Improvement of Pneumatic Chuck in Flexible Linear Stepping Actuator with Backdrivability

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***Abstract*— The progress of Japanese aging society is getting worse. Therefore, the development of rehabilitation devices and power assistive devices is desired from the viewpoint of quality of life. In such devices, it is required to use human-friendly soft actuators. In ideal, the soft actuator with both a longer stroke and a larger generated force is required. Therefore, we have developed a various type of flexible linear stepping actuators that can push and pull the flexible tube while changing the gripping position of the tube. In this paper, the improvement of the pneumatic chucks for gripping the tube to increase the generated force is described. The construction and the operating principle of the improved pneumatic chucks are described. Generated force of the tested chuck is investigated. As a result, the actuator with improved chuck can generate larger force that is almost same as the theoretical generated force without slip.**

***Index Terms*— Pneumatic chuck, Pneumatic flexible stepping actuator, Backdrivability, Pneumatic balloon, Soft actuator**

I. INTRODUCTION

The progress of Japanese aging society is getting worse [1]. Therefore, developments of rehabilitation devices and power assistive devices are required from the viewpoint of quality of life [2-5]. For example, K. Yamamoto developed a wearable power assisted suit using pneumatic balloon actuator for nursing care [2]. T. Noritsugu also developed a power assisted wear using pneumatic rubber muscle for nursing care [4]. As a wearable pneumatic drive system using the rubber muscle, H. Kobayashi also developed a muscle suit for factory application [5]. In such devices, it is required to use human-friendly soft actuators in order to prevent to injure human body. McKibben type rubber artificial muscle is well known as one of soft actuators with large generated force. However, the muscle has a problem of small displacement compared with its length. The maximum displacement of the muscle is less than one fourth of its original length [6].

As a flexible actuator with a longer stroke, the flexible pneumatic cylinder was proposed and tested [7]. The various rehabilitation devices using the cylinders were proposed and tested [8,9]. The validity of the tested devices was confirmed as a wrist rehabilitation device. However, the generated force of the cylinder is insufficient, that is only 15 N, to apply to power assistive and rehabilitation devices for whole upper limb including shoulder and arm. In addition, it is difficult to realize a flexible displacement sensor with long stroke while deforming its form according to the actuator's shape. In ideal, a flexible actuator that can generate both larger force and longer displacement is required.

Therefore, in the previous study, the linear flexible stepping actuators with a long stroke and a large generated force using pneumatic balloons and pneumatic chucks was proposed and tested [10, 11]. The tested actuator can push or pull the flexible tube while changing the gripping point of the flexible tube by using the pneumatic chucks. To improve the moving speed of the actuator, a linear stepping actuator using typical pneumatic cylinders was proposed and tested [12]. A flexible robot arm using three tested actuators was also successfully developed [12]. However, the generated force of the tested linear stepping actuator is much smaller than the theoretical generated force of the pneumatic cylinders installed into the actuator because of slip of the pneumatic chuck. In the next step, it is necessary to improve the generated force by redesign the pneumatic chuck.

In this paper, the construction and the operating principle of redesigned pneumatic chuck that can be installed into the flexible actuators are described.

II. PREVIOUS FLEXIBLE LINEAR STEPPING ACTUATORS

A. Balloon Type Flexible Linear Stepping Actuator

In the previous study [12], as a flexible pneumatic actuator that can generate larger force and work with a longer stroke, a balloon type flexible linear stepping actuator was proposed and tested.

Fig. 1 shows the schematic diagram of the inner construction and view of the tested actuator. The actuator consists of two doughnut-shaped balloons such as a diaphragm, two pneumatic driven chucks set on left side of the actuator, a moving round stage with a pneumatic driven chuck and a flexible tube as a rod. The moving stage with a chuck located on the center of the actuator is sandwiched by two balloons. The doughnut-shaped balloon that consists of a silicone rubber film with thickness of 0.5 mm has the outer diameter of 48 mm and the inner diameter of 26 mm. The actuator has the length

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of 102 mm and the outer diameter of 60 mm. The mass of the actuator without flexible tube (rod) is about 360 g.

Fig. 2 shows a schematic diagram of the pneumatic chuck using balloon and mechanical chuck [11]. The chuck consists of doughnut-shaped balloons with the inner diameter of 24 mm and the outer diameter of 36 mm, a ring-shaped plastic plate and a mechanical chuck. The mechanical chuck is made of 8 plastic claws set on the stage with the inclined angle of 45 deg. The inclined angle was calculated to maximize the holding force of the chuck. The generated force of the balloon calculated from the supply pressure of 500 kPa was 280 N and the holding force of the chuck was half, that was 140 N.

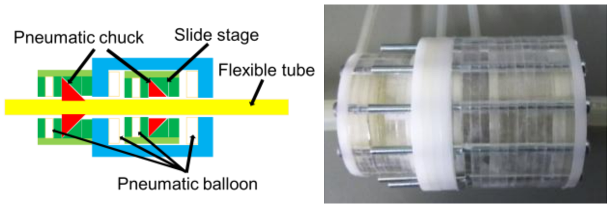


Figure 1. Schematic diagram of inner construction and view of balloon type flexible stepping actuator.

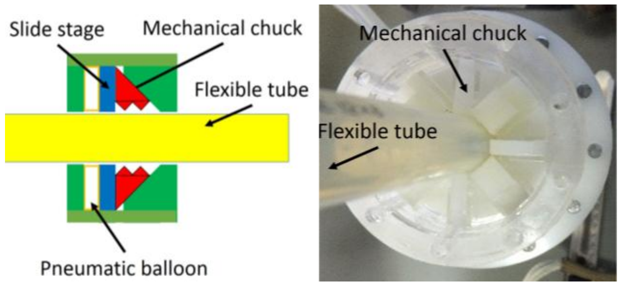


Figure 2. Schematic diagram of inner construction and view of pneumatic chuck using balloon and mechanical chucks.

The operation of the tested actuator is shown in Fig.3. The operating principle is as follows: First, as shown in Fig.3 (a), the both side chucks are driven in order to hold the tube. In the condition, the left side balloon is driven and the moving stage moves toward right as shown in Fig.3 (b). When the moving stage reaches at the right side wall by giving the input pressure, the chuck on the stage is activated to hold the tube as shown in Fig.3 (c). After that, while the left side balloon and left side chuck are released, the right side balloon is driven. The chuck on the moving stage keeps holding the tube, the flexible tube is pushed toward left as shown in Fig.3 (d). By repeating this procedure, the tube can move toward left every certain stroke. The actuator has the length of 102 mm and the outer diameter of 60 mm. The mass of the actuator without flexible tube (rod) is about 360 g. Its stroke is same as the width of the balloon chamber of 5 mm that same to about 5 mm/s of actuator's speed. From the experiment result of the generated force, it found that the maximum generated force was about 90 N even if the theoretical generated force of the balloon is about 140 N. However, the speed of the actuator is slow, that is 5 mm/s.

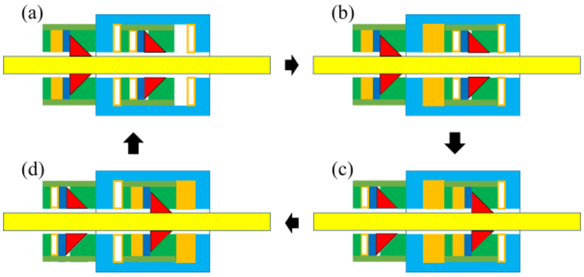


Figure 3. Operation of tested actuator.

B. *Cylinder Type Flexible Linear Stepping Actuator*

In order to increase the speed of the actuator, a cylinder type flexible linear stepping actuator was also proposed and tested [12]. As a method of speed up, typical pneumatic cylinders were used instead of pneumatic balloons as shown in Fig. 4. The actuator consists of six double acting type pneumatic cylinders (three of them have the stroke of 50 mm (Koganei Co., PBDA 16x50-M) and the others have the stroke of 5 mm (Koganei Co., PBDA 16x5-M)) and three pneumatic chucks. By using two moving stages with different strokes, the actuator can move faster every 50 mm and realize positioning with the resolution of 5 mm. The inner cylinder diameter of 16 mm is decided so that the generated force of three cylinders can be larger than the maximum holding force of the chuck, that is 90 N, when the supplied pressure of 500 kPa is applied. The ends of the six cylinders are connected with a base stage with the pneumatic chuck, they are set every 60 degrees with radius of 33 mm from the center of the base stage. The rod ends of each three cylinders are also connected with the moving stage with the pneumatic chuck. The improved actuator has a length of 133 mm and an outer diameter of 80 mm. The mass of the actuator is 0.7 kg.

The cylinder type actuator can also realize the positioning resolution of 5 mm by using shorter stroke cylinders. Both balloon and cylinder type actuators also have backdriability when the pneumatic chuck is not driven. However, the generated force of the actuator is same as the previous balloon type actuator. It can be confirmed that the generated force of the actuator depends on the gripping ability of the pneumatic chuck.

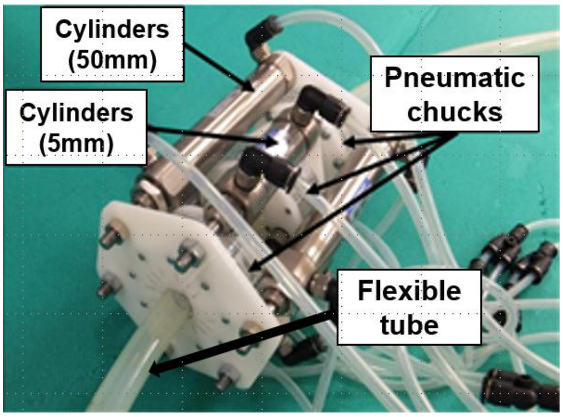


Figure 4. View of cylinder type linear flexible stepping actuator.

III. Ball Core Type Pneumatic Chuck

The maximum generated force of the tested both actuator was 90 N as described in chapter Ⅱ. However, the theoretical generated gripping force of the actuator calculated by the sectional area of the balloon for the chuck is 140 N. It means that slip occurs between the mechanical chuck and the surface of the flexible tube. The slip is caused by the deformation of the flexible tube. Generally, the tube is easy to deform toward the center of the tube because the tube has a hole in the center.

Therefore, by using a rigid solid rod instead of the flexible tube, the holding ability can be improved. However, it means that the flexibility of the actuator will be lost. In ideal, it is better to only use the solid rod at the point of gripping the tube. Therefore, a pneumatic chuck using the moving core is proposed and tested.

A. *Construction and Operating Principle*

At first, a steel ball was used as a moving core. Fig. 5 shows the schematic diagram of the inner construction and the view of the proposed pneumatic chuck using the ball core. It is called a "ball core type pneumatic chuck". The chuck consists of the steel ball, plastic plates with a hole, the doughnut-shaped balloon mentioned above, three short silicon tubes as a backup spring. Each short silicon tube has the outer diameter of 6 mm, the inner diameter of 2 mm and the length of 4 mm. The steel ball is inserted into the flexible tube with silicone grease. The steel ball and three silicone tubes are covered by a plastic cover with a hole.

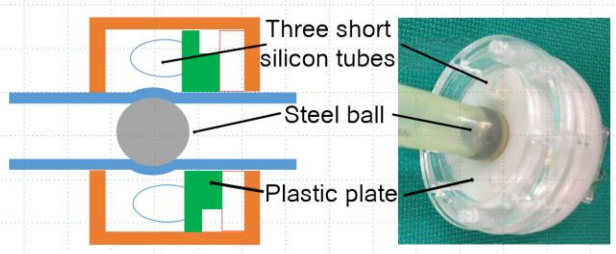


Figure 5. Schematic diagram of the inner construction and view of ball core type pneumatic chuck.

Fig. 6 shows the operating principle of the ball core type chuck. The operating principle of the chuck is as follows: First, as shown in Fig.6 (a), right side balloon is pressurized. Then, the balloon pushes the steel ball toward left through the plastic plate with a hole while deforming the tube. When the ball reaches at the left side wall, the ball is pushed and held from both sides by the left side wall and the plate. They work as a chuck. When the supplied pressure is released as shown in Fig.6 (b), three silicon tubes work as a backup spring and move the plastic plate toward the right side as shown in Fig.6 (c). Then, the ball is released. Under the condition that the chuck is released, the flexible tube can move while sliding the steel ball along inner wall of the tube. It means that the actuator has backdrivability while the chuck doesn't work.

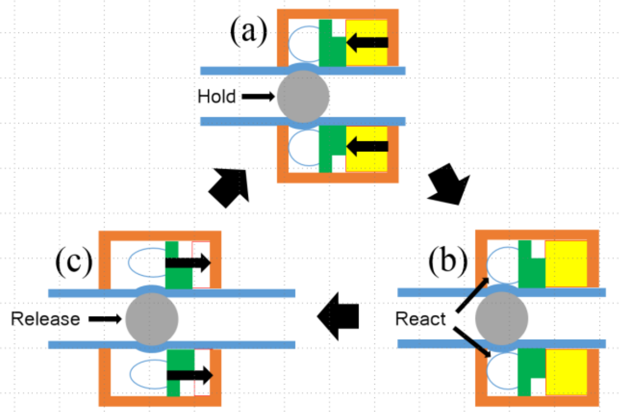


Figure 6. Operating principle of ball core type chuck.

B. *Friction and Holding Characteristics*

In the core type chuck, the frictional force when the chuck doesn't work is serious concern with the back-drivability of the actuator. In the ball core type chuck, the combination of the outer diameter of ball and the inner diameter on the plastic plate is related to the frictional force and holding ability of the chuck. Therefore, the frictional force and generated force of the linear stepping actuator using the various size of steel ball were investigated.

Fig. 7 shows the relationship between the inner diameter of hole on the plastic plate and the static frictional force of the chuck. Fig. 8 shows the relationship between the inner diameter of the plastic plate and the generated force of the actuator. In the experiment, steel balls with the outer diameter of 9.5 and 10.0 mm were used. As a flexible tube, a soft type polyurethane tube with the inner diameter of 9 mm and the outer diameter of 12 mm (SMC Co., TUS 1209N-20-X74) was used. In both figures, these measured results are obtained by taking the average of 20 trials with each steel ball. The blue and red lines show the result using the steel ball with the outer diameter of 9.5 and 10.0 mm, respectively. In addition, the experimental results when the ball removes from the chuck is excluded. The generated force of the cylinder type actuator with tested chucks is measured by using the force sensor (NIDEC-SHIMPO Co., FGPX-100). Then, the theoretical maximum generated force when the supplied pressure of 500 kPa is applied is 140 N.

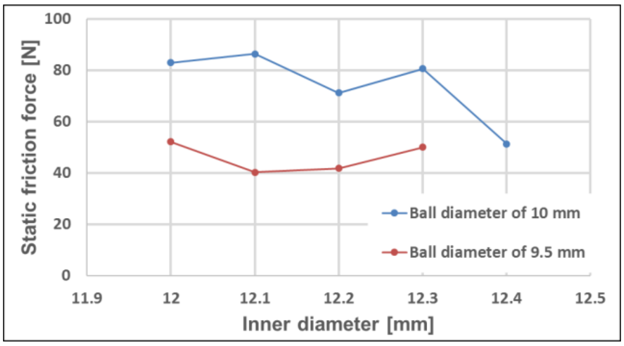


Figure 7. Relation between the inner diameter of the hole on the plate and the static frictional force of the chuck.

From Fig. 7, it can be seen that the frictional force of the ball core chuck is relatively large compared with the case using the previous one that is less than about 5 N. It seems that the case using smaller ball (9.5 mm) is superior to the case using lager ball (10 mm). However, from the results of the generated force as shown in Fig.8, the generated force of the actuator using smaller ball is lower than the case using previous one that is 90 N. From both figures, it can be found that the combination using steel ball with the outer diameter of 10 mm and the plate with the inner ball of 12.4 mm is optimal, because the chuck with this combination has both largest generated force and lower frictional force.

The maximum generated force using the optimal combination is about 120 N. Compared with theoretical holding force of 140 N, this value becomes small because of frictional force between ball and tube. It is also superior to the previous one. However, in some case, it is found that once the chuck is driven, the steel ball does not return to the initial position and it continues to work as a chuck. It means that the backdrivability of the actuator is lost. In addition, the tested chuck has relatively large static frictional force that is more than 50 N. As a result, it can be concluded that the ball core type chuck is not suitable to use the flexible actuator with backdriavility. Therefore, it is necessary to consider another type of pneumatic chuck.

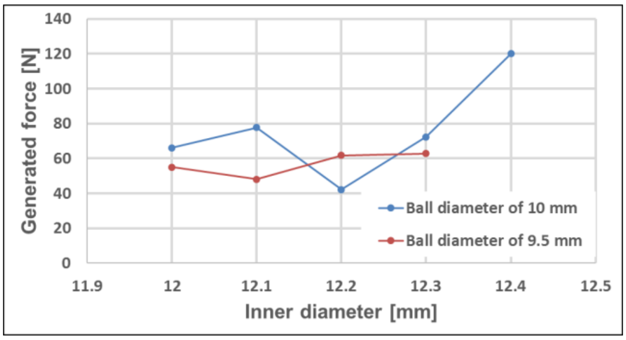


Figure 8. Relation between the inner diameter of the hole on the plate and the generated force of the actuator.

IV. MAGNETIC CORE TYPE PNEUMATIC CHUCK

In the case using the ball core type chuck, the larger friction is occurred by using larger outer diameter of the ball than the inner diameter of the flexible tube in order to move the ball according to the movement of the chuck. If the core can move according to the chuck without contact, the frictional force when the chuck doesn't work can be reduced. Based on this concept, a core using permanent magnets is proposed and tested.

A. Construction and Operating Principle

Fig. 9 shows the view and the schematic diagram of the new developed chuck mechanism. It is called a "magnetic core type pneumatic chuck". The chuck consists of two kinds of neodymium ring-shaped magnets, a flexible tube as a rod, I-shaped cylindrical plastic core and elements of the previous pneumatic chuck using the balloon and mechanical chucks as shown in Fig. 2. The mechanism of the mechanical chuck and the balloon is almost same as the previous one. Compared with the previous one, two claws are used in the mechanical chuck. Each claw has a slope with angle of 45 degrees on the surface contacted with the pushing plate. The pushing plate on the balloon also has slope in order to push the claws.

The I-shaped cylindrical plastic core consists of plastic disks with a hole and the ring-shaped neodymium magnet with the outer diameter of 8.5 mm and the inner diameter of 5.5 mm (surface magnetic flux density of 375 mT). They are penetrated by a screw and a nut. In the mechanical chuck, the ring-shaped neodymium magnet with the outer diameter of 20 mm and the inner diameter of 12 mm (surface magnetic flux density of 332 mT) is inserted into the chuck so that the flexible tube can pass through the inner bore of the magnet.

Fig. 10 shows the operating principle of the magnetic core type pneumatic chuck. The operating principle of the tested chuck is as follows. The inner core with the magnet can move along to the inner wall of the flexible tube freely. By attracting both magnets in the chuck and the core each other, the cylindrical core can automatically track the movement of the chuck. When the supplied pressure is applied to the balloon, the balloon pushes two claws through the pushing plate. At the same time, these claws push the flexible tube toward the center of the tube at the point of gap on the core. By clamping the tube from both inner and outer sides of the tube, the chuck can hold the tube surely.

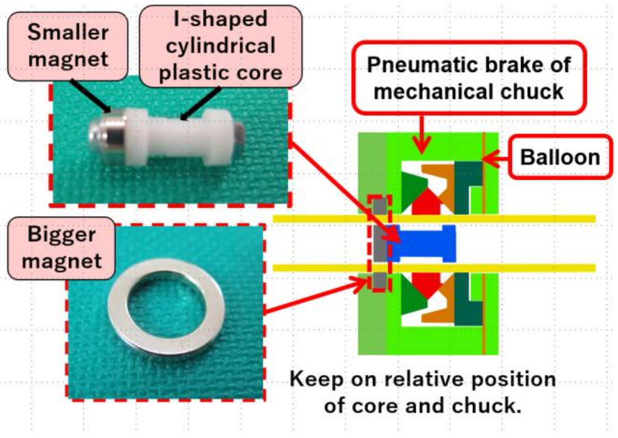
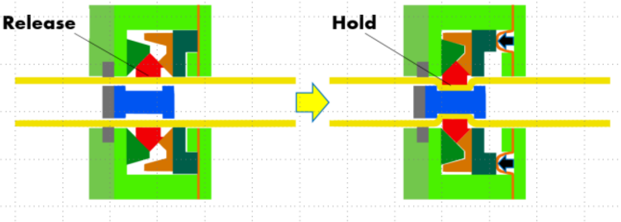


Figure 9. Schematic diagram of inner construction and view of magnetic core type chuck.



(a) Releasing

(b) Holding

Figure 10. Operating principle of magnetic core type chuck.

B. *Friction and Holding Characteristics*

The frictional force of the magnetic core type chuck with no supply pressure is investigated by pulling the tube with a force sensor (NIDEC-SHIMPO Co., FGPX-100). As a result of 20 times measurements, the average frictional force of 11.4 N can be obtained. The value is much smaller than that using ball core type chuck.

Fig. 11 shows the experimental setup to measure the generated force of the actuator. The experimental setup consists of the cylinder type flexible linear stepping actuator with cylinder stroke of 100 mm, the tested chuck, a flexible tube as a rod and the force sensor. The measurement of the generated force is carried out as follows. First, the tested chuck is driven and holds the tube. After that, three cylinders in the actuator are driven. While the flexible tube connected to the force sensor is pulling, the generated pulling force is measured by the force sensor.

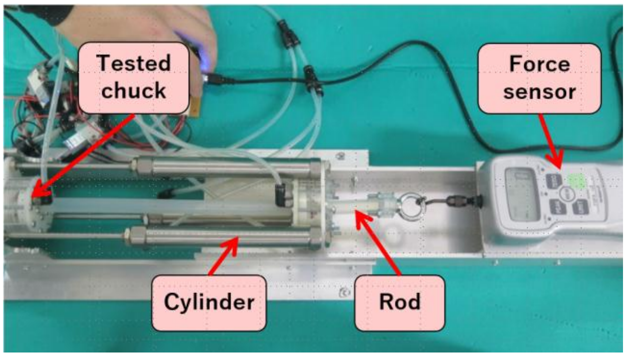


Figure 11. Experimental setup for measuring the generated force of the actuator.

Fig. 12 shows the transient response of the generated force by measuring through the force sensor. From Fig.12, it can be seen that the generated force reaches at 260 N. This value is almost same as the theoretical value calculated by the supplied pressure of 500 kPa and amount of sectional area of three pneumatic cylinders, that is about 270 N. It seems that the difference between the measured and theoretical generated force of the actuator is due to the elastic deformation of the flexible tube. As a result, it can be confirmed that the tested chuck can generate holding force of more than 260 N even if the sliding friction without working the chuck is about 10 N.

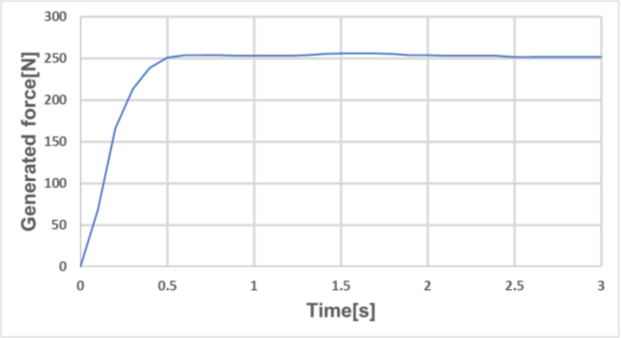


Figure 12. Transient response of generated force when the actuator is driven.

V. CONCLUSIONS

In order to increase the generated force of the flexible linear stepping actuator, the novel pneumatic chucks using two types of cores were proposed and tested. One is a "ball core type pneumatic chuck" that the pneumatic balloon holds the steel ball installed into the flexible tube from both sides of the ball. The construction and the operating principle of the chuck was described. The frictional and generated force of the actuator using tested chuck were investigated. As a result, the generated force of 120 N can be obtained by using the steel ball with the outer diameter of 10 mm and the pushing plate with the inner bore of 12.4 mm.

The other is a "magnetic core type pneumatic chuck" using the mechanical chuck driven by the balloon and the moving core with neodymium magnet. It can be confirmed that the cylindrical core can automatically track the movement of the chuck by using the ring-shaped magnet in the chuck. As a result, it can be confirmed that the tested chuck can generate holding force of more than 260 N even if the sliding friction of the chuck is small, that is about 10 N.

As a future work, the flexible linear stepping actuator with the magnetic core type chucks is going to be applied to rehabilitation devices or robots because of its larger generated force, wider moving area and backdrivability.

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