Active Bending Mechanism Employing Granular Jamming and Vacuum-Controlled Adaptable Gripper

Takashi Mitsuda and Shinsaku Otsuka

Ritsumeikan University

Correspondence concerning this article should be addressed to Takashi Mitsuda, College of Information Science and Engineering, Ritsumeikan University, Kusatsu, Shiga, 525–8577, Japan. E-mail: mitsuda@is.ritsumei.ac.jp

To cite this article: T. Mitsuda and S. Otsuka, "Active Bending Mechanism Employing Granular Jamming and Vacuum-Controlled Adaptable Gripper," in *IEEE Robotics and Automation Letters*, vol. 6, no. 2, pp. 3041-3048, April 2021, doi: 10.1109/LRA.2021.3058914.

Active bending mechanism employing granular jamming and vacuum-controlled adaptable gripper

Takashi Mitsuda[1], *Member*, *IEEE*, and Shinsaku Otsuka[2]

***Abstract*— We propose a bending mechanism in this study capable of wrapping around objects of various shapes and increasing its stiffness simply via the evacuation of internal air. Unlike vacuum splints requiring manual wrapping and pneumatic bending devices based on granular jamming requiring a complicated combination of two separate air control systems, our proposed mechanism can wrap itself around objects using a single air evacuation system. An elastic container enveloping polystyrene foam beads and urethane sponges is employed in this mechanism. The compression of the sponges, caused by the evacuation of internal air, results in bending, while the stiffness of the mechanism increases simultaneously due to granular jamming. On embedding sponges having different stiffnesses, the resulting differences in the onset of sponge shrinkage cause sequential bending, which reduces the gaps between the mechanism and the target object. First, we developed a mattress-shaped bending mechanism that can be used as a vacuum splint and does not need to be manually wrapped around an object. Thereafter, an adaptable gripper was developed using the same bending mechanism. The gripper can wrap around objects having various shapes and increase its stiffness simply by evacuating internal air; it can even lift heavy objects.**

***Index Terms*— End effectors, grasping, and soft robotics.**

I. Introduction

An increase in the density of particles due gravitational compression leads to a significant increase in the viscosity of these particles, which is similar to grains in a silo. In this regard, granular jamming refers to the phase transition of particles from fluid to solid [1]. In the field of robotics, granular jamming refers to an artificial phase transition whereby the stiffness of particles in an elastic container increases due to the evacuation of internal air as shown in Fig. 1(a). This variable stiffness of particles embedded in elastic containers is utilized in many applications. As such, Mitsuda et al. [2] developed a cylinder-shaped mechanical element with granular jamming and employed it in a force display, a haptic glove [3], a robot manipulator [4], an orthosis for training [5], and a wearable chair [6]. Recently, many researchers in the field of soft robotics [7], [8] have developed this technology and suggested several applications such as robot grippers [9]-[11], haptic displays [12]-[15], robot manipulators [16]-[19], and deformable robots [20], [21].

Granular jamming was first reported in 1961 for the medical purpose of affixing bodies [22]. Since then, many commercial products having various shapes have been introduced for affixing bodies. For example, a vacuum splint is a small mattress-shaped product containing plastic beads for maintaining the posture of a limb or a trunk (see Fig. 1(b)). After the mattress wraps around a body, evacuating the inside air increases its stiffness and fixes its shape, thus acting as an orthopedic cast. During this wrapping process, there should be no gap between the mattress and the body to ensure that the body is fixed tightly. Otherwise, gaps remain even after evacuating the internal air because the mattress becomes rigid without changing its shape.

This problem can be addressed simply by adding soft pneumatic actuators to the mattress for altering its shape such that it conforms with the posture of the body. Many studies have combined pneumatic actuators and granular jamming and developed various devices, as described above [4], [10-12], [14], [16], [18-21]. However, the inclusion of pneumatic actuators requires additional control devices, which increases the complexity and cost of the product. Specifically, for application in medical orthoses, these products must be easy to use.

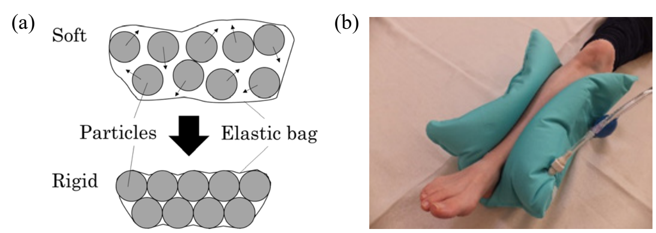

Fig. 1. (a) Schematic illustration of granular jamming. (b) an example of vacuum splint (Tatsuno Cork Kogyo Co Ltd., Cubeads[R]).

Manuscript received: September 10, 2020; Revised January 8, 2021; Accepted January 29, 2021.

This paper was recommended for publication by Editor Kyu-Jin Cho upon evaluation of the Associate Editor and Reviewers' comments. This work was supported by JSPS KAKENHI Grant Number JP18K04064.

[1]T. Mitsuda is with College of Information Science and Engineering, Ritsumeikan University, Kusatsu, Japan mitsuda@is.ritsumei.ac.jp

[2]S. Otsuka was with Graduate School of Information Science and Engineering, Ritsumeikan University, Kusatsu, Japan tsuka0704@outlook.jp

Digital Object Identifier (DOI) : see top of this page.

To address these problems, a previous study [23] of an active bending mattress with granular jamming by embedding sponges between the particles was published in a domestic journal in Japanese. Evacuating internal air bends the mattress and simultaneously increases its stiffness via granular jamming. Thus, the mattress can wrap around objects of various shapes; its stiffness is also increased due to the evacuation of the air inside it. This simple structure and easy application make it suitable for medical products. However, when the mattress wraps around objects, gaps may appear depending on the shape of the object because each point of mattress bends simultaneously. To solve this problem, we improved the mechanism by embedding sponges of different stiffnesses within the mattress to realize sequential bending motion, which reduces the gaps between the mattress and the target object. The first contribution of this study shows the mechanical properties and the wrapping performance of the proposed mattress, comparing with the original mattress [23] and a commercial vacuum splint.

The second contribution of this study is to apply the proposed bending mechanism to a robot gripper. Most conventional soft pneumatic grippers utilize the expansion of soft containers by compressing internal air [10], [11], [24]-[28]. Although these grippers are highly elastic, their low stiffnesses make them unsuitable for holding heavy objects. Consequently, many researchers have incorporated granular jamming or other similar mechanisms affording variable stiffnesses with such grippers to increase the rigidity as required [10], [11], [29]-[31]. Although these systems can control the motion and stiffness of the gripper independently, they are more complex than conventional soft grippers because they require vacuum air control in addition to the compressed air control.

By sharing a vacuum pump [32], coupling vacuum-driven actuator and granular jamming mitigates this problem. However, independent vacuum control systems are still required because the actuator and the container of beads (i.e., granular jamming) are separated. In contrast, the proposed gripper achieves a similar function using a vacuum control system alone because the container of beads itself bends, thereby reducing cost and complexity. A similar idea of embedding origami skeletons rather than beads and sponges inside a soft container has been proposed [33]. The cylindrical soft gripper using the mechanism, which wraps objects placed in it by shrinking itself, has also been proposed [34]. In contrast, the gripper proposed in this study consists of fingers that realize sequential bending motion, which enable the gripper to grip objects having various shapes. The proposed gripper cannot control the grasping motion and stiffness independently. However, the stiffness of the gripper is low initially, enabling it to wrap around target objects of various shapes; after performing the grasping motion, this stiffness is increased, enabling it to hold heavy objects.

In this paper, the mattress-shaped bending mechanism employing granular jamming, which was mainly developed for affixing bodies in medical applications, is firstly discussed. Thereafter, the proposed robot gripper featuring fingers based on the bending mechanism is discussed.

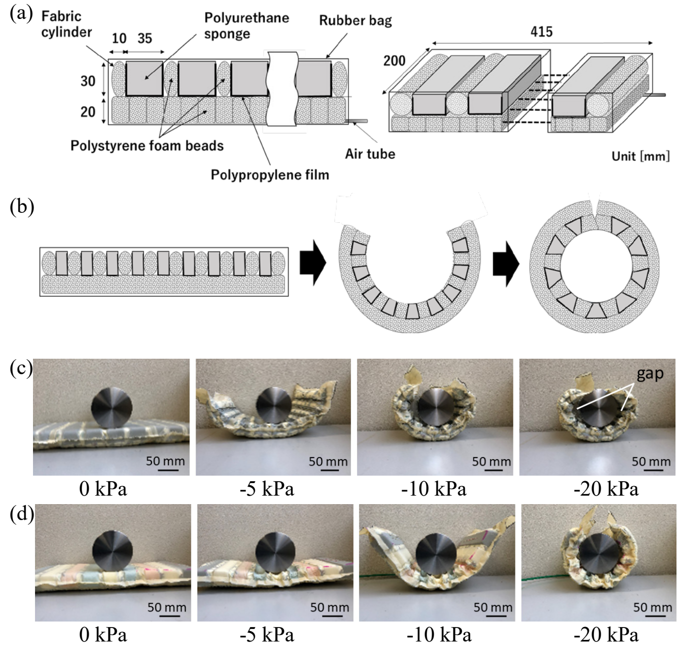

Fig. 2. Mattress-shaped bending mechanism: (a) structure; (b) bending via internal air evacuation; (c) bending of the mattress-shaped mechanism embedded with sponges of the same stiffness; and (d) bending of the mattress-shaped mechanism embedded with sponges of different stiffnesses.

II. Bending Mechanism Using Granular Jamming

A. *Structure and Function*

Fig. 2(a) shows the structure of the mattress-shaped bending mechanism employing granular jamming. The structure comprises a soft envelope composed of rubber (thickness: 0.19 mm), which contains polystyrene foam beads (diameter: 1.5 mm, foaming ratio: 15, density: 0.066 g/cm^3) in the lower space and the beads and urethane sponges in the upper space. Evacuating the air inside it through an outlet in the envelope compresses the sponges and gradually transforms the beads from a fluid state to a solid state. The sponges are rectangular parallelepipeds, and polypropylene films with a thickness of 0.15 mm are fixed on both sides and at the bottom of the sponges. Owing to the rigidity of the films, decreasing the internal air pressure compresses the upper part of the sponges, resulting in the bending of the mechanism (Fig. 2(b)(c)(d) and Fig. 6(b)). The bending angle is determined mainly by the balance between the compression force, generated by the vacuum created, and the restoring force of the sponges. Therefore, the bending angle of this mechanism can be increased by increasing the internal vacuum pressure.

B. *Embedding Sponges with Different Stiffnesses*

Evacuating the air inside the aforementioned mechanism compresses all the sponges simultaneously. Accordingly, when the shapes and stiffnesses of the sponges are identical, the mattress undergoes a uniform bend, which can occasionally create a gap between itself and the target object (Fig. 2(c)). To address this problem, we embedded sponges having different stiffnesses (INOAC corp., urethane foam #2,3,4,5,6) in the mattress. The densities of the sponges were 20, 21, 35, 40, and

50 g/cm^3, respectively. The sponge with the lowest stiffness was positioned at the center of the mattress, while those with higher stiffnesses were located on both sides; in this configuration, the stiffnesses of the sponges increased linearly on moving away from the center of the mattress. Therefore, on evacuating internal air, the mattress first bends at the center, followed by the bending of its outer edges (Fig. 2(d)). This successive bending motion enables the mattress to wrap around an object without creating any gaps.

C. Embedding Polystyrene Foam Beads

Apart from polystyrene foam, other materials can also be used for the beads embedded in this mechanism. Coffee grains [9,12,14,17-19,29] have been frequently employed for granular jamming in robotic applications. Different materials or different shape of beads lead to different mechanical properties [15, 16, 20, 29]. In this study, polystyrene foam was employed because its low weight is more suitable for medical orthoses. The stiffness of polystyrene foam depends on the foaming ratio, and that of the beads affects the rigidity of the mechanism. To increase the stiffness and avoid any plastic deformation, we employed beads whose foaming ratio (15) is smaller than that of polystyrene foam beads typically used to fill commercial bean bags (usually greater than 30).

To maintain the stiffness of this mechanism, the beads must always be distributed evenly irrespective of their shapes. Therefore, the beads in the lower space of the mechanism were subdivided and enveloped in multiple bags made of air-permeable cloth. The beads between the sponges in the upper space were enveloped in an air-permeable bag with an elliptical cross-section. The cross-section of the bag is an important factor affecting the bending of the mattress under vacuum pressure. When a plate bends, the inner arc length decreases, whereas the outer arc length increases. In this mechanism, the particles under the sponges do not alter their shapes due to the high rigidity of the film attached to the sponges. Consequently, when the mattress bends, the distance between the bottoms of adjacent sponges decreases. In the case of a bag having an elliptical cross-section, the particles under it form a trapezoid whose top is shorter than its bottom (Fig. 3), which promotes bending of the mattress. Decreasing the distance between the bottoms of the sponges results in an upward movement of the particles, which alters the cross-section of the bag. This is feasible due to the gaps between the elliptical bags and the sponges. In contrast, when the bag between sponges has a rectangular cross-section, the beads in the rectangular bag establish complete contact with the beads at the bottom, without any gaps between them. Consequently, the portions between sponges become rigid under vacuum, thereby fixing the distance between the bottoms of the sponges and reducing the bending angle of the mattress.

D. Width and Interval of Sponges

The maximum bending angle of this mechanism depends on the width, height, and interval of the sponges. In a previous study [23], the relationship between these sponge parameters and the bending angle was examined. Therefore, we only present a summary and the optimal parameters in this paper. For a constant height and interval of sponges, the maximum bending angle increases with the width of the sponge, because the two hard films on both sides of the sponge are in contact with each other when the width of the sponge is small. In contrast, when the width of a sponge is large, the tops of the sponges sink under vacuum pressure, which affects the bending of the mechanism. Previous experimental results show that the largest bending angle was obtained when the width, height, and interval of the sponges were 35, 30, and 25 mm, respectively. Furthermore, on increasing the width beyond 35 mm, the bending angle decreased.

A narrower interval of sponges increases the curvature of the mattress. Previous experimental results show that a bending mechanism without particles between the sponges (where adjacent sponges were connected by interweaving a hard film) exhibits the maximum curvature. However, evacuating the air inside this mechanism leads to the sinking of the top of the sponges, which pushes out the hard film between sponges. The resulting projections of the hard film hinder the wrapping of the mechanism around a body. Furthermore, using particles between sponges is beneficial because these particles conform to the shape of the target object, thereby minimizing gaps. Therefore, in this study, sponges with a width of 35 mm and an interval of 10 mm were used. The mass of the bending mechanism shown in Fig. 2(a) is 380 g.

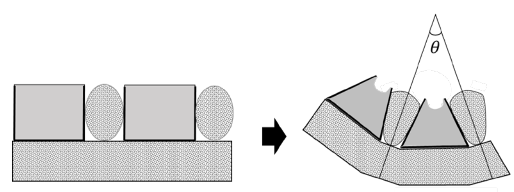

Fig. 3. Sectional view of the mattress when it undergoes bending due to the evacuation of internal air.

E. Relationship between Vacuum Pressure and Bending Angle

The bending angle of the mattress is determined by the balance between the bending moment, caused by the compression of the sponge under vacuum, and the restoring force of the sponges.

In this study, we examined the relationship between internal air pressure and the bending angle of the mechanism. The internal air pressure was varied from 0 to -10 kPa in steps of 2 kPa; thereafter, from -10 kPa to -80 kPa, in steps of 10 kPa. The bending angle defined in Fig. 3 was measured thrice using photographs, and the averaged results were taken.

Fig. 4 depicts the results of these experiments. It can be seen that the bending angle increases with the vacuum pressure; however, this increase diminished beyond -40 kPa, which was likely caused due to the sinking of the tops of the sponges. The wrapping process (i.e., bending) almost ceases when the vacuum pressure is less than -40 kPa. Therefore, the stiffness of the mattress wrapping around objects can be adjusted by varying the internal air pressure from -40 kPa to the lowest air pressure, which is approximately -80 kPa for the small vacuum pump used in this study.

The difference in the stiffness of the sponges affected the minimum vacuum pressure required for bending rather than the rate of increase in the bending angle. The harder sponges required a higher vacuum pressure than the softer ones to undergo bending; in other words, the onset of bending was influenced by the sponge stiffness. This is appropriate for the sequential bending of this mechanism

F. Bending Stiffness

A previous study [2] has shown that the stiffness of a mechanism employing granular jamming is proportional to its internal vacuum pressure. The bending mechanism proposed herein contains sponges that could affect the stiffness. Therefore, the bending stiffness of the mattress shown in Fig. 2 was compared with that of a similarly-shaped mattress containing only polystyrene foam beads.

The mattresses were wrapped around a cylinder having a diameter of 100 mm, and their shape was fixed by decreasing the internal air pressure to -80 kPa. As shown in Fig. 5(a), an aluminum plate was connected to a force gauge via a wire and applied to pull open the top of the bent mattress at a rate of 50 mm/min by using a universal testing machine (Imada, MX2-500N). Results show that the reaction force increased proportionally with the displacement (Fig. 5(b)). The stiffness, calculated by dividing the reaction force with the displacement at 20 mm, was 3.7 N/mm for the mattress with beads and 1.5 N/mm for the mattress with sponges as well as beads (Fig. 2(a)). The area moment of inertia of a plate is proportional to the cube of its thickness. The thickness of the mattress with beads was 50 mm; in contrast, the lower part of the proposed mattress (i.e., thickness of the beads under the sponges) was 20 mm, indicating that the stiffness of the lower part of the proposed mattress must be 0.064 times that of the mattress with beads (i.e., 0.24 N/mm) according to the beam theory. However, the measured stiffness of the suggested mattress was considerably higher than this value, indicating that the upper part of the mattress, which contained sponges, contributed toward the stiffness as well.

Next, the bending stiffness of the proposed mechanism was examined when the internal air pressure was varied between -30 kPa and -80 kPa in steps of 10 kPa; these results are shown in Fig. 5(c). Similar to the mechanism with beads, the stiffness of the proposed mattress was proportional to the internal air pressure.

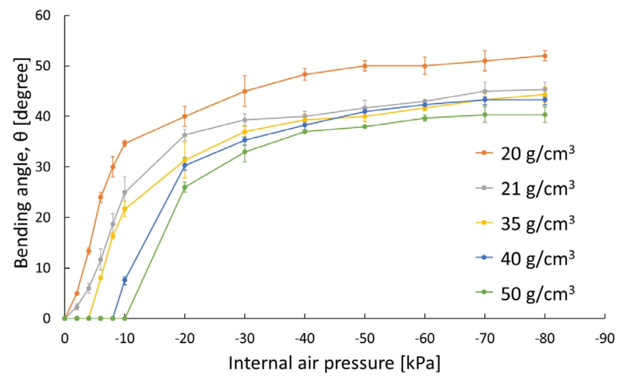

Fig. 4. Relationship between internal air pressure and bending angle of the mattress with sponges of different stiffnesses (densities)

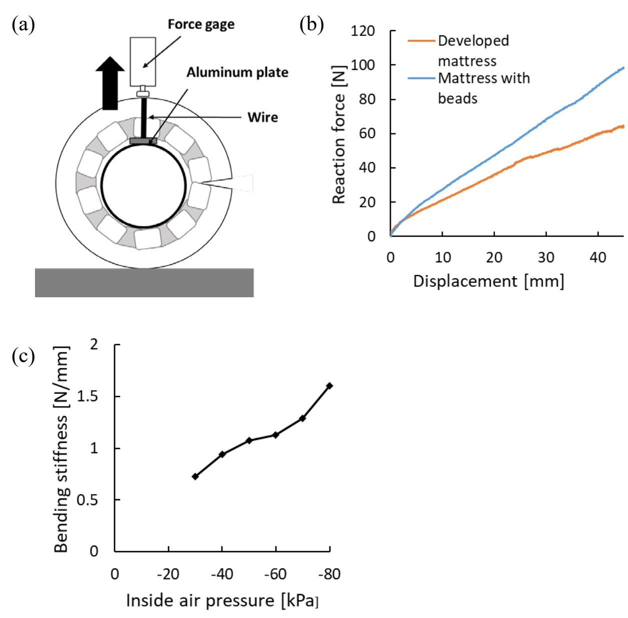

Fig. 5. (a) Experimental setup for measuring bending stiffness; (b) bending stiffness of the developed mattress and that with beads; and (c) relationship between bending stiffness and internal air pressure.

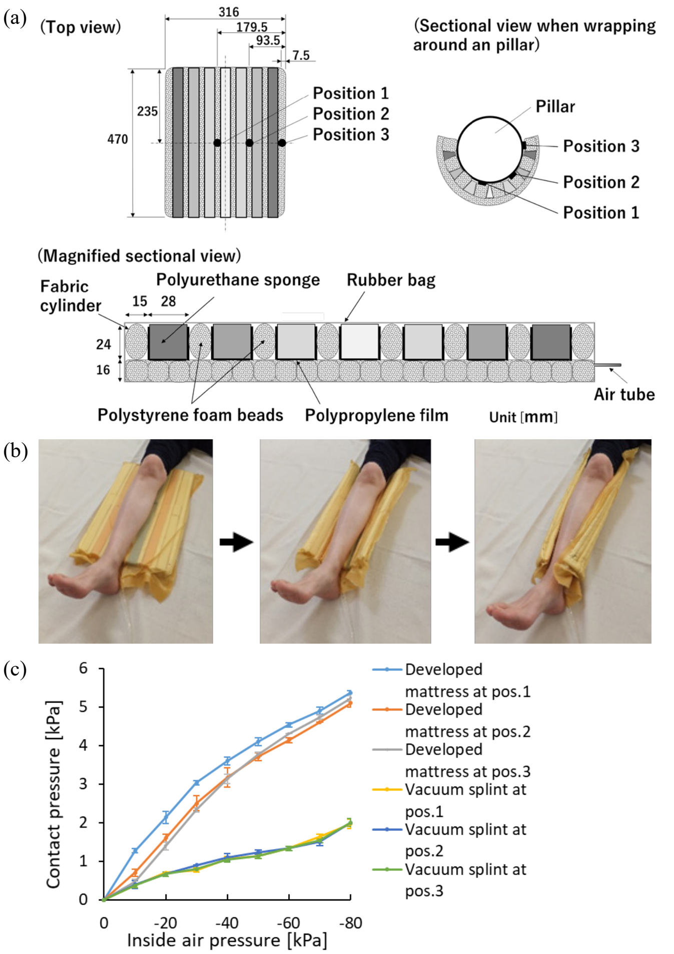

Fig. 6. (a) Structure of the developed mattress featuring a shape similar to that of a commercial vacuum splint, and the positions at which contact force was measured. Darker color indicates stiffer sponge; (b) Wrapping motion of the developed mattress around a leg by decreasing the internal air pressure (c) contact pressure between the cylinder and the developed mattress and that between the cylinder and the vacuum splint.

G. Relationship between Contact Force and Vacuum Pressure

As described above, the bending moment increases with the internal air pressure. Therefore, when the mattress wraps around an object, the contact force is considered to increase with the internal vacuum pressure. In this study, we examined the relationship between contact force and vacuum pressure and compared it with that for a commercial mattress with beads (i.e., a vacuum splint, AS ONE Corp., #3345). The experiment was conducted using a developed mattress (Fig. 6(a)), whose shape is identical to that of the vacuum splint. This developed mattress features embedded sponges having different stiffnesses (INOAC Corp.; Urethane foam #2, 3, 4, 5). The sponge at the center is the softest, whereas harder sponges were placed at the posterior positions. Fig. 6 (b) shows that the mattress automatically wraps around a leg without gaps by decreasing the inside air pressure, which shows the applicability of the mattress as a vacuum splint. The numbers in Fig. 6(a) represent the positions at which the contact force was measured. Each mattress was wrapped around a cylinder, and the air inside them was evacuated before measuring the contact force thrice via a pressure sensor. Fig. 6(c) presents the average values of contact force.

The contact force increased with the vacuum pressure for both mattresses. The contact force of the vacuum splint was attributed to its low shrinking under vacuum. For the same internal pressure, the contact force of the developed mattress was greater than that of the vacuum splint. The contact force of the proposed mattress differed according to the measurement positions when the inside vacuum pressure was low. In contrast, the contact force of the vacuum splint did not vary with position. As reported in a previous study, when employing sponges having identical stiffnesses, the contact force remains constant regardless of the measurement position [23]. Therefore, the variation in contact force with respect to the measurement position for the proposed mattress is likely due to the arrangement of sponges having different stiffnesses. The contact forces in wrapping are determined not by a single bending torque at the measurement position but by the combination of various bending torques in the mattress. Further studies are required to investigate the relationship between the contact forces and the arrangement of the sponges having different stiffnesses.

H. Wrapping Performance

To examine the wrapping performance of the developed mattress (Fig. 2), rods with various cross-sections were used. These were placed on the plate mattress, whose internal pressure was then reduced to -70 kPa. As shown in Fig. 7, the proposed mattress could wrap around a small rod (diameter: 60 mm), a large rod (diameter: 100 mm), and a rod with an elliptical cross-section (major axis: 110 mm and minor axis: 90 mm); for the elliptical cross-section, both horizontal and vertical major axes were tested using the same rod. Moreover, when wrapping around these objects, the proposed mattress did not create any large gaps, proving its ability to automatically wrap around objects with different curvatures. When the mattress wrapped around a square rod (width: 85 mm), two gaps appeared because of the limited curvature of the mattress (see Fig. 4). By decreasing the thickness of the mattress, its maximum bending curvature could be increased; however, the stiffness would also be reduced. When the inside air was evacuated after wrapping the same square rod manually, the mattress retained its shape without creating any gaps (Fig. 7(f)).

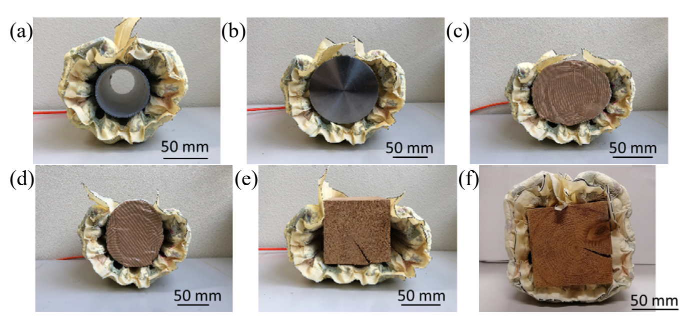

Fig. 7. Images of the proposed mechanism wrapped around (a) a small rod (dia. 60 mm), (b) a large rod (dia. 100 m), (c) a horizontal elliptical rod (major axis 110 mm and minor axis 90 mm), (d) a vertical elliptical rod, (e) a square rod (width 85 mm), and (f) proposed mechanism manually wrapped around the same square rod.

III. Robot Gripper Using Bending Mechanism Based on Granular Jamming

In this study, a soft robot gripper was developed using the bending mechanism described above. This gripper featured six bendable fingers and could simultaneously increase the stiffness of all its fingers, enabling it to hold heavy objects with a relatively low holding force.

A. *Structure and Functions*

Fig. 8(a) depicts the structure of the developed gripper, which consists of six fingers that can spread radially. All the fingers are connected to an outlet at the central base; this outlet is used to evacuate the air inside the fingers to increase their stiffness simultaneously. The structure of all the fingers is fundamentally identical to that of the bending mechanism described in previous sections, with the exception that the fingers are rod-shaped.

The sponges at the proximal portion of the fingers are softer than those on the distal portions, which enables the fingers to wrap around an object without creating any gaps. The internal beads in the lower portion of the fingers were not divided into small containers because the beads were not partially distributed by gravity owing to the narrower space than that in the mattress-shaped bending mechanism. The beads between the sponges were enclosed in an elliptical bag, similar to those in the mattress-shaped mechanism. The beads, hard films attached to sponges, permeable bags, and outer envelope in the fingers were all composed of the same material as those in the mattress-shaped bending mechanism. The mass of the gripper, with the air tube connected, was 110 g.

Fig. 8(b) and (c) present images of the gripper before and after evacuating the inside air. Fig. 9 presents the changes in the shape of a single finger of the gripper when its internal air pressure was altered. Thus, the bending angles of the fingers can also be controlled by regulating internal air pressure, similar to the mattress-shaped bending mechanism.

B. *Stiffness*

The relationship between the stiffness of the fingers and the internal air pressure was examined by measuring the reaction force and displacement; this was realized by pulling the proximal edge of a finger upwards at a rate of 50 mm/min. The universal testing machine described in Section II F was used for these measurements. During the experiment, the internal air pressure was varied from -10 kPa to -70 kPa in steps of 10 kPa, and three measurements were taken. Similar to that in the mattress-shaped bending mechanism, the reaction force was proportional to the displacement. Fig. 10 depicts the relationship between bending stiffness (i.e., the quotient of the reaction force when the finger was pulled upward by 20 mm) and the internal air pressure. Furthermore, the bending stiffness of the finger was proportional to the internal air pressure, which was similar to that in the mattress-shaped mechanism.

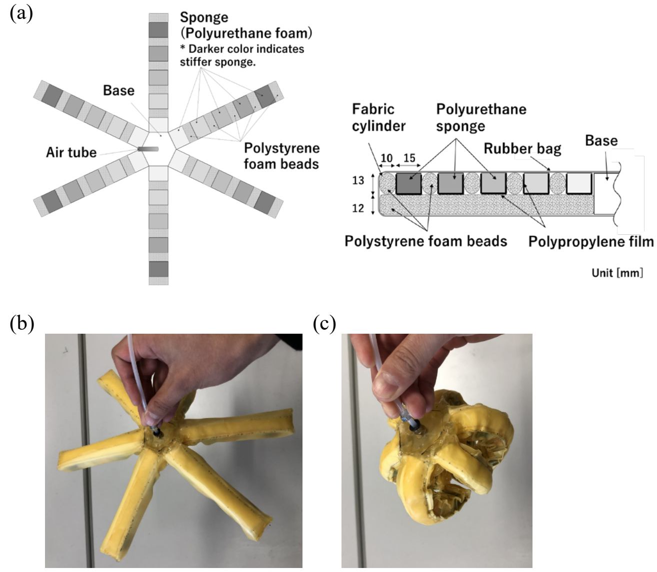

Fig. 8. Adaptable gripper using the bending mechanism: (a) structure of fingers; (b) structure of the gripper; (c) grasping action.

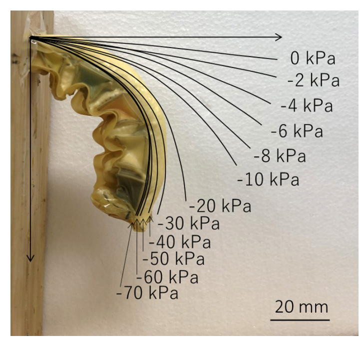

Fig. 9. Variations in the shape of a finger subjected to different internal vacuum pressures.

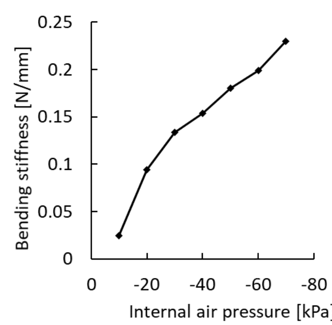

Fig. 10. Relationship between bending stiffness of the finger-shaped bending mechanism and internal air pressure.

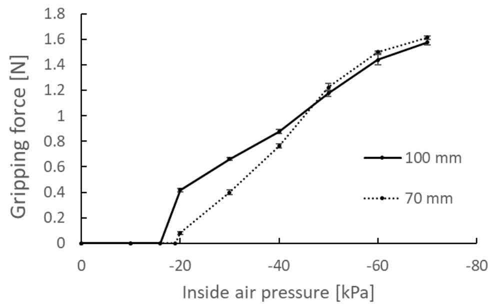

Fig. 11. Gripping force of the gripper for rubber balls with diameters of 100 mm and 70 mm.

C. Relationship between Internal Air Pressure and Gripping Force

The holding force at the proximal portion of the developed gripper was measured when it grasped a rubber ball (diameter: 100 mm or 70 mm) placed on the floor, by using a load cell (thickness: 3 mm, diameter: 12 mm). For the ball having a diameter of 100 mm, the central base of the gripper was in contact with the surface of the ball; for that having a diameter of 70 mm, however, the base was approximately 25 mm above the surface of the ball because the fingers of the gripper hit the floor when bending. Therefore, all parts of the fingers touched the former ball, whereas only the proximal portions of the fingers touched the latter one. The holding force was measured as the internal air pressure was varied from -30 kPa to -70 kPa in steps of 10 kPa, and the measurements were repeated thrice. Fig. 11 depicts the results thus obtained. For both the balls, the holding force was proportional to the internal air pressure of the fingers. This indicates that the holding force increases with the stiffness of the finger, which is a potential disadvantage of this mechanism; this is caused using a singular system for both vacuum control (used to achieve bending motion) and stiffness adjustment. However, the holding force at an internal air pressure of -70 kPa was 1.6 N, which was sufficient for the finger to hold a ball weighing 1340 g due to its high stiffness, as explained in the following subsection (Fig. 12(k)).

D. Gripping Performance

To examine the gripping performance of the developed gripper, it was used to grip and pick up objects with various shapes and masses; for this purpose, the internal pressure was reduced to -70 kPa. As shown in Fig. 12, the gripper could pick up an apple (diameter: 80 mm and mass: 235 g), a bottle (diameter: 100 mm and mass: 510 g), a wooden block (90 mm × 90 mm × 160 mm and mass: 550 g), a wooden board (90 mm × 37 mm × 57 mm and mass: 231 g), a banana (mass: 288 g), a snack packet (230 mm × 140 mm × 45 mm and mass: 196 g), a sponge cake (mass: 118 g), and a pen (diameter: 15 mm and mass: 17 g). To examine the maximum weight that could be lifted, a ball with a diameter of 70 mm (weighing 40 g) was grasped and a weight was hung from the ball. The maximum weight that the developed gripper could hold was 1340 g; when the weight was increased to 1440 g, the ball slipped from the fingers of the gripper.

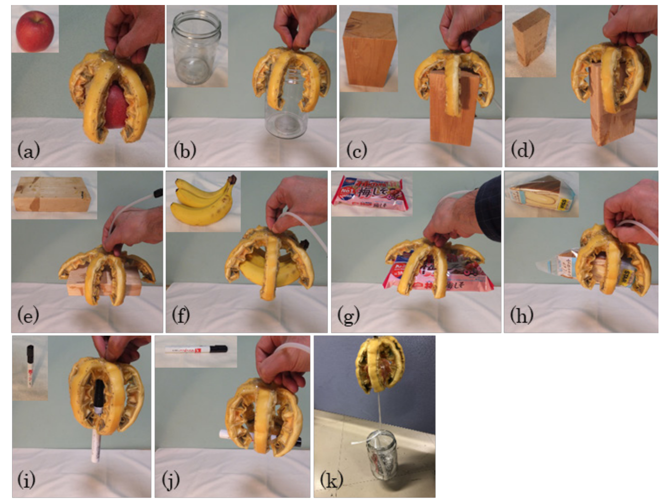

Fig. 12. Images showing the gripper grasping various objects. (a) apple, (b) bottle, (c) wooden block,(d) wooden board, (e) wooden board, (f) banana, (g) snack packet, (h) sponge cake, (i) pen, (j) pen, (k) a weight of 1340 g.

IV. Conclusion

In this paper, we proposed a bending mechanism that wraps around objects of various shapes and increases its stiffness simultaneously by evacuating the air inside it. Owing to the sequential bending of the proposed mechanism, the gaps between the device and the target object could be reduced without additional air control systems. Contrary to the conventional systems that couples pneumatic actuators and granular jamming, the proposed mechanism bends by itself only by decreasing the inside air pressure. Thus, the simple structure is suitable for commercial applications. Two applications of the proposed bending mechanism are described here.

Firstly, this paper demonstrated the mattress-shaped device that can be used as a vacuum splint. It automatically wrapped around a leg without gaps only by decreasing the inside air pressure. This is a significant advantage of the proposed device because conventional vacuum splints require manual wrapping. The mattress-shaped device can be used not only for medical purposes but also for fixing body to mechanical devices such as wearable robots, seats in vehicles, and head-mount displays, though the durability and comfort must be examined.

Secondly, this paper demonstrated a soft robot gripper. The grasping test showed that the gripper can pick up objects having various shapes and masses owing to the sequential bending of the fingers and the increased stiffness after grasping. To use the proposed soft robot gripper in manufacturing, the tact time, which depends on the air control system, is an important factor that should be examined.

The proposed bending mechanism can also be employed in protective systems for transportation, toys, and other applications as a soft pneumatic actuator. The essential properties of the proposed mechanism, such as durability, stiffness, and reaction speed, can be varied depending on the application. However, in terms of its ability to wrap around objects, this mechanism can be improved via three distinct approaches as follows.

The first approach is to improve the wrapping function without creating gaps. Placing sponges with different stiffnesses can reduce the gap; however, this is impractical for all shapes. A simple solution is to control the bending of each sponge independently; however, this would necessitate a significantly more complex structure and control system. This could be addressed by employing airbags as the force sensors and air valves actuated via air pressure.

The second approach is to realize the ability to conform to the shape of a dent on the target object; for this, the mechanism should be able to bend in one direction at the entrance and in the opposite direction at the exit of the dent. The proposed mechanism can only bend along one specific direction, rendering it unable to conform to the hairpin-like bends in dents. Thus, as described above, future research should focus on developing a mechanism that can conform to the shape of a dent simply via the evacuation of internal air without requiring additional electronic control devices.

Finally, the third approach is to achieve ability to form curved surfaces, considering that the proposed mechanism can only form curved lines. A lattice composed of a rod-shaped bending mechanism can form curved surfaces. Alternatively, a plate containing cubic sponges with hard bottom and side surfaces can also form a curved surface. Therefore, further studies should also focus on realizing and optimizing these mechanisms depending on requirements of potential applications.

REFERENCES

[1] B. Chakraborty and B. Behringer, “Jamming of granular matter,” in *Encyclopedia of Complexity and Systems Science*, Meyers R, Ed. New York, NY: Springer; 2009, pp.4997–5021.

[2] T. Mitsuda, S. Kuge, M. Wakabayashi M, et al, “Wearable force display using a particle mechanical constraint. presence,” Presence: Teleoper. Virtual Environ., vol. 11, no. 6, pp.569–577, 2002.

[3] T. Mitsuda and S. Kawamura, “Development of a haptic display with Particle Mechanical Constraints,” *Proc. of JSME Annual Conf. on Robotics and Mechatronics*. 2002:1P1-F10 (in Japanese).

[4] T. Mitsuda and S. Kawamura, “Development of a flexible arm using controllable viscoelastic elements,” *SICE Division Conference Program and Abstracts*, 486, 2002 (in Japanese).

[5] T. Mitsuda, M. Wakabayashi and S. Kawamura, “Development of an upper-limb training orthosis using particle mechanical constrains,” *Proc. of JSME Annual Conf. on Robotics and Mechatronics,* 2A1-3F-E3, 2003 (in Japanese).

[6] T. Mitsuda, M. Wakabayashi and S. Kawamura. “Development of wearable chair using pneumatic passive elements,” *J. Robot. & Mechatron.*, vol. 16, no. 3, pp. 256–263, 2004.

[7] M. Uchiyama, “Soft robotics,” *J. Robot. Soc. of Japan*, vol. 17, no. 6, pp. 756–757, 1999 (in Japanese).

[8] C. Laschi, B. Mazzolai and M. Cianchetti, “Soft robotics: Technologies and systems pushing the boundaries of robot abilities,” *Sci. Robot.,* vol. 1, no. 1, eaah3690, 2016.

[9] E. Brown, N. Rodenberg, J. Amend et al., “Universal robotic gripper based on the jamming of granular material,” *PNAS*, vol. 107, no. 44, pp. 18809–18814, 2010.

[10] Y. Wei, Y. Chen, T. Ren et al., “A novel, variable stiffness robotic gripper based on integrated soft actuating and particle jamming,” *Soft Robot*., vol. 3, no. 3, pp. 134–143, 2016.

[11] P. Jiang, Y. Yang, M. Chen et al. “A variable stiffness gripper based on differential drive particle jamming” *Bioinspir. & Biomimetics*, vol. 14, no. 3, 036009, 2019.

[12] M. Li, T. Ranzani, S. Sareh et al., “Multi-fingered haptic palpation utilizing granular jamming stiffness feedback actuators,” *Smart Mat. & Struc.*, vol. 23, no. 9, 095007, 2014.

[13] Y. Kurihara, M Koge, R. Okazaki et al., “Large-area tactile display using vibration transmission of jammed particles,” *IEEE Haptics Symposium (HAPTICS)*, pp. 313–317, 2014.

[14] A. A. Stanley and A. M. Okamura, “Controllable surface haptics via particle jamming and pneumatics,” *IEEE Transactions on Haptics*, vol. 8, no. 1, pp. 20–30, 2015.

[15] I. Zubrycki and G. Granosik, “Novel haptic device using jamming principle for providing kinaesthetic feedback in glove-based control interface,” *J. Intel. & Robot. Syst.*, vol. 85, pp. 413–429, 2017.

[16] A. Jiang, G. Xynogalas, P. Dasgupta et al., “Design of a variable stiffness flexible manipulator with composite granular jamming and membrane coupling,” *IEEE/RSJ Int. Conf. on Intel. Robots and Syst*., pp. 2922–2927, 2012.

[17] N. G. Cheng, M. B. Lobovsky, S. J. Keating et al., “Design and analysis of a robust, low-cost, highly articulated manipulator enabled by jamming of granular media,” *IEEE Int. Conf. on Robot. and Autom.,* pp. 4328–4333, 2012.

[18] M. Cianchetti, T. Ranzani, G. Gerboni et al., “Soft robotics technologies to address shortcomings in today's minimally invasive surgery: the STIFF-FLOP approach,” *Soft Robot*., vol. 1, no. 2, pp. 122–131, 2014.

[19] T. Ranzani, M. Cianchetti, G. Gerboni et al., “A soft modular manipulator for minimally invasive surgery: design and characterization of a single module,” *IEEE Trans. on Robot*., vol. 32, no. 1, pp. 187– 200, 2016.

[20] E. Steltz, A. Mozeika, N. Rodenberg et al., “JSEL: jamming skin enabled locomotion,” *IEEE/RSJ Int. Conf. on Intel. Robots and Syst*., pp. 5672–5677, 2009.

[21] T. Yanagita, T. Kamagata and Nakamura T, “Development of an endoscopic support device using veering-out tube with stiffening capability by granular jamming -application to a large intestine of dead swine,” *Trans. of the Soc. of Instr. & Control Eng.*, vol. 51, no. 5, pp. 290–296, 2015 (in Japanese).

[22] J. Loeb and C. Haeberle, “Ligature, particularly for surgical use,” French patent. 1961:FR1270443A.

[23] S. Otsuka and T. Mitsuda, “Development of a mechanical element that changes the shape and rigidity by vacuum pressure,” *Trans. of the JSME,* vol. 85, no. 876, 19-00046, 2019 (in Japanese).

[24] Y. Hao, Z. Gong, Z. Xie et al., “Universal soft pneumatic robotic gripper with variable effective length,” *Chinese Control Conference*, pp. 6109–6114, 2016.

[25] J. Zhou, S. Che and Z. Wang, “A soft-robotic gripper with enhanced object adaptation and grasping reliability,” *IEEE Robot. Automat. Lett*., vol. 2, no. 4, pp. 2287–2293, 2017.

[26] W. Wang, Y. Torigoe and S. A. Hirai, “Prestressed soft gripper: Design, modeling, fabrication, and tests for food handling,” *IEEE Robot. Automat. Lett*., vol. 2, no. 4, pp. 1909–1916, 2017.

[27] Y. Fei, J. Wang and W. Pang, “A novel fabric-based versatile and stiffness-tunable soft gripper integrating soft pneumatic fingers and wrist,” *Soft Robot.*, vol. 6, no. 1, pp. 1–20, 2019.

[28] Z. Wang, K. Or and S. Hirai, “A dual-mode soft gripper for food packaging,” *Robot. & Autonom. Syst.*, vol. 125, 103427, 2020.

[29] V. Wall, R. Deimel and O. Brock, “Selective stiffening of soft actuators based on jamming,” *IEEE Int. Conf. on Robot. and Autom.,* pp. 252–257, 2015.

[30] Y. Hao, T. Wang, Z. Xie et al, “A eutectic-alloy-infused soft actuator with sensing, tunable degrees of freedom, and stiffness properties,” *J. of Micromech. & Microeng.*, vol. 28, no. 2, 024004, 2018.

[31] M. Al-Rubaiai, T. Pinto, C. Qian et al., “Soft actuators with stiffness and shape modulation using 3D-printed conductive polylactic acid material,” *Soft Robot*., vol. 6, no. 3, pp. 318–332, 2019.

[32] M. A. Robertson and J. Paik, “New soft robots really suck: Vacuum-powered systems empower diverse capabilities,” *Sci. Robot.*, no. 2, eaan6357, 2017.

[33] S. Li, D. M. Vogt, D. Rus et al., “Fluid-driven origami-inspired artificial muscles,” *PNAS*, vol. 114, no. 50, pp. 13132–13137, 2017.

[34] S. Li, J. J. Stampfli, H. J. Xu et al., “A vacuum-driven Origami “Magic-ball” soft gripper,” *IEEE Int. Conf. on Robot. and Autom.,* pp. 7401–7408, 2019.