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Development of Encountered-type Haptic Interface that can Independently Control Volume and Rigidity of 3D Virtual Object

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Abstract

This paper describes the development of an encountered-type haptic interface that can independently present the physical characteristics of 3D virtual objects, such as shape and rigidity, in the real world. This interface consists of nonexpandable balloons, syringe pumps, pressure sensors, linear actuators, and a PC. To change the rigidity of the balloon, the volume of air in the balloon is controlled by using a linear actuator and a pressure sensor based on Hooke's law. Furthermore, to change the volume of the balloon, the exposed surface area of the balloon is controlled by using another linear actuator with a trumpet-shaped tube. Performance tests of the system were conducted, and the effectiveness of the proposed interface was verified.

Categories and Subject Descriptors (according to ACM CCS): H.5.1 [INFORMATION INTERFACES AND PRESENTATION]: Multimedia Information Systems—Artificial, augmented, and virtual reality

1. Introduction

Various haptic interfaces that can generate a reaction force from virtual objects to the user's body have been developed. These can present the arbitrary characteristics of a virtual object, such as shape, rigidity, weight, and texture. Such interfaces can be applied to exploration and object manipulation in a virtual environment, 3D shape modeling, art and entertainment, and training applications such as a surgery simulator.

A haptic interface can be classified into three types: exoskeleton type, tool-mediated type, and encountered type. An exoskeleton-type haptic interface can present a haptic sensation to the attached part of a user's body by using mechanical linkages. However, it can only be used in large spaces with less spatial constraints; furthermore, such an interface must be calibrated to fit the size of a user's body, and detaching it from the user is cumbersome. A tool-mediated-type interface can present a relatively more accurate haptic sensation because it is fixed on the ground. However, as the user touches virtual objects through a tool that is attached to the end effector of the interface, the virtual objects cannot be touched with the bare hand. An encountered-type interface presents a virtual object through the deformation of the interface itself; therefore, users can operate virtual objects instinctively using their bare hands. However, such interfaces tend to require complicated hardware and software. The encountered-type interface is suitable as a clay-modeling tool that users can use with their bare hands or as a medical training simulator in which users can touch virtual organs directly as in an actual surgery. However, to the best of the authors' knowledge, no encountered-type interfaces have been investigated for such applications. In this study, we focus on an encountered-type haptic interface.

An encountered-type haptic interface can be classified into three types: a manipulator-type display, an uneven surface display, and a 3D shape display. The manipulator-type display can present a contact sensation with a virtual object to a user's fingertip by moving the end effector of the manipulator. The end effector presents the proximal surface of the contact area of virtual objects and the user's hand [YMS*04] [HT98]. However, it is difficult for a user to touch an arbitrary-shaped virtual object with the user's entire palm. FEELEX1 [IYN01] and inFORM [FLO*13] are examples of uneven surface displays. Both consist of linear actuator arrays. By changing the length of each linear actuator, an uneven surface can be presented at the top of the array. A haptic jamming display has been developed [SGO13] [SO15]. It consists of many individual silicone cells. Each cell contains a granular material, and the vacuum line of each cell makes the cell rigid by jamming the particles inside. Each cell position is controlled by using a solenoid and a node-pinning cable.

They can display uneven surfaces with a rigidity distribution to represent the surfaces of virtual objects. However, they cannot display the 3D shape of virtual objects, especially those that have a narrow center.

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VolFlex+ [EYI07], a 3D shape display, has been developed to increase the expressive ability of an encountered-type haptic interface. It consists of 10 computer-controlled movable rubber balloons. It can present the 3D shape of a virtual object in the real world by changing the position and volume of each balloon. It can also realize a 3D object that has a narrow area in the middle. However, as each balloon is made of rubber, the rigidity of each balloon cannot be controlled. The individual control of the volume and the rigidity of each balloon remains an unresolved issue in a 3D shape display.

In this study, a novel structure for controlling the volume and rigidity of a balloon is proposed. This structure can individually control the balloon's volume and exposed surface area. To change the rigidity of the balloon, the volume of air in the balloon is controlled by using a linear actuator and a pressure sensor based on Hooke's law. Furthermore, to change the volume of the balloon, the exposed surface area of the balloon is controlled by using another linear actuator with a trumpet-shaped tube. A prototype balloon unit was developed. Through some performance evaluation tests, the effectiveness of the proposed method was verified..

2. Basic Principle of Independent Control of Volume and Rigidity

In this study, an encountered-type haptic interface is proposed. This interface can present the physical characteristics of a 3D virtual object, such as the volume and rigidity, by independently controlling the volume and rigidity of a balloon. As applications of this system, the presentation of a virtual liver for a surgery simulator and a virtual clay were considered. For example, this system can present a tumor of any size and rigidity in the liver by integrating the balloon into a gel mock-up model of the liver. As a first step in this study, a new method to independently control the volume and rigidity of one balloon is proposed.

2.1 Control Method for Rigidity of Balloon

Basically, the rigidity of a balloon is controlled by changing its internal air pressure by controlling the position of the piston in a cylinder that is connected to the balloon. If the balloon is made of a stretchable material such as gum, the greater the inside air pressure, the larger is the volume. However, this is undesirable because the purpose of this system is to present any rigidity at any volume independently. Therefore, we solved this problem by using a nonexpandable material such as polyethylene to produce the balloon. The position of the piston is proportional to the internal pressure of the balloon based on Hooke's law, as shown in Fig. 1. Furthermore, it is possible to change the rigidity interactively by changing the volume of the inner air based on deformation information such as the inner pressure measured using a pressure sensor.

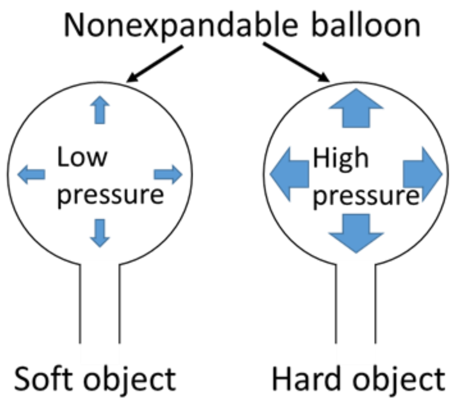

Figure 1: Basic principle of rigidity modification

2.2 Control Method for Volume of Balloon

As the balloon is made of a nonexpandable material, it is impossible to control its volume by simply changing the amount of air in it. As shown in Fig. 2, a method to change the exposed surface area of the nonexpandable balloon by sliding the balloon in a trumpet-shaped tube is proposed. When the balloon is almost inside the tube, the exposed surface area is small. Therefore, the exposed balloon is small in volume. On the other hand, when the balloon emerges into free space from the tube, the exposed balloon is large in volume. In this regard, the trumpet-shaped mouth of the tube enables the balloon to be taken in and out from the tube smoothly.

As mentioned above, by combining the control methods for the rigidity and volume of the balloon, the volume and rigidity can be changed independently.

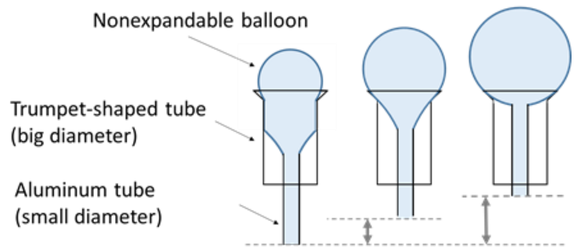

Figure 2: Basic principle of volume modification

3. Development of Prototype System of Balloon

3.1 System Configuration

The prototype system for controlling the volume and rigidity of a balloon consists of the main body of an encountered-type haptic interface, a control board, and a PC (Fig. 3).

The encountered-type haptic interface (for one balloon), as shown in Fig. 4, comprises the rigidity control part and the volume control part. In Fig. 4, linear actuator 1 is used to control the volume of the balloon, and linear actuator 2 is used to control the rigidity of the balloon. These linear actuators (ELCM2F10K, Oriental Motor Co. Ltd.) have a stroke of 100 mm with 0.01 mm accuracy.

The Device Art Toolkit [ESY*10] is used for the input and output of data to the PC. This toolkit was developed in our laboratory, and it can realize various functions for sensing and actuating various gadgets using a group of module-type electronic circuit boards.

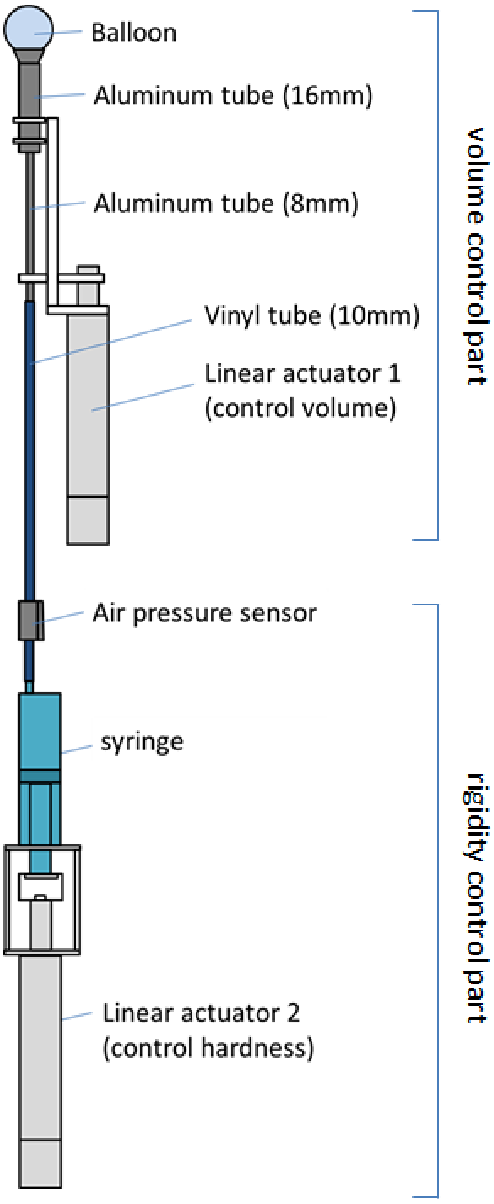

Figure 4: Mechanical configuration (for one balloon)

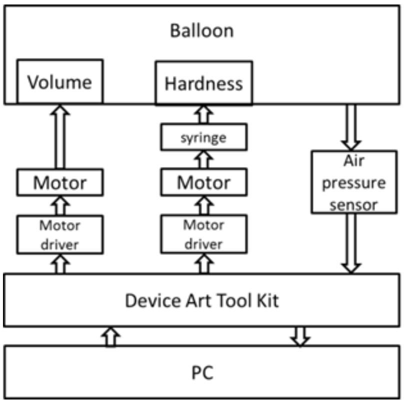

Figure 3: System configuration

3.2 Rigidity Control Unit

As shown in Fig. 5, a nonexpandable balloon is connected to a syringe pump with an air tube. Linear actuator 2, shown in Fig. 4, is attached to the syringe pump to control the position of the piston. The rigidity of the balloon can change as the inner pressure of the balloon can be controlled by the position of the piston of the syringe using the linear actuator. Furthermore, an air pressure sensor (PPE-P01A-H6, CKD) is connected between the balloon and the syringe to detect changes in the inner pressure of the balloon.

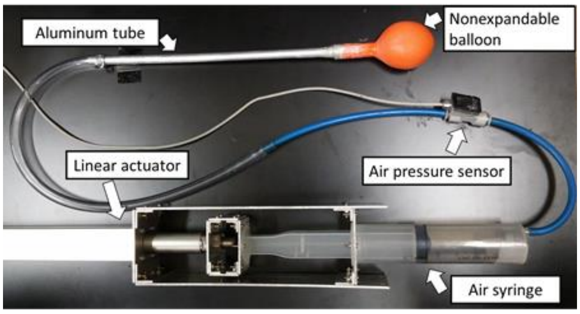

Figure 5: Rigidity control unit

To produce the nonexpandable balloon, a 0.015-mm-thick polyethylene film was attached to the aluminum pipe, as shown in the left-hand side of Fig. 6. To make the spherical surface of the balloon as smooth as possible, the polyethylene balloon was covered with a rubber balloon, as shown in the right-hand side of Fig. 6. The inner diameter of the syringe is 29 mm, and therefore, the volume of the air inside the balloon can be changed by at most 6.605 mm3. Furthermore, as the stroke of the linear actuator is 100 mm and its maximum speed is 150 mm/s, it is possible to vary at most 66.05 cm3 at a rate of 99.08 cm3/s. As a result, the balloon can be expanded from its minimum to its maximum volume in 0.73 s.

Figure 6: Balloon structure (left: inner bag made of polyethylene, right: rubber balloon used as outer bag)

3.3 Volume Control Unit

Linear actuator 1, shown in Fig. 4, controls the exposed surface area of the balloon by moving the balloon relative to the trumpet-shaped tube (Fig. 7). The trumpet-shaped tube consists of a funnel with 16-mm diameter and 125-mm height. The aluminum tube has 8-mm diameter and 255-mm height. However, the friction between the tube and the balloon is increased owing to the use of the rubber balloon. This makes the relative movement between them difficult. Therefore, the balloon is sprayed with a powdered lubricant to realize smooth relative movement between the tube and the balloon.

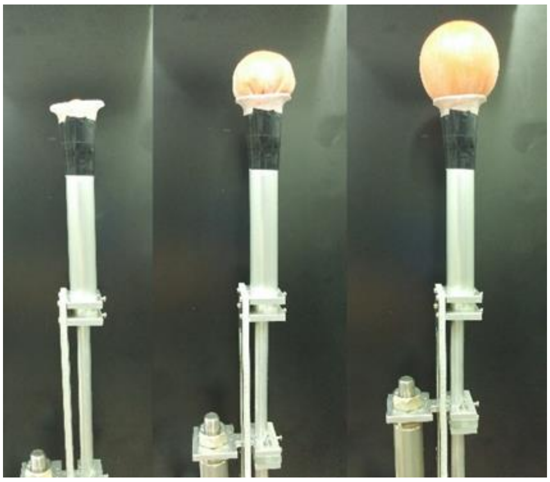

Figure 7: Volume control unit

4. Presentation Evaluation Tests

In this study, we develop a new deformation mechanism for a balloon that allows the volume and rigidity of the balloon to be changed individually. The alternative ranges of the volume and rigidity of the balloon are summarized below.

4.1 Performance of Rigidity Change Ability

4.1.1 Presented Range of Rigidity

As the first step in the evaluation of the basic characteristics, the internal pressure characteristics of the balloon were measured. The piston was pushed in increments of 5 mm for diameters of 10, 20, 30, and 40 mm. Because the air is a compressive fluid, a lookup table that defines the relationship between the position of the piston and the diameter of the balloon was required in order to control the diameter.

With regard to measuring the volume of the balloon, as the balloon did not become a complete sphere, its width changed depending on the measurement location. As only a part of the balloon was exposed, the diameter of the balloon was measured from the top of the trumpet-shaped tube to the top of the balloon, as shown in Fig. 8. A force gauge attached to a linear actuator was used to measure the diameter. First, the gauge was lowered by 0.1 mm from the mid-air position of the balloon. When the force value of the gauge was changed, indicating that the gauge touched the balloon, the height was measured. Furthermore, in advance, the height of the force gauge was measured when it was lowered to the tip of the trumpet-shaped tube. The difference between these two heights was used as the value of the diameter of the balloon. The relationship between the position of the piston and the inner pressure of the balloon was measured as shown in Fig. 9. From this data, the lookup table was prepared and used in following experiments.

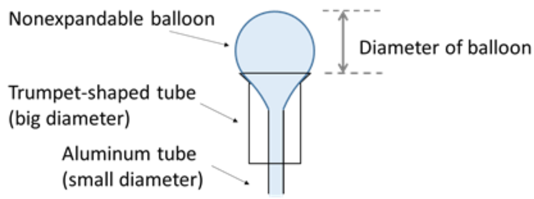

Figure 8: Method for measuring diameter of balloon

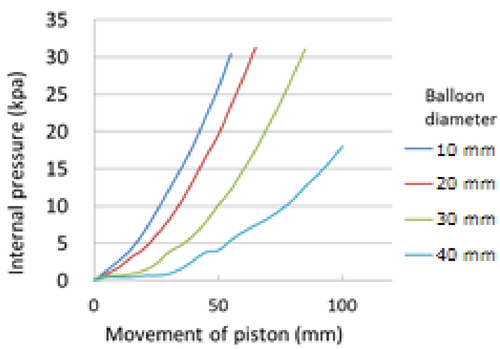

Figure 9: Internal pressure characteristics of balloon

As the plastic deformation of the polyethylene film of the balloon occurs when the internal pressure of the balloon is more than 35 kPa, the range of the internal pressure of the balloon is set from 0 to 30 kPa. Furthermore, because the system uses a piston for adjusting the volume of the inner air, the volume control ability is limited. The larger the diameter of the balloon, the smaller is its maximum internal pressure. Considering our target applications such as a surgery simulator and a virtual clay, the rigidity of a human liver is about 5 kPa and a paper cray is about 14 kPa (Fig.10 and 11). These values were measured with a real gel model of a liver and a real paper cray by using the force gauge and the actuator that described above. Moreover, the relationship between the indentation and the reaction force of the balloon in each condition were plotted in Fig.10 and 11. Therefore, our system has a sufficient rigidity range for the target applications.

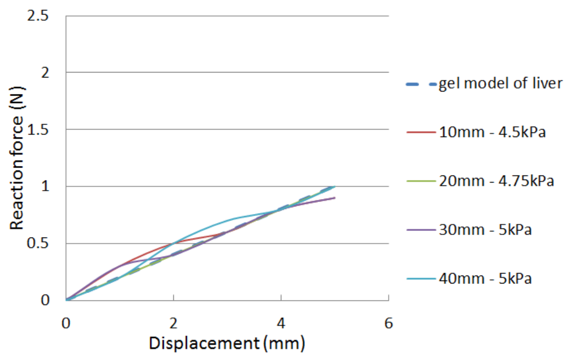

Figure 10: Relationship between indentation and reaction force of a gel model of a liver

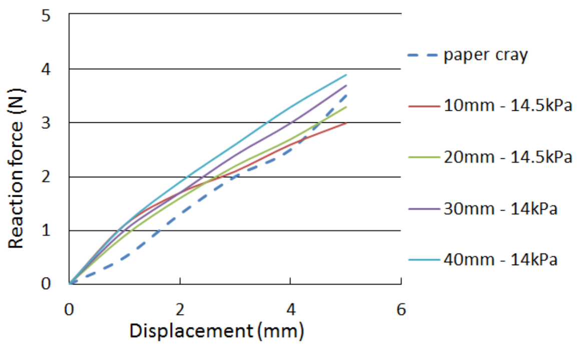

Figure 11: Relationship between indentation and reaction force of a real paper cray

4.1.2 Relationship between Rigidity and Reaction Force

To evaluate the actual rigidity change with the system, the reaction force applied from the balloon to the fingertip-like probe of a force sensor was measured at intervals of 1 cm on the probe. The relationship between the indentation of the probe and the reaction force on the probe is shown in Fig. 12. The diameters of the balloon were 10, 20, 30, and 40 mm. From these results, it is confirmed that the system could control the reaction force to the user's fingertips by controlling the internal pressure of the balloon. A proportional relationship between the indentation and the reaction force is found in the system.

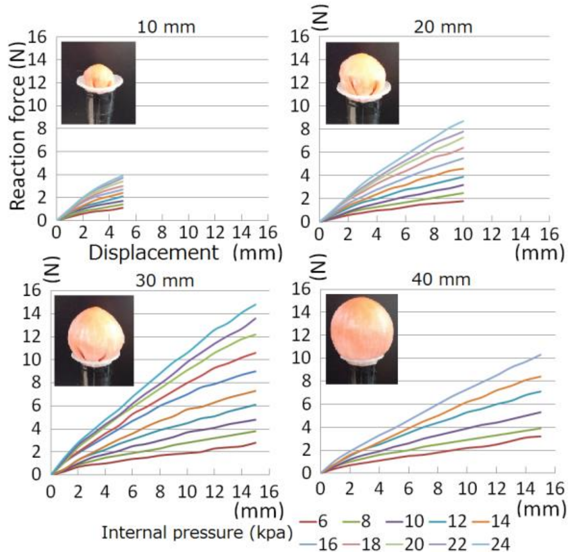

Figure 12: Relationship between indentation and reaction force of the balloon

The actual state of touching the balloon is shown in Fig. 13. First, a target state of the internal pressure of the balloon was set, and the position of the piston was controlled so that the internal pressure did not change from the initial state. At this time, the lower the internal pressure, the larger was the indentation to the balloon (left-hand side of Fig. 13), and the higher the internal pressure, the smaller was the indentation to the balloon (right-hand side of Fig. 13).

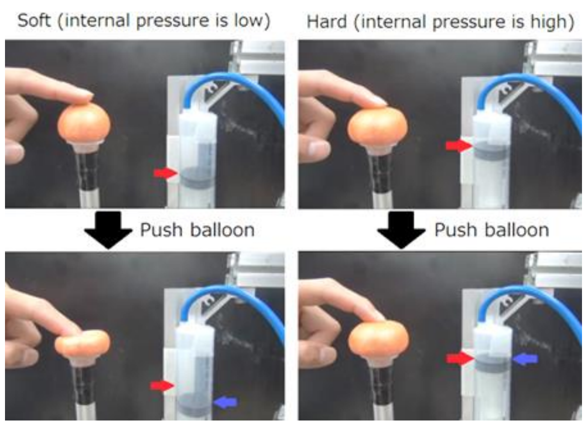

Figure 13: Modification of rigidity of balloon

4.2 Performance of Volume Change Ability

The relationship between the movement of the linear actuator, which was connected to the trumpet-shaped tube, and the size of the balloon was measured (Fig. 14). The volume of the balloon was measured while changing the position of the rod of the linear actuator in intervals of 5 mm. The internal pressure was fixed at 10 kPa.

In addition, with regard to the basic characteristic of the outer rubber balloon, it becomes necessary to inflate the rubber balloon itself as the diameter of the balloon increases. To maintain the spherical shape of the balloon, the internal pressure of the balloon must be at least 5 kPa at a balloon diameter of 40 mm.

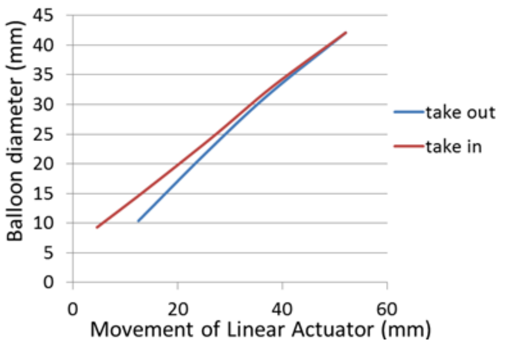

Figure 14: Relationship between movement of linear actuator and balloon diameter

Furthermore, a hysteresis behavior between the movement of the linear actuator and the volume of the balloon was found when the balloon was taken in and out of the tube. The speed of the increase in the balloon diameter by the linear actuator when the balloon was taken in the tube was smaller than that when the balloon was taken out of the tube. Therefore, it is necessary to consider the characteristic of the hysteresis of the volume change speed in practical applications.

In consideration of the range of the volume of the balloon, the diameter of the tumor is used to evaluate the progress of liver cancer. Medical doctors examine tumors with diameters exceeding 20 mm [CN]. As the maximum balloon diameter in our system was 40 mm, this system has sufficient ability to present the shape of a tumor in the liver.

4.3 Simultaneous Change in Volume and Rigidity

In this section, the characteristics of the balloon with regard to the simultaneous change of the volume and rigidity were evaluated. Four tasks of changes in volume and rigidity were selected. Each initial and target condition of the diameter and rigidity of the balloon was set as shown in Table 1. The diameter and internal pressure were measured during the change. In this experiment, the diameter of the balloon, which is the relative position of the top surface from the lowest height of the surface, as shown in Fig. 8, was measured using a laser range finder (LG-500, Keyence) in real time.

Table 1: Initial and target conditions of balloon in each task

	<Initial condition>			<Target condition>	
	Balloon diameter (mm)	Internal pressure (kpa)		Balloon diameter (mm)	Internal pressure (kpa)
task1	20	10	→	40	15
task2	20	15	→	40	10
task3	40	10	→	20	15
task4	40	15	→	20	10

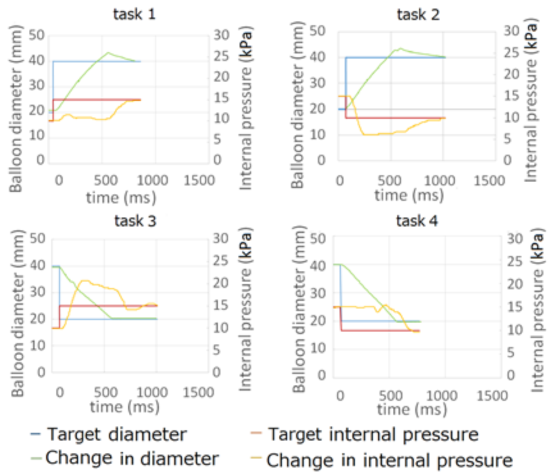

Figure 15: Time series variations of volume and rigidity of balloon

As shown in Fig. 15, the change in volume and rigidity could be controlled simultaneously within 1 s. Separating the time taken to change the volume and rigidity of the balloon indicates that the volume change is completed in 0.5 s and the rigidity change, even within 0.5 s. In each situation, the diameter of the balloon was changed first. Then, the internal pressure was allowed to reach the target pressure as it was determined by the volume of the inner air and diameter of the balloon. In addition, the pressure was feedback-controlled by using a pressure sensor value, whereas the diameter was controlled by simply moving the tube to the target position. As shown in the bottom left of Fig. 15, in the task, when the diameter of the balloon was decreased, the internal pressure of the balloon was increased. As the speed of the change in diameter was too fast and the internal pressure was not controlled in time, there was a section in which the internal pressure rose more than necessary. In the future, it is therefore necessary to improve the control method.

5. Discussion

By fabricating one balloon in the system and conducting the performance tests, it is confirmed that it is possible to present the volume and rigidity of the balloon independently. In the current system, changing the volume and rigidity of the balloon took 1 s owing to the performance of the linear actuator. Furthermore, the presentation range of the rigidity of the balloon is strongly dependent on the stroke of the actuator. Though the conditions required for our target applications are satisfied, this system has room for improved performance to realize other applications that require a wider presentation range and more flexibility.

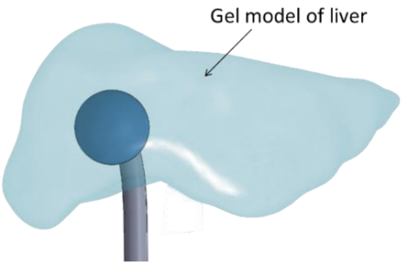

Figure 16: Example of liver tumor by using our technique

As an application of a surgical training system, one possible implementation is shown in Fig. 16. A balloon that represents a tumor is placed in the gel model of a liver. A user can touch the gel model and feel the rigidity of the liver. By changing the volume and rigidity of the tumor, medical students can experience the characteristics of a real liver with their bare hand. To realize this system, we conducted a feasibility performance evaluation test with a medical doctor specialized in gastroenterological surgery. Four rigidities of the balloon were presented under four conditions in consideration of the progress of human liver cancer. The doctor touched the balloon under each condition and reported that the rigidities of the balloon were similar to those of a real liver. This result suggested that the proposed system could be applied to the training of medical students.

In addition, by using an array of our proposed balloon system in a manner similar to VolFlex+, the expression ability of the system would be increased. However, if the system were to consist of multiple balloons, it would become difficult to increase the density of the balloons because the actuators would interfere with each other. To present a 3D shape more effectively, more flexibility, such as a position change function, is required. We plan to use nine units to constitute the presentation part. By doing so, it would become possible to place the balloons in a body-centered cubic lattice-like formation, which is rotated by 90° in the upper layer (left-hand side of Fig. 17). This structure could be used to present various object shapes by changing the volume and the vertical and horizontal position of the balloons (right-hand side of Fig. 17).

The balloons produced using the proposed system are covered with a gel sheet to simulate the surface of the liver, and it is considered that applications such as the shape and rigidity of the entire liver can be realized (Fig. 18).

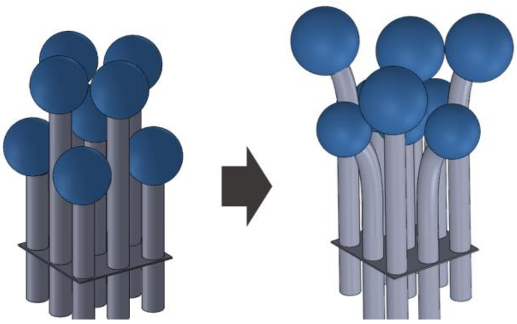

Figure 17: Example of position and volume modification of balloon array

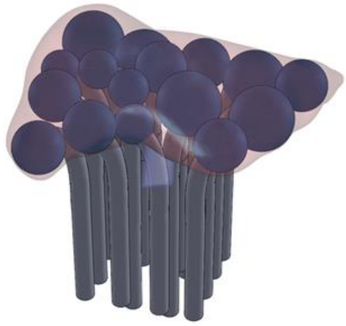

Figure 18: Example of a virtual liver by using our technique

As a method for improving the shape representation capability, visual information could be projected onto a film covering the entire balloon. Visual information plays a very important role along with tactile information in the recognition of objects. Therefore, for each object, it is effective to present visual information in consideration of the shape change.

Furthermore, it is necessary to develop an algorithm using which the system can immediately determine the size and position of each balloon to create a 3D representation of any 3D shape input.

6. Conclusion

In this study, we proposed a mechanism for an encountered-type haptic interface that can individually represent any rigidity and volume of a balloon. Through performance tests, the usefulness of the mechanism was confirmed by elucidating the relationship between the movement of the linear actuator and the size of the balloon in the prototype system.

In future works, we plan to develop a mechanism for controlling the position of the balloon. By duplicating the mechanism and combining them, an encountered-type haptic interface will be developed. This can be applied to 3D shape design, medical training, and so on.

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