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Development of a peristaltic flexible transfer system for transporting feces under microgravity: Construction and validation of transport models

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Abstract— **In this study, we propose a peristaltic flexible transfer system for transferring feces in a free piping route. Currently, human feces is incinerated and disposed in space, such as on the International Space Station. As feces contain a large amount of reusable organic matter and water, the ability to recycle feces will improve the performance of manned space technology. However, existing space toilets are not designed to reuse feces, and the transportation of feces from the toilet bowl to the collection area is a technical challenge. A method for transporting intermittent supplies such as feces with less energy and water consumption is required. In a previous study, a peristaltic transfer system was developed based on the peristalsis of the intestinal tract of living organisms. In this method, multiple pump units driven by low air pressure generate peristaltic motion, which enables horizontal, vertical, and curved transfer of simulated feces. However, because the frame of each unit is rigid, the transport path cannot be changed flexibly, and the design must be adapted to the installation location. Therefore, the frame must be flexible.**

We propose a peristaltic flexible transfer system for transferring feces in a free piping route. First, we construct a simple model of content transfer using the peristaltic flexible transfer system and calculate the transfer rate based on data obtained from basic characteristic experiments of a single unit. Then, we conduct an actual content transfer experiment using the transfer system and compare the results with the simplified model results.

I. INTRODUCTION

In recent years, long-duration stays in space have been required for effective space utilization [1] and lunar and Martian exploration [2-3]. For many years, environmental control life-support technologies, such as oxygen and drinking-water supply [4] and waste disposal [5], have been studied to enable astronauts to stay in space for a long time. For example, a manned round-trip mission to Mars is estimated to take approximately three years [6]. As replenishing supplies is difficult, a regenerative Environmental Control and Life Support System (ECLSS) is required [7]. The ECLSS regenerates air and water from carbon dioxide, feces, and food waste. The International Space Station (ISS) is currently implementing urine reuse. Urine is transported to a condensate reclaimer through air suction and transformed to water [8]. However, the reuse of feces has not yet been realized. As feces contain reusable organic matter in addition to water, these are expected to improve the performance of the ECLSS if reused. Feces need to be collected and transferred to condensate reclamation [9] and oxygen production systems to achieve reuse. However, in contrast to urine, feces have properties similar to those of highly viscous fluids and cannot be efficiently transported through air. In addition, transporting and collecting feces with a large amount of water using gravity are difficult, as is the case with ground-based toilets, because feces are transported in a microgravity environment. Currently, the ISS uses a toilet that has a fan to suck feces into a bag with the help of air flow [8]. Although this method can collect feces under microgravity, the transfer distance is relatively short, and the feces are not reused; feces are sealed in a bag and must be removed from the bag for reuse. As previously mentioned, the transfer of feces is a technical challenge for the reuse of feces.

Several problems occur when existing methods for transporting highly viscous fluids are directly applied to space applications. For example, although a Mohno pump [10] and screw pump [11] can transport highly viscous fluids and solid-liquid mixtures, they are large and heavy owing to the mechanism of rotating a spiral-shaped rigid rod, and creating a layout other than a straight line is difficult. A tube pump [12] has been proposed; however, it must be filled with an incompressible fluid and consumes a large amount of water to transport feces. These pumps are capable of stable transport when the material to be transported is supplied continuously; however, transporting an intermittent supply such as feces is difficult. Studies have been conducted on the use of toilets in space; however, the reuse of feces has not been considered [13-14].

Therefore, we focused on the peristaltic movement of the intestinal tract as a method of transporting feces [15]. The intestinal wall muscles contract and relax to transmit opening

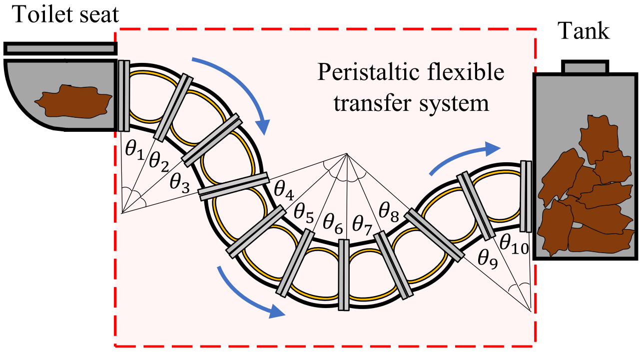

Figure 1. Concept of peristaltic flexible transfer system.

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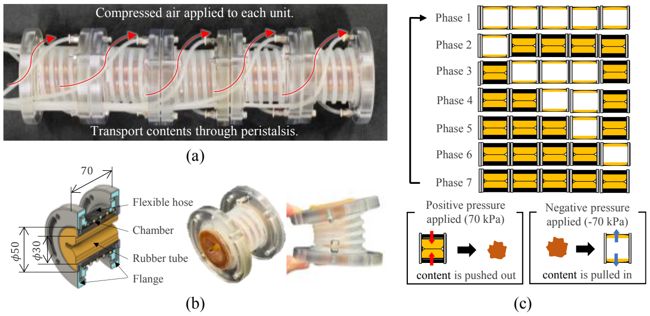


Figure 2. (a) Peristaltic flexible transfer system. (b) Cross-sectional view of a single unit of the peristaltic flexible transfer system and its appearance when bent. (c) Example of drive pattern of the peristaltic flexible transfer system when five units are connected

and closing movements in the direction of transport, and the bolus is transported. In previous studies, various fluids, such as powders [16], highly viscous fluids [17], solid-liquid mixtures [18], and sediments [19], were successfully transported using peristaltic pumps based on the peristalsis of biological intestinal tracts. Therefore, we developed a peristaltic transfer system based on the peristalsis of the intestinal tract of living organisms to transfer feces in a microgravity environment [20]. The system consists of multiple pump units driven by low air pressure. The chambers of each unit are supplied with air pressure to control the pumps to close and release, thereby reproducing peristalsis. This method has been used to transfer the average volume of human feces horizontally and vertically through curved tubes [21]. Both transfer rates are expected to be 80 % or higher. The system consists of independent units; therefore, when the device malfunctions owing to wear of the rubber tube or when the housing is damaged, only the unit in question needs to be replaced for easy repair. The system also has the advantages of high safety and low impact on the contents, because it is driven by low air pressure. However, as the frame of each unit is rigid, the system must be designed to match the installation location. For example, for a transfer route with a curved pipe, units of appropriate shape and size must be fabricated. In addition, responding flexibly to sudden changes in the transfer route is not possible. Therefore, the frame must be flexible.

In this study, we propose a peristaltic flexible transfer system for transferring feces through free piping routes. Fig. 1 displays the concept of the proposed system. Because the system can freely bend pipes, it can be connected to a toilet bowl, waste collection tank, and reclamation system, regardless of the installation location or space, and can flexibly transfer content. We construct a simple model for content transfer using a peristaltic flexible transfer system and calculate the transfer rate based on data obtained from basic characteristic experiments of a single unit. We also conduct experiments using the transfer system and compare the results with the simplified model results. The main contributions of this study are as follows:

- We proposed and developed a peristaltic flexible transfer system that can transfer contents in a free piping route. Unlike existing methods, the flexible transfer system can freely bend pipes and flexibly transfer contents.
- A simple content transfer model using a flexible transfer system was constructed. This model enables the prediction of the actual transfer rate from theoretical values and allows for the theoretical design of the transfer system arrangement and transfer planning.

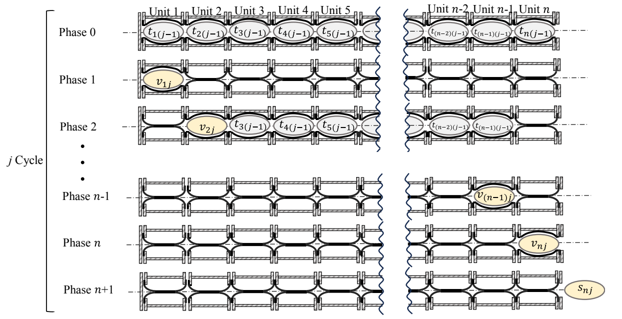


Figure 3. Approximate model of peristaltic flexible transfer system at cycle j when n units are connected.

II. Design of Peristaltic Flexible transfer system

A. Peristalsis of the Intestinal Tract of an Organism

The intestinal tract of an organism comprises two types of muscles: circular and longitudinal. These two muscle types contract and relax while the bolus is transported. This is known as peristaltic movement. The bolus is transported as follows.

1. The intestinal tract senses stimulation through contact with bolus.
2. The annulus muscle contracts upon sensing a stimulus and pushes out the bolus.
3. After the contraction, the annulus relaxes and returns to its original state.

This movement is repeatedly propagated to transport the bolus.

B. Peristaltic Flexible Transfer System

Figs. 2(a) and (b) show the proposed peristaltic flexible pump. The device consists of a rubber tube (latex rubber), a flexible hose (olefin elastomer and polypropylene), and flanges (polymethyl methacrylate). Air is applied to the chamber between the rubber tube and flexible hose when compressed air is applied to the air inlet connected to the flange. When a positive pressure is applied to the chamber, the rubber tube contracts and the inside of the tube is closed. Applying a negative pressure to the chamber causes the rubber tube to expand and open. When multiple units are connected, air pressure is applied to each unit to reproduce peristalsis and transport the contents in the pump tube. As shown in Fig. 2(b), the flexibility of the flexible hose allows the pump to bend up to 25° per unit. In the conventional method, acrylic pipes with a curved shape had to be developed to match each transfer route; however, in this method, each unit can be set within a range of 0° to 25°, allowing the piping to be freely installed even in a space with a limited layout environment. As an example, Fig. 2(c) shows the peristaltic pattern of five connected units in which the contents of the first unit are pushed in under positive pressure and pulled out to the rear unit under negative pressure. Each phase is driven over *m* cycles. The driving time for each phase is 2 s.

C. Construction of a Simplified Transport Model

A theory of transfer performance is developed for content transfer by using a peristaltic flexible transfer system and a simplified model. In this model, we consider a system of *n* connected flexible pump units. The driving pattern is shown in Fig. 2(c) for five connected units, which can be extended to *n* connected units (Fig. 3). The peristaltic motion of this system transports the contents inside the unit through the pushing action of positive pressure and the pulling action of negative pressure. If the content volume at the j-th transfer cycle of the i-th unit is v_{ij}, bending angle is θ_{ij}, and transfer rate at that time is $R_{ij}(v_{ij}, \theta_{ij})$ $(0 \leq R_{ij} \leq 1)$, then the transfer volume, s_{ij}, is

$$s_{ij} = R_{ij} v_{ij}\ . \tag{1}$$

$R_{ij}(v_{ij}, \theta_{ij})$ is the combination of the positive-pressure transfer rate, $r_{ij}(v_{ij}, \theta_{ij})$, and negative-pressure transfer rate, $r'_{ij}(v_{ij}, \theta_{ij})$, acting on the contents of the j-th cycle of the i-th unit. Therefore, the transfer rate, $R_{ij}(v_{ij}, \theta_{ij})$, is

$$R_{ij} = r_{ij} + r'_{ij}\ (r_{ij} + r'_{ij} < 1)\ . \tag{2}$$

We consider the transfer rate, $r'_{ij}(v_{ij}, \theta_{ij})$, of negative pressure. When a unit to which a negative pressure is applied opens, the pressure inside the unit decreases. This causes the contents to be drawn into the unit. Pressure P_1 in the unit can be expressed by the following equation based on the Boyle–Charles law, where P_0 is the atmospheric pressure, V_0 is the volume of the unit when closed, and V_1 is the volume of the unit in the open state.

$$P_1 = \frac{P_0 V_0}{V_1}\ . \tag{3}$$

The pressure on the contents increases because of the blockage of the previous unit. If the elasticity of the rubber is ignored, then the pressure is equal to the supply pressure, P_{in}, of the previous unit. As $P_{in} \ll P_1$, the pressure in the unit is considerably lower than the pressure at the left end of the previous unit, and a force is generated to pull the contents into the unit. As accurately modeling the behavior of the contents at this time is difficult, the increase in the transfer rate due to the pressure difference is taken as the transfer rate, $r'_{ij}(v_{ij}, \theta_{ij})$, due to negative pressure. When negative pressure is simultaneously applied to multiple units, as in Phase 2, the calculated transfer rate may exceed 1. Therefore, $R_{ij}(v_{ij}, \theta_{ij})$ is given by the following equation, considering the case where the transfer rate exceeds 1.

$$R_{ij} = \begin{cases} r_{ij} + r'_{ij}\ (r_{ij} + r'_{ij} < 1) \\ 1\ (r_{ij} + r'_{ij} \geq 1) \end{cases} \tag{4}$$

Values $r_{ij}(v_{ij}, \theta_{ij})$ and $r'_{ij}(v_{ij}, \theta_{ij})$ are determined from data obtained by conducting experiments without considering the physical and chemical properties of the contents. When positive pressure is applied to push the contents into a unit, the contents transported by each unit are transferred to the next unit. However, when negative pressure is simultaneously applied to multiple units to pull the contents into one unit, the contents may be transported to a unit farther away than the next unit. Because these behaviors are complex and vary depending on the gravitational environment and the direction of conveyance, the present model simply assumes that the contents are conveyed to the next unit.

Next, we consider the content volume, v_{ij}, during the j-th cycle of conveyance of the i-th unit. We define t_{ij} as the content volume remaining after the i-th unit's j-th cycle of transfer. As v_{ij} can be expressed as volume $s_{(i-1)j}$ transported by the i-1 unit in the j-th cycle plus the residual volume of the i-th unit in j-1 cycle, v_{ij} is expressed as

$$v_{ij} = s_{(i-1)j} + t_{i(j-1)}. \tag{5}$$

Substituting (5) into (1) yields

$$s_{ij} = R_{ij} s_{(i-1)j} + R_{ij} t_{i(j-1)}\ . \tag{6}$$

By solving the asymptotic equation, we can express s_{ij} as

$$s_{ij} = \sum_{l=1}^{i} \left\{ \left(\prod_{k=l}^{i} R_{kj} \right) t_{l(j-1)} \right\}\ . \tag{7}$$

Therefore, the total transport volume, S, of the system when driven from m cycles by the peristaltic flexible transfer system is given as

$$S = \sum_{j=1}^{m} s_{nj} = \sum_{j=1}^{m} \left[\sum_{l=1}^{i} \left\{ \left(\prod_{k=l}^{i} R_{kj} \right) t_{l(j-1)} \right\} \right]\ . \tag{8}$$

III. BASIC CHARACTERISTIC EXPERIMENT

The basic characteristic tests of a single unit of the peristaltic flexible transfer system are conducted to derive transfer rate $r_{ij}(v_{ij}, \theta_{ij})$ due to positive pressure and transfer rate $r'_{ij}(v_{ij}, \theta_{ij})$ due to negative pressure.

A. Positive-pressure Experiment on a Single Unit

1) Purpose of the Experiment

We thought that the transfer rate of the peristaltic flexible transfer system is proportional to the transfer performance of a single unit. Therefore, we lifted water using a single unit of the peristaltic flexible transfer system, and compared the differences in the lifting rate due to different bending angles and input volumes. The transfer rate due to positive pressure is calculated from the lifting rate results.

2) Experiment Summary

The experimental setup is shown in Fig. 4 (a). A single unit is fixed to a jig whose bending angle can be freely adjusted. The bending angle of the unit is θ, and the top of the unit is horizontal to the ground. Compressed air at -70 kPa is applied from an air compressor through a vacuum generator to the chamber of a single unit. Water is then fed into the tube

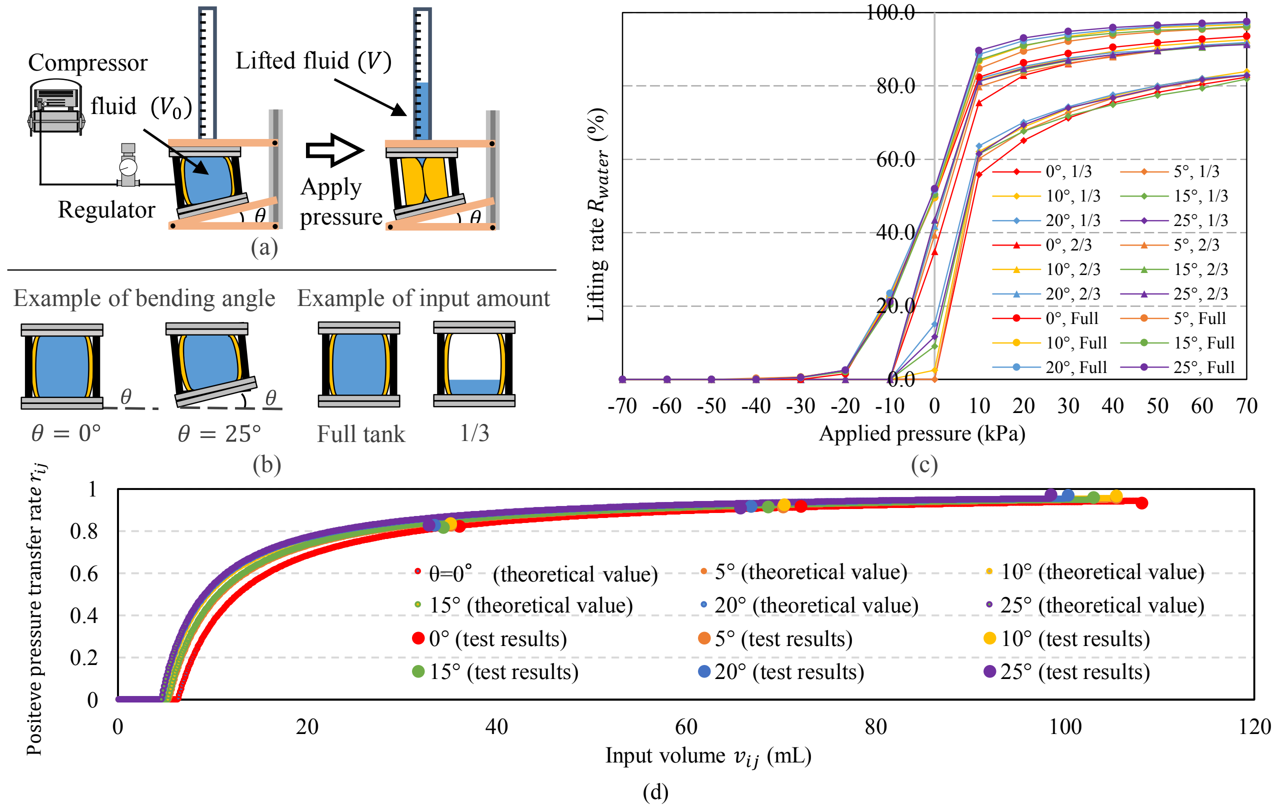


Figure 4. (a) Experimental environment for the positive-pressure test of single units. (b) Examples of the bending angle and input volume. (c) Percentage of water lifted by the single unit under each condition. (d) Positive-pressure transfer rate.

of the single unit. The volume at this time is V_0. After water is injected, the pressure in the chamber of the single unit is increased by 10–70 kPa, and the volume of water lifted, V, is measured. We experimentally determined ± 70 kPa as the pressure at which the rubber tube completely opens and closes. This experiment is conducted five times for each of the six conditions of $\theta = 0°,\ 5°, 10°,\ 15°,\ 20°,$ and $25°$ and for each of the three conditions of V_0 = full tank, 2/3 of full tank, and 1/3 of full tank volume of the unit (Fig. 4(b)). The water-lifting rate, R_{water} [%], of a single unit can be expressed as follows:

$$R_{water} = \frac{V}{V_0} \times 100\,. \tag{9}$$

The full volume of the single unit in this experiment is 108.1, 105.4, 105.4, 103.0, 100.3, and 98.5 mL at 0°, 5°, 10°, 15°, 20°, and 25°, respectively. The maximum applied pressure of 70 kPa is the maximum pressure that the inner rubber tube of the single unit can withstand.

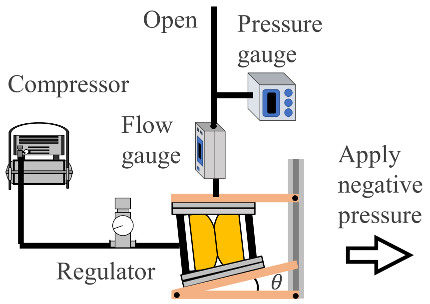
3) *Experimental Results and Discussion*

Fig. 4(c) shows a graph of the water-lifting rate for the single unit under various conditions. The lifting rate tends to converge at 60–70 kPa, irrespective of the bending angle. This is because the expansion and restoring forces of the rubber are balanced when negative pressure is applied, and the rubber contracts when positive pressure is applied. A comparison of the lifting rates when the maximum pressure of 70 kPa is applied confirms that the difference in the bending angles has almost no effect on the lifting rate. However, the lifting rate improves as the input volume increases, reaching approximately 82.5 %, 91.7 %, and 96.2 % when the input volume is the full tank volume, 2/3 of the full tank volume, and 1/3 of the full tank volume, respectively. These results suggest that the lifting rate of a single unit is significantly affected by the input volume owing to the application of positive pressure.

Based on the aforementioned experimental results, we consider the transfer rate, $r_{ij}(v_{ij}, \theta_{ij})$, due to positive pressure when the bending angle is θ_{ij} and the input volume is v_{ij}. The lifting rate of a single unit in the case of positive pressure depends on the input volume because the residual volume after lifting depends only on the bending angle and not on the input volume. Therefore, if $V_{residual}$ is the residual volume and V_{full} is the fully loaded volume of a single unit, then the lifting rate, $r_{ij}(v_{ij}, \theta_{ij})$, due to positive pressure is given by the following equation:

$$r_{ij} = \begin{cases} 0 \ (0 \le v_{ij} \le V_{residual}) \\ 1 - \dfrac{V_{residual}}{v_{ij}} \ (V_{residual} \le v_{ij} \le V_{full}) \end{cases}. \tag{10}$$

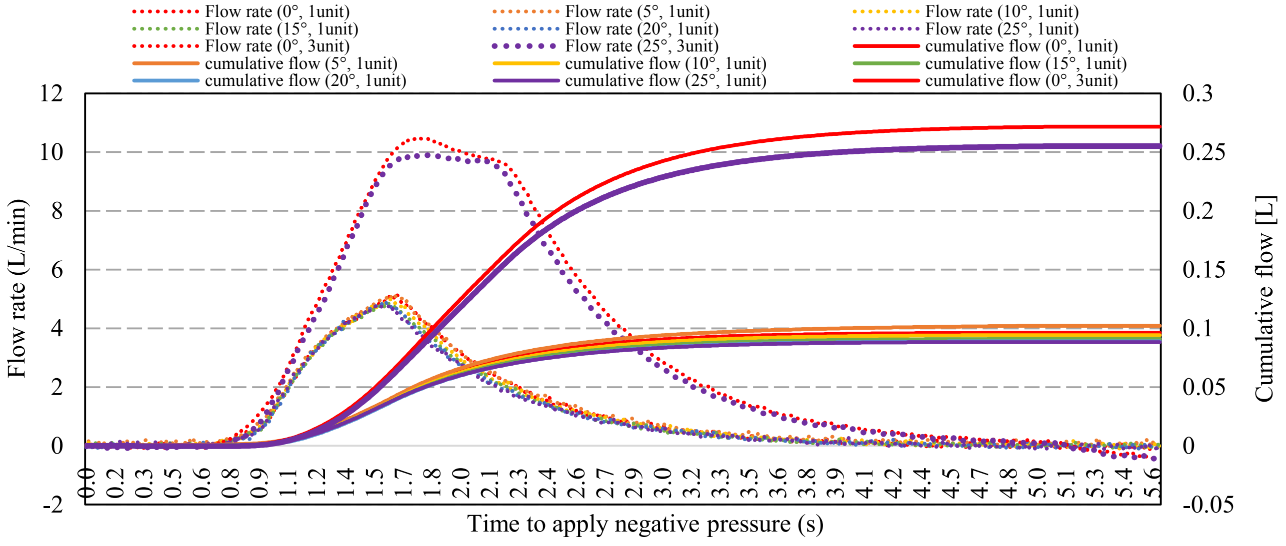
The values of $V_{residual}$ are 6.35, 5.43, 4.78, 5.32, 4.67, and 4.59 mL at 0°, 5°, 10°, 15°, 20°, and 25°, respectively. Fig. 4(d) shows a graph of the theoretical values of the transfer rate when these values are substituted into (10). The horizontal axis in Fig. 4(d) represents the volume of the contents, v_{ij}, and the vertical axis represents the transfer rate, $r_{ij}(v_{ij}, \theta_{ij})$, due to positive pressure. The transfer rate at full tank capacity is slightly higher than the theoretical value, which we consider to be the effect of measurement error. Fig.



(a)

	n = 1						n = 3	
θ (°)	0	5	10	15	20	25	0	25
$V_{2.0}$ (L)	0.066	0.068	0.065	0.063	0.062	0.062	0.133	0.126
V_s (L)	0.096	0.102	0.094	0.091	0.089	0.088	0.272	0.255
r'_{ij}	0.68	0.67	0.69	0.69	0.70	0.70	1.38	1.43

(c)



(b)

Figure 5. (a) Experimental environment for negative-pressure test of the units. (b) Time-series data of flow rate and cumulative flow. (c) Negative-pressure transfer rate under each condition.

4(d) shows the closeness of the experimental and theoretical values, thus supporting the validity of the theoretical values.

B. Negative-pressure Experiment on a Single Unit

1) Purpose of the Experiment

The flow rate for a single unit of a peristaltic flexible transfer system and the cumulative flow are measured when negative pressure is applied, and the differences due to the bending angle and the number of connected units are compared. From the experimental results, the transfer rate due to negative pressure is calculated.

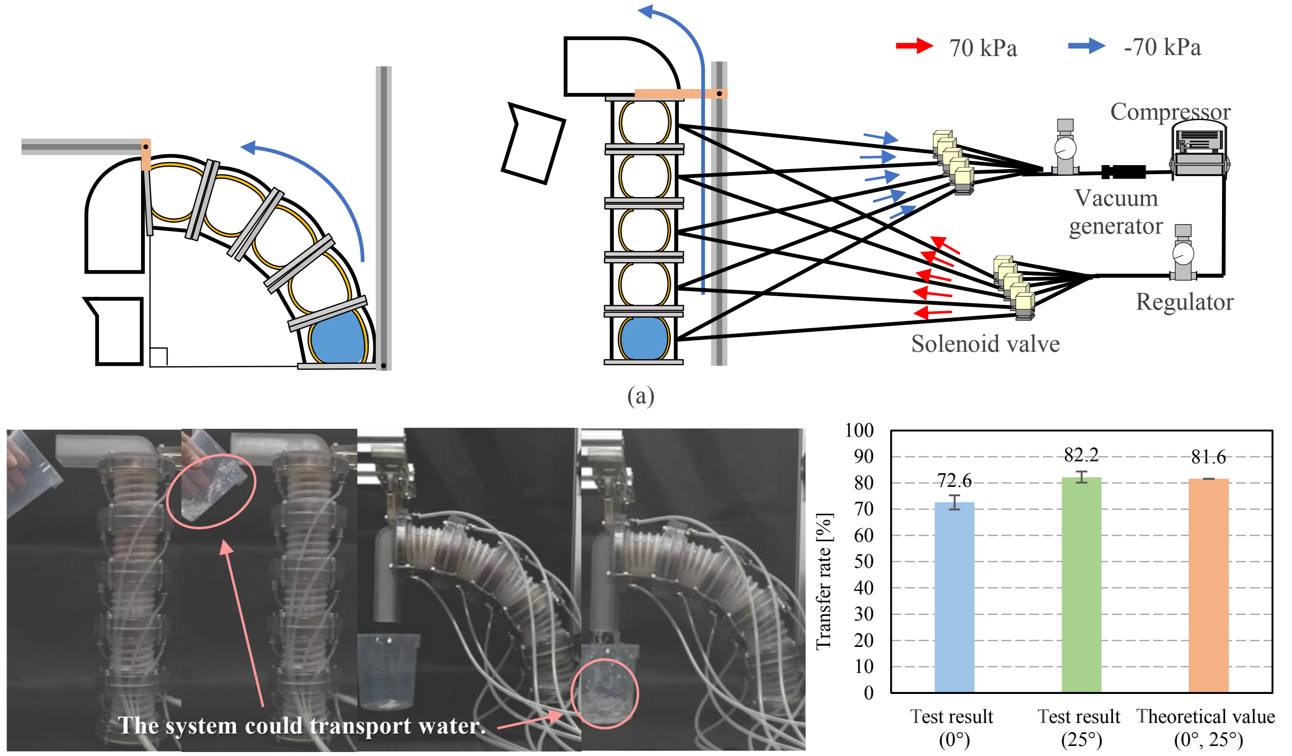
2) Experiment Summary

The experimental setup is shown in Fig. 5(a). The n connected units are fixed to a jig whose bending angle can be freely adjusted. The bending angle of a single unit is θ. Air compressed at 70 kPa is applied to the chambers of all units from an air compressor through a pressure-reducing valve. Then, negative pressure of −70 kPa is generated by applying compressed air to the chambers of all units for 5 s to draw in outside air, and the time-series data of the flow rate and cumulative flow are acquired. The experiment is conducted five times each for six conditions of θ = 0°, 5°, 10°, 15°, 20°, and 25° when n = 1 and five times each for two conditions of θ = 0° and 25° when n = 3. As the actual time in which negative or positive pressure is driven in one phase of a peristaltic flexible transfer system is 2.0 s, the transfer rate due to negative pressure can be expressed as the ratio of the cumulative flow drawn in 2 s to the steady-state value of the cumulative flow due to negative pressure. Therefore, if the steady-state value of the cumulative flow in a single unit is V_S and the cumulative flow drawn in 2 s in n connected units is $V_{2.0}$, the transfer rate, r', due to negative pressure is given by the following equation:

$$r'_{ij} = \frac{V_{2.0}}{V_S} \,. \tag{11}$$

3) Experimental Results and Discussion

The time-series data for the flow rate and cumulative flow under each condition are shown in Fig. 5(b), where the horizontal axis represents the time since the start of negative-pressure application to the unit, the first vertical axis (left side of the graph) represents the flow rate, and the second vertical axis (right side of the graph) represents the cumulative flow. The cumulative flow rate at s = 2.0 s, cumulative flow rate at the steady state, and transfer rate due to negative pressure are shown in Fig. 5(c). As presented in Fig. 5(b), the flow rate begins to increase at approximately 0.6 s after the start of negative-pressure application and reaches a maximum at s = 1.6 s and 1.7 s for $n = 1$ *and* 3 units, respectively. Fig. 5(c) shows that the volume drawn by the unit in 2 seconds is almost constant regardless of the bending angle, and that it depends only on the number of units regardless of the bending angle. The reason for this is that although the volume of the unit (V_S) decreases due to



(a) (b) (c)

Figure 6. (a) Experimental environment for water transport in five connected units. (b) Water transfer among five connected units. (c) Comparison of water transfer results at 0° and 90° with theoretical values.

bending angle, the volume drawn by the unit in 2 seconds ($V_{2.0}$) also decreases, so the transfer rate r'_{ij} remains unchanged. Fig. 5(c) shows that the coefficient of negative pressure is $r'_{ij} \approx 0.69 \ and \ 1.41$ for $n = 1 \ and \ 3$ units. Thus, when multiple units are connected and negative pressure applied, the negative pressure transfer rate r'_{ij} may exceed 1. In this case, as shown (4), the transfer rate R_{ij} is considered as 1.

IV. WATER-LIFTING EXPERIMENT WITH FIVE CONNECTED UNITS

A. *Purpose of the Experiment*

Water-lifting experiments are conducted using a peristaltic flexible transfer system comprising five connected units. The transfer rate in the system is measured and compared with the theoretical value calculated by using a simplified model.

B. *Experiment Summary*

The experimental setup is shown in Fig. 6(a). Five connected units are fixed to a jig whose bending angle can be freely adjusted, and 108.1 mL of water is injected into the first unit. Positive or negative pressure is applied to the device by using a solenoid valve controlled by employing a microcomputer (Arduino UNO) via a pressure-reducing valve from an air compressor. A vacuum generator is used to generate negative pressure. Positive pressure is 70 kPa, and negative pressure is −70 kPa. The pressure-drive pattern is shown in Fig. 2(c). Water is lifted using the pushing action of positive pressure and the pulling action of negative pressure, and the ratio of the volume of water lifted to the input volume is calculated as the transfer rate. This entire experiment is performed three times for each of the following two cases: the sum of the bending angles of the five connected units is 0° and 90°.

C. *Experimental Results and Discussion*

Fig. 6(b) shows the water lifted under each condition. Fig. 6(c) shows the theoretical values of the transfer rate using the simplified model, calculated by substituting the values obtained from the experiments in section III into (8) and the transfer rate at that time. From the experiments in section III, the theoretical values at 0° and 25° bending degrees are equal because no difference in transport rate occurs with bending angle. The transfer rate at 0° is lower than the theoretical value obtained by using the simplified model, and the transfer rate at 90° is close to the theoretical value. This is because the water is lifted in the direction of antigravity. When the bending angle is 0° which the potential energy of the 5th unit is greater than the 25° bending degree, the bending is particularly susceptible to the effects of gravity and the force of return in the opposite direction of the lift is likely to be generated by hitting the cover at the end of the fifth unit with a large force. However, when the bending angle is 90°, the bending is less affected by gravity and the risk of hitting the cover at the end of the fifth unit and returning is lower. Therefore, the value at 90° is closer to the theoretical value than that at 0° is. However, in all the cases, the conveyance rate is high, and the performance of the peristaltic flexible conveyance system is sufficient. Future experiments should be conducted in a simulated microgravity environment or horizontal transport system using a fluid with high viscosity to verify the transport performance. In addition, we should consider the shape of the toilet bowl to transport the contents into the peristaltic flexible transfer system.

V. CONCLUSION

In this study, we proposed a peristaltic flexible transfer system. A simple model was constructed for transporting contents, and the transport rate was calculated based on the data obtained from basic characteristic experiments on a single unit. The transfer rate of a single unit under positive pressure was confirmed to be dependent on the input volume of the contents and the bending angle. The transfer rate under negative pressure was confirmed to depend on the number of units and was constant regardless of the bending angle. In an experiment using a transfer system with five connected units to transport the contents, the transfer rate values were close to the theoretical values when the bending angle was 90° and lower than the theoretical values when the bending angle was 0°. These results can be attributed to the 0° angle being more susceptible to the effects of gravity. In this study, water was selected as the transport content, and the transport performance of the peristaltic flexible transport system was investigated using a simple model. However, to apply the system to a space toilet, transport experiments using simulated feces should be conducted to verify transport performance.

In this study, water was selected as the content for transport, and the transport performance of the peristaltic flexible transport system was investigated using a simple model. However, to apply the system to a space toilet, transport experiments using transfer and simulated feces should be conducted to verify the transport performance. In the future, this system will be used to transport simulated feces and its performance will be compared. In addition, we plan to conduct transport experiments in a microgravity environment.

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