer, whole bricks were printed at once. Assembly of a single bending actuator with four soft bricks and one bending brick took approximately 2 hours 35 minutes with Objet 260 Connex multi-material 3-D printer (Stratasys, Ltd.). After the post-processing of 3-D printed bricks, such as removing support materials, no additional process was needed, and users could plug and play the soft bricks with typical LEGO bricks.

III. PERFORMANCE OF SOFT LEGO BENDING ACTUATORS

Performances of the assembled soft LEGO bending actuator, such as bending angle and tip force with pneumatic actuation, were tested. The results will be described in the following section. Specifically, the flexure design of the bending brick was determined based on the following experimental results.

A. *Experimental Setup*

Three types of assembled bending actuators (nonpatterned, patterned with 0.3 mm slits, and patterned with 0.6 mm slits) were tested for three soft bricks and four soft bricks lengths. Two samples were fabricated for each type and length. Each sample was tested twice.

B. *Bending Performance with Pneumatic Actuation*

The assembled bending actuators were pneumatically actuated up to 60 kPa without load, while bending angle was recorded at every 5 kPa. Experimental procedures were video recorded and analyzed later. To avoid effects of viscoelasticity, the pneumatic pressure was gradually increased and steadied for a few seconds at every 5 kPa.

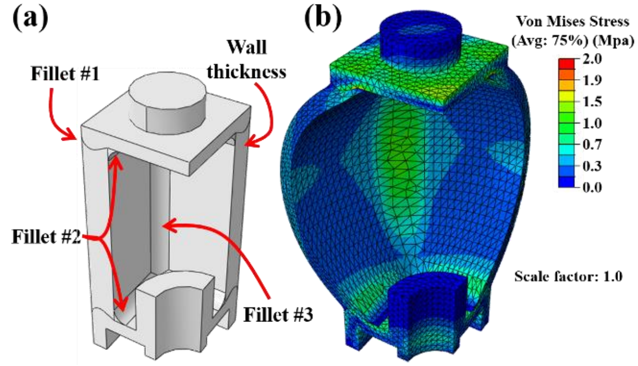

Figure 7. The quarter symmetric model of the soft brick for finite-element analysis. (a) An initial state of the model. Arrows indicate design parameters for the Taguchi method. (b) The finite-element analysis result with the final design and levels of the maximum von Mises stress (an average of 75%).

TABLE I. ORTHOGONAL ARRAY FOR THE TAGUCHI METHOD

Experiments	Parameters				Results	
	Fillet #1[a]	*Fillet #2*[b]	*Fillet #3*[c]	*Wall thickness*[d]	*S/N ratio #1*[e]	*S/N ratio #2*[f]
1	0	0	0	1.5	-22.42	18.58
2	0	0.5	0.5	2	-14.53	13.34
3	0	1	1	2.5	-7.56	7.36
4	0.5	0	0.5	2.5	-1.85	8.00
5	0.5	0.5	1	1.5	-11.74	18.66
6	0.5	1	0	2	-5.72	14.27
7	1	0	1	2	-7.45	14.71
8	1	0.5	0	2.5	-1.20	8.32
9	1	1	0.5	1.5	-15.26	19.13

a, b, c, d. unit of the values are mm

e. Each S/N ratio was evaluated from three von Misses stress results

f. Each S/N ratio was evaluated from maximum expansion displacement of the soft brick

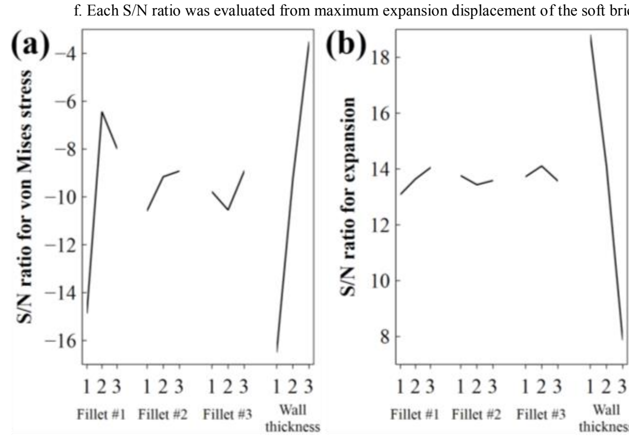

Figure 8. Response graphs of S/N ratio #1 and #2. (a) The S/N ratio of the maximum von Mises stress. Sensitive factors are fillet #1 and wall thickness. (b) The S/N ratio of the maximum expansion displacement. Wall thickness is the most sensitive factor.

Fig. 9 (a) shows a four brick-long soft bending actuator with a patterned bending brick containing 0.3 mm slits at 0 kPa and 60 kPa of air pressure. Bending angle (θ) was defined as an angle between red dashed lines in Fig. 9 (a). Graphs (b), (c), and (d) show experimental results with nonpatterned bending bricks as well as patterned bending bricks with 0.3 mm slits, and 0.6 mm slits, respectively. In the graphs, marks represent average values and error bars show standard errors. Standard errors are less than 3.0.

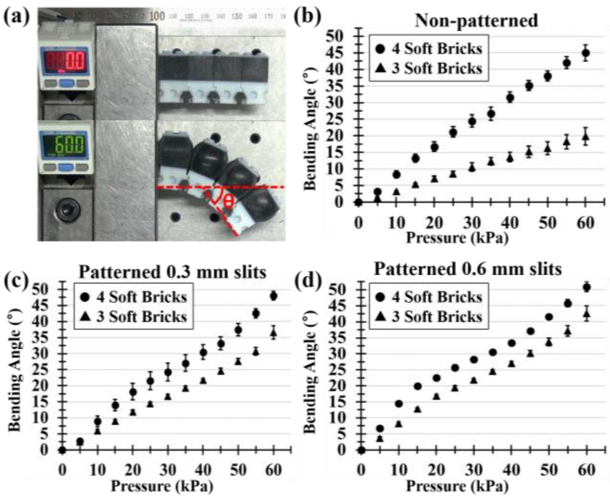

Figure 9. Experimental results about bending performance. (a) Bending angle (θ) was defined as the angle between red dashed lines in the photo. (b) Bending performance of soft bending actuators with nonpatterned bending bricks. (c) and (d) Bending performance of soft bending actuators with patterned bending bricks with 0.3 mm and 0.6 mm slits, respectively. Error bars represent standard errors, and marks represent mean values.

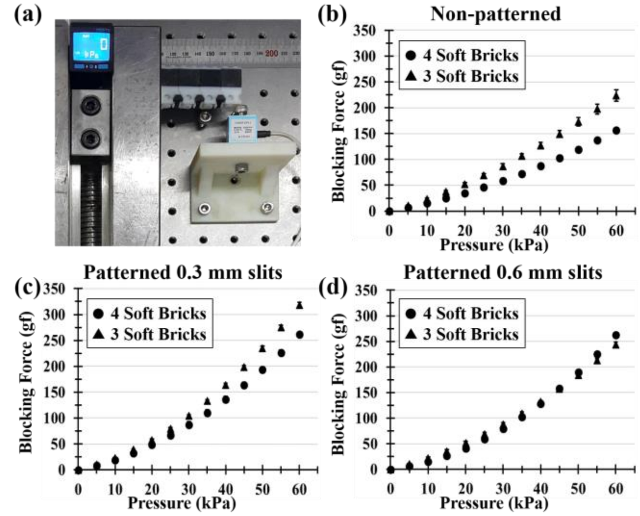

Figure 10. Experimental results about tip blocking force performance. (a) Blocking force of the soft bending actuator was measured as shown in picture. (b) Blocking force of soft bending actuators with nonpatterned bending bricks. (c) and (d) Blocking force profile of soft bending actuators with patterned bending bricks with 0.3 mm and 0.6 mm slits, respectively. Error bars represent standard errors, and marks represent mean values.

Maximum bending angle for four brick-long bending actuators was 51.0° by patterned bending bricks with 0.6 mm slits at 60 kPa of air pressure. Nonpatterned bending bricks and patterned bending bricks with 0.3 mm slits could bend 45.0° and 48.1°, respectively. Three brick-long bending actuators could bend up to 19.8°, 36.6°, and 42.6° with nonpatterned bending bricks, patterned bending bricks with 0.6 mm slits, and patterned bending bricks with 0.3 mm slits, respectively.

Three samples of the four brick-long actuators with patterned 0.3 mm slits were tested to check fatigue effect. They were pressurized up to 35 kPa for 3 seconds and ventilated to 0 kPa for 3 seconds. After 500 cycles of repetitive actuation, they showed similar performance compared with the first actuation in terms of bending angle.

C. Blocking Force with Pneumatic Actuation

Tip blocking force was also tested. A loadcell was located at the end tip of the soft bending actuators (Fig. 10 (a)). While air pressure gradually increased, pressure and tip force were simultaneously recorded with a data acquisition system (myRio-1900, National Instruments).

Graphs in Fig. 10 (b), (c), and (d) show experimental results for bending actuators with nonpatterned bending bricks as well as patterned bending bricks with 0.3 mm slits and 0.6 mm slits, respectively. The four brick-long bending actuators with patterned bending bricks with 0.6 mm slits generated maximum 262.6 gram-force (gf) at 60 kPa of air pressure. However, this was similar to the bending actuator with 0.3 mm slits that generated 261.7 gf at 60 kPa of air pressure. On the other hand, for the bending actuators with the length of three bricks, the greatest force, 318.7 gf, was generated with the bending actuators assembled with patterned bending bricks with 0.3 mm slits. The second greatest blocking force was 243.1 gf with bending actuators with 0.6 mm slits.

D. Selection of Design of Bending Brick

The nonpatterned bending brick had worse performance compared to both patterned bending bricks. When the bending occurred, the flexures of the nonpatterned bending brick were not only compressed but also stretched simultaneously. However, the flexures in patterned bending bricks only suffered compression, thanks to the patterns on the top of the bending bricks. Moreover, heights of flexures in patterned bending bricks were lower compared to flexures in the nonpatterned bending brick. This might be a reason as to why the nonpatterned brick had poor performances in terms of both blocking force and bending angle.

As a result, the bending brick with patterned 0.3 mm slits was selected as the final design. Aside from blocking force and bending performances, this design also had an advantage in enduring self-deflection. The four brick-long bending bricks with patterned 0.3 mm slits had an average of 14.1 % less self-deflection than the bending bricks with 0.6 mm slits.

IV. Discussion

Soft LEGO bricks were designed to be seamlessly assembled with both LEGO Classic and LEGO Technic bricks. Specific design parameters of the soft brick were decided based on the Taguchi method with finite-element analysis, and design of the bending brick was selected from experimental results. Using the soft LEGO with the final designs, we examined the potential that soft LEGO could be used as the bottom-up design platform.

A. Soft LEGO as Toy and Educational Platform

Fig. 11 shows a horse-like toy robot as an example of using soft LEGO and LEGO Classic bricks. Thanks to the identical form factors of soft LEGO and LEGO Classic, they were harmoniously assembled together.

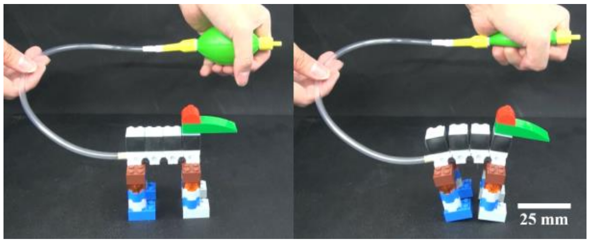

Figure 11. A horse-like toy robot was assembled with LEGO Classic and soft LEGO. The toy robot could easily be actuated with a simple hand pump.

Users can actuate the soft bending actuator with an easily available mini hand pump. Single pumping of the mini pump could actuate the four brick-long soft bending actuator up to approximately 50 kPa of pneumatic pressure. As shown by the experimental results, the meaningful motion could be generated with the hand pump. Assembling process of the toy robot and the movement are included in the supplementary video.

B. Soft LEGO as Bottom-up Design Platform

One of the biggest advantages of the soft LEGO is that connection between soft and hard structures is simple and robust. Users can use both the interlocking mechanism of LEGO Classic and pin joint mechanism of LEGO Technic. Hybrid robots using both soft material-based mechanisms and hard material-based mechanisms can be easily built by assembling soft LEGO with traditional LEGO bricks. To see the feasibility of the soft LEGO as the bottom-up design platform for hybrid robots, a hybrid gripper that uses both soft and hard material-based mechanisms was assembled and tested (Fig. 12).

LEGO Mindstorm currently provides only DC motor-based actuation components. Thus, we proposed pneumatic pump and solenoid valve modules with 3-D printed custom cases (Fig. 12 (b) and (c)). The LEGO EV3 programmable brick did not support these custom pump and valve modules. Therefore, EVShield for Arduino (mindsensors.com) was employed as a controller (Fig. 12 (a)).

The base structure of the gripper was built with regular bricks and the electrical motor module from LEGO Technic sets. The motor module drove scissors linkage structure as the hard material-based mechanism. On the other hand, at the end of the scissors linkage structure, four brick-long soft bending actuators were attached as fingers (Fig. 12 (d)). These bending actuators generate a soft bending motion as the soft material-based mechanism. The hard material-based mechanism generates relatively large open and closing motions of the gripper and generates a larger force than soft mechanism. Even if the soft material-based mechanism generates slower motion than the hard mechanism, it enables the gripper to safely interact with objects. The hybrid gripper could safely grasp and move a 52.0 g egg by cooperation of the hard and soft mechanisms (Fig. 13). Assembling process and the grasping test are included in the supplementary video.

V. Conclusion

In this article, we introduced the new modularized design for soft robotics. Soft LEGO borrowed the interlocking mechanism of common LEGO, which is simple, reliable,

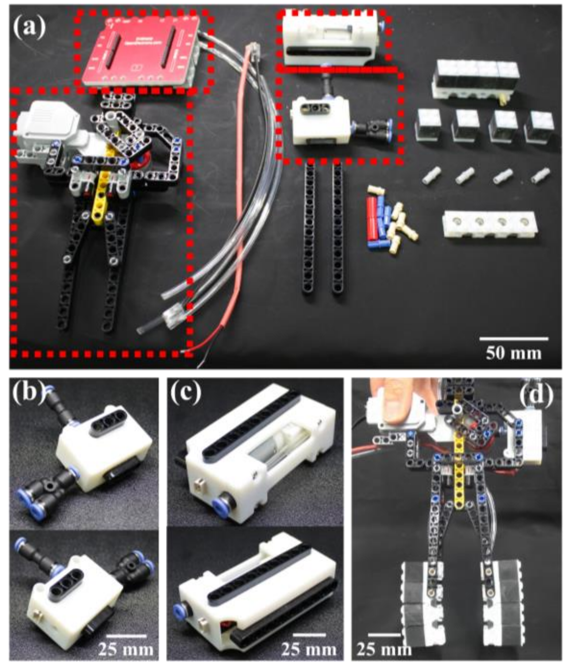

Figure 12. Soft-and-hard hybrid gripper with pneumatic air pump and solenoid valve modules with custom cases for LEGO Mindstorm and Technic. (a) The air pump module, solenoid valve module, half-assembled soft gripper, a control board, and bricks. (b) The pneumatic solenoid valve module with custom case. (c) The pneumatic pump module with custom case. (d) Fully assembled hybrid gripper.

versatile, and popular worldwide for use for education and entertainment.

The general public is unfamiliar with elastomer curing-based fabrication methods for soft robotics. However, with soft LEGO, users do not need to worry about fabrication methods. Soft LEGO enables users to build pneumatically actuated soft robots by an assembling process as simple as playing with LEGO. Users only worry about what to build and how to assemble with soft LEGO. Soft LEGO bricks will expand the potential of LEGO and enable hobbyists to go beyond what can be done with the typical LEGO.

The Taguchi method was employed to enhance the robustness of the soft bricks with finite-element analysis. Instead of building an analytical model, this methodology can be used for soft robotics to optimize their designs statistically with minimal trials. However, soft robots with complex structures and motions require a more accurate and elaborate finite-element analysis method.

Even if we enhanced the design, the robustness of soft LEGO was limited due to the 3-D printing materials regarded to have poorer material properties than elastomers, such as silicon and urethanes. Even so, 3-D printer makers have tried to improve material properties, and a 3-D printer company recently introduced a new flexible material (Agilus30, Stratasys Ltd.). We tested samples of the soft bricks printed with this material, and they could endure up to average 150.7 kPa of pneumatic actuation. For now, these new materials are relatively expensive and more time may be needed for them to become popularly used. In addition, soft LEGO was fabricated with the jetting-type multi-material 3-D printer, which is relatively more expensive than fused filament fabrication type 3-D printers. In the future, designs of the soft LEGO bricks

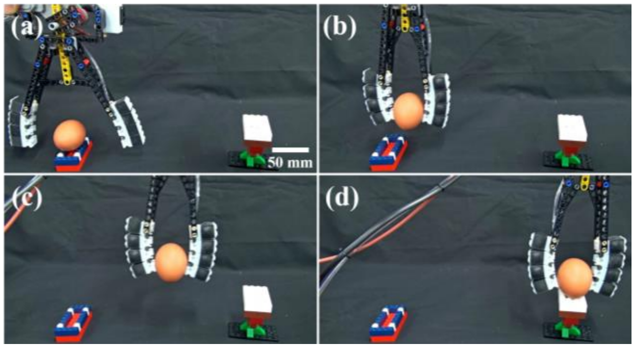

Figure 13. Soft-and-hard materials hybrid gripper grasped and moved an egg from one place to another. (a), (b), (c), and (d) The grasping motion in sequence.

will be tested and modified for printing with dual nozzles FFF type 3-D printer. Meanwhile, the ultimate goal is to reduce manufacturing costs by using mass production techniques, such as injection molding with materials that have appropriate properties.

In this paper, soft LEGO was only controlled by simple on-off actuation. Soft LEGO, especially the soft bending bricks, could be integrated with a soft sensor, as demonstrated in our previous research [30], to measure the bending angle. In addition, the pneumatic solenoid valve was used to control soft LEGO bending actuator. In addition to bricks introduced in this paper, new bricks with complex designs and functions integrated with control components will be explored in the future.

We hope that soft LEGO expands the base of soft robot researchers and popularizes soft robotics to the public. As the ultimate goal, it would be great to share the design of soft LEGO as an open source with researchers from various fields and with educators for STEM (Science, Technology, Engineering, and Mathematics) learning. Furthermore, soft LEGO would give new possibilities to LEGO itself as a soft robotic toy for entertainment robotic kits for kids and kidults.

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