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Research Article

IMPROVEMENT OF A MICROMANIPULATION SYSTEM BY USING A FUNCTIONAL SURFACE WITH A GROOVE STRUCTURE

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ABSTRACT:
The demand for micro parts like a micro electron mechanical system has increased in recent times. With that, the improvement in the functions of micromanipulation equipment operating the minute object is required. Physical phenomena at the microscale differ from those of the normal scale due to the "scale effect". In micromanipulation task, when the grasped object is placed at an arbitrary position, the natural fall of the object by gravity cannot be expected. This is because it is difficult to arrange an object at an arbitrary position. In this study, a method to place an object at an arbitrary position by generating a force between the floor and the object is proposed. The floor of functional surface has a fine groove into which enough liquid is injected to generate a liquid bridging force between the floor surface and a small object. The width of the groove can is reduced by applying an area load to the floor which generates a liquid cross-linking force corresponding to the size of the object. As the grooves become finer, the capillary phenomenon occurs. Therefore, the liquid can be supplied to the groove regardless of the attitude of the floor surface. By using the proposed floor surface, the speed and stability of the work in which the object in the micro manipulation work is placed on the floor surface is improved, and contributes to the development of the micro manipulation function.

Keywords: *Micromanipulation, Liquid-bridging-force, Functional-surface, Capillary phenomenon, Wettability*

1. INTRODUCTION

In micromanipulation, there are several types of techniques, such as the gripper [1], electrostatic force [2], liquid bridging force [3], and optical tweezers [4]. Among them, many gripper types have been proposed. Gripper type micromanipulators have many moving parts, and they solve the drawback that operation is limited [5]. Challenges to micromanipulation work include its visibility and operability, which are poor on a microscale. To solve this problem, we proposed a micromanipulation system using virtual reality [6]. Placing a gripped object on the floor provides another challenge due to the scale effect which means that the normal fall of the object due to the gravitational force cannot be expected in the micromanipulation work when the gripped minute object is placed at the optional position. To solve this problem, a method of placing an object at an arbitrary position by generating a force between the floor and the object is proposed. A floor surface with a fine structure on the surface has previously been studied [7]. Additionally, methods such as self-alignment [8] and electro wetting on dielectric [9], among others, are effective in utilizing such a method using the droplets. However, these methods can be problematic, making it necessary to

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to supply liquid to the floor in advance. There is also a risk of evaporation of floor liquid during the work. The purpose of this study is to develop a novel micro manipulation system that does not impose the load on an object. For this purpose, we used only pure water to execute pick-and-place operations. Many similar studies have used energy such as electromagnetic forces to manipulate objects. Therefore, this method is significant since the operation can be performed only with pure water. In this study, we propose a functional floor that can supply liquid during the operation. Because this floor uses only liquid for micromanipulation task, it may not damage the object. The proposed floor surface has fine grooves, where sufficient liquid is injected to generate a bridging force between the floor surface and a small object. The width of the groove can be reduced by applying a surface load to the floor perpendicular to the direction of the groove. This delivers a liquid bridging force suitable for the size of the object. As the groove becomes finer, capillary action occurs within the groove making it possible to supply the liquid to the groove without depending on the altitude of the floor surface. The speed and stability of the operation, in which the object in the micromanipulation work is placed, are improved, leading to the development of micromanipulation function. Since the work is carried out only with liquid, the purpose of carrying out the work without damaging the object is also achieved.

2. MICROMANIPULATION SYSTEM

As described in Section 1, the micromanipulation device is effective for objects which are difficult to operate using a typical manipulation device. Some objects in micromanipulation are easily affected by external forces like cells. To solve this, there are methods utilizing liquid bridging forces and liquid flow [6], and optical tweezers that use the reflection pressure of light [7]. Optical tweezers can easily perform the action of placing an object on the floor in another micromanipulation device. However, the force for grasping the object is small. In this research, we proposed a micromanipulation system that utilizes a liquid bridging force [7]. In the method using the liquid bridging force, the operation of placing the object on the floor becomes less difficult, and the problem is solved.

3. THEORY OF FLUIDS ON A FUNCTIONAL SURFACE

Wettability: Wettability refers to the affinity of a liquid to a solid surface. Its size is influenced by the contact angle, which is determined by the balance of the liquid-solid, solid-gas, and gas-liquid interfacial tensions. This relationship is represented by Young's Eq. (1). The interfacial tension between the solid and liquid is r_s. Gas-liquid interfacial tension is r_l, and the liquid-solid interfacial tension is r_{sl}. The contact angle is θ. [10]

$$r_s = r_l + r_{sl} \cos\theta \tag{1}$$

Capillary phenomenon: The capillary phenomenon refers to a phenomenon in which the liquid level inside the tube rises and becomes higher than the liquid level outside the tube after touching the tube with the liquid. The water level inside the tube, which rises due to the capillary phenomenon occurs when a fine tube is erected at right angles to the water surface and is given by Eq. (2). The inner diameter of the tube is r. The height of the raised liquid level is h, and its density is ρ. The gravitational acceleration is g. The surface tension of a liquid is σ. [11]

$$h = \frac{2\sigma\cos\theta}{\rho g r} \tag{2}$$

Liquid bridging force: When a small amount of liquid between particles in contact with each other in the gas phase, this causes liquid bridging. Through the surface tension acting on the liquid bridge, and the pressure that is generated inside, the attraction between each particle occurs. The force generated is called the liquid bridging force and is expressed by Eq. (3). The negative pressure in the liquid bridge is p_L. The particle radius is r_0 and the radius of curvature from the inside of the liquid surface is r' . The liquid bridging force is F_L. $P_L = r_0 p_L/\sigma$. [12]

$$F_L = \pi r'^2 P_L + 2\pi\sigma r' \tag{3}$$

Capillary phenomenon, and liquid bridging force are important elements in this study. The liquid bridging force increases or decreases depending on the size of the liquid bridging generated for the object. The curvature radius from the liquid surface is determined by the size of the liquid bridge, i.e., the greater the width of the groove, the greater the liquid bridging force. Therefore, it is ideal to increase the width of the groove. However, when the width becomes larger than the object, the object sinks into the groove. Therefore, the groove width should be adjusted according to the size of the object. The liquid is supplied to the floor surface by utilizing a capillary action; it can be supplied without being affected by the altitude of the floor surface.

4. FUNCTIONAL SURFACE GENERATION METHOD

A 3D printer (AGILISTA made by KEYENCE) is used to fabricate the grooved floor. The material of the floor used as a model material for 3D printers is AR-M2, a UV curable resin from KEYENCE. The AR-M2 is cured or laminated with a UV lamp. The printing precision is 635×400 dpi. The resolution in the Z direction is 20µm, and 15µm using high resolution. A 3D model of the floor surface is illustrated in Fig. 1(a). Dimensions for this groove are 300µm in width, and 500µm in depth with a liquid supply port for the groove. Because the groove can be deformed by applying a load, its width can be adjusted by applying a load perpendicular to the groove. Its body dimensions are: Depth 26mm, height 6.0mm, width 3.7mm. The groove dimensions are: Depth 20mm, height 0.49mm, width 0.3mm. (Fig. 1(c)) The groove width was set at 0.3mm, because in our previous research that was using some material [7] , the minimum width for generation capillary force is 0.1mm. For this reason, the groove width was set to 0.3mm, as it is close to 0.1mm when the floor surface is compressed.

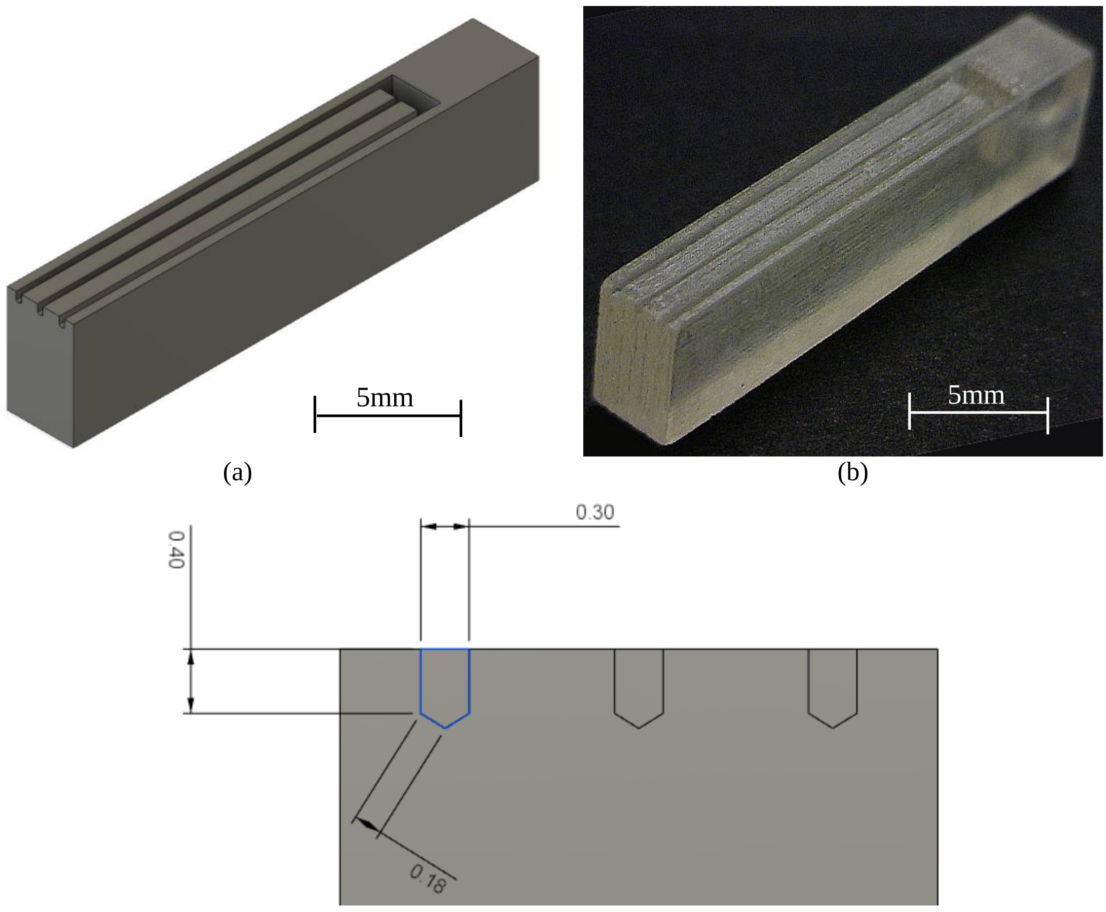


Fig. 1. Produced functional floor (a) 3D Models, (b) Production, (c) groove dimensions

5. EXPERIMENTAL METHOD

In the first experiment, by compressing at intervals of 100μm is shown in Fig. 2, the amount by which the width of the groove should be compressed is determined. A clamp is used to compress the functional floor surface. As the groove becomes thinner due to compression, the parameter corresponding to the groove width r changes in Eq. (2), and the capillary phenomenon occurs. After confirming that the capillary action is caused by the above experiment, the liquid supplied to the inside of the groove is brought into contact with the microbeads (φ 600μm), and a liquid bridging force is generated between the functional floor surface and microbeads. The value of the liquid bridging force is measured. Figure 3 depicts the second experiment. The measurement is conducted under two conditions: one with the functional floor (groove) compressed by 500μm, and the other without compression. Measurements are performed on an electronic balance. In Fig. 2, the functional surface is raised, which is in contact with the microbeads by the liquid bridge at every 20μm. Data is transmitted every 0.25s from the electronic balance, and 13 data values were collected. The average value is calculated as the value of the liquid bridging force on the graph. Both experiments used pure water since water can be used to protect objects from adverse effects. The density of water is 998.233kg/m^3, and its surface tension is 72.75mN/m. (20 °C)

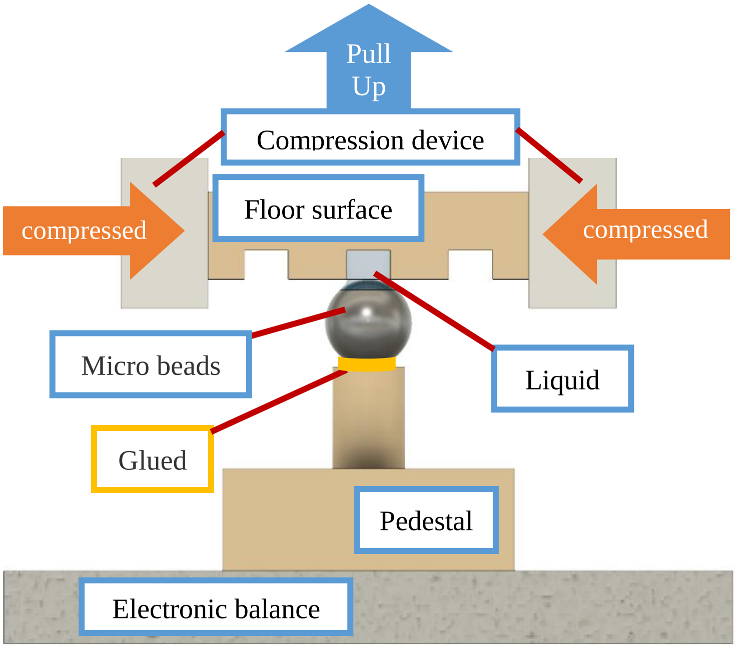


Fig. 2. Outline of liquid bridging force measurement experiment

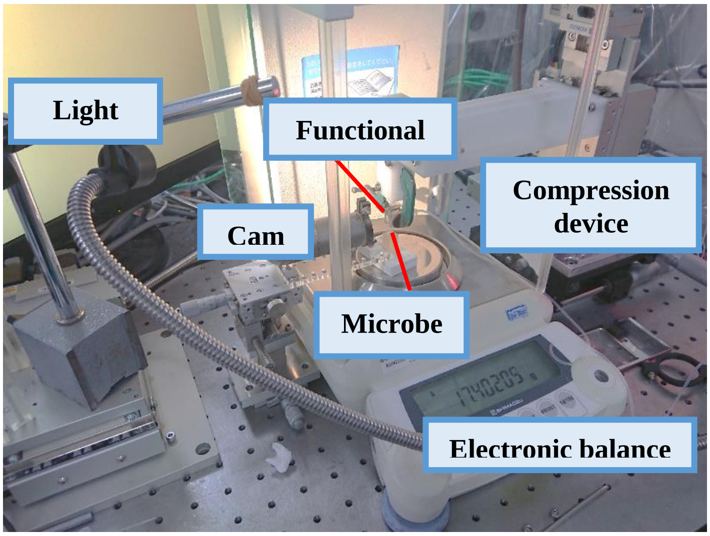


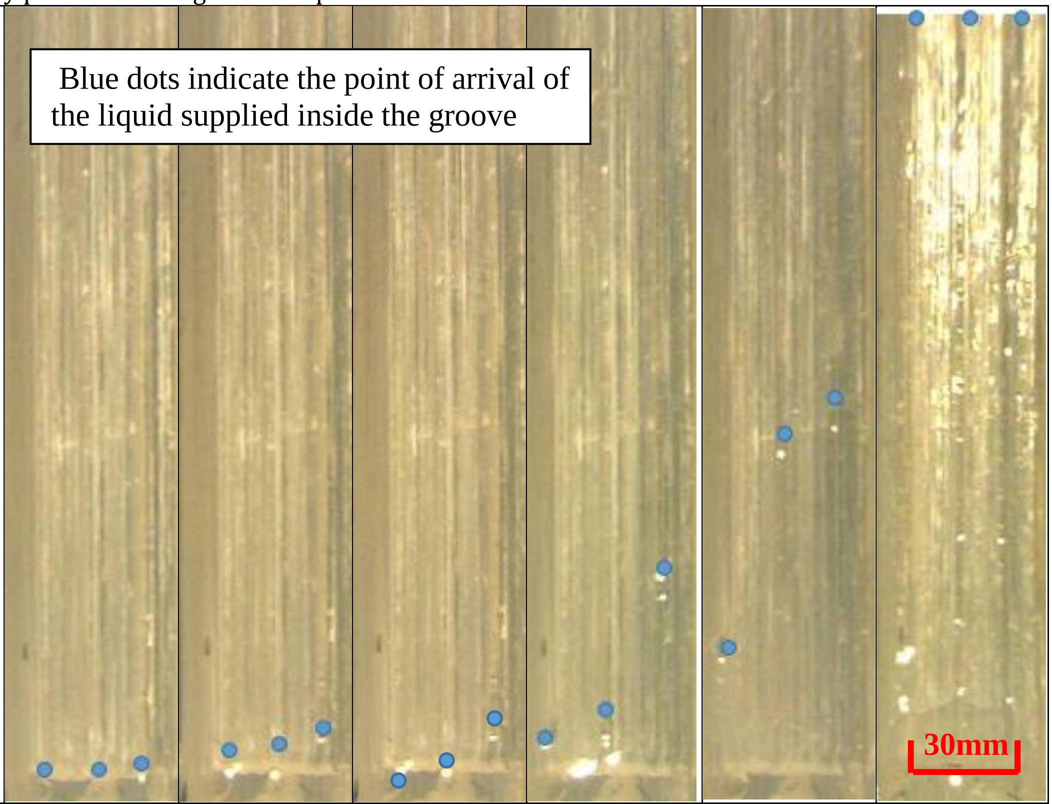
Fig. 3. Measurement experiment of liquid bridging force

6. Result and discussions

Table 1 shows the results of compressing the floor surface with clamps at intervals of 100µm to show the extent of the compression width at which capillary action occurred. The blue circular dots in Table 1 represent the ends of the liquid pulled by capillary forces. From this result, the capillary force started when the compression width exceeded 300µm. It was also confirmed that the compression width necessary to obtain sufficient capillary force was 500µm. Of the 10 trials, 8 were successful and reproducible at a compression width of 500µm.

Liquid bridging force results are shown in Fig. 4. The maximum liquid bridging force was 0.0828mN in the uncompressed state and 0.0765mN in the compressed state, indicating that the liquid bridging force was stronger in the uncompressed state than in the 500µm compressed state. Using a basic capillary, the liquid bridging force between the capillary and the target generated for microbeads with a diameter of 600µm is approximately 0.0539µm. This floor surface demonstrates sufficient force because the liquid bridging force exceeding it is generated between objects.

Table 1: Capillary phenomenon against compression width

Floor plan						
Compression Width (µm)	0	100	200	300	400	500
The supply of liquid to a groove	Not available	Not available	Not available	Available (Insufficient)	Available (Insufficient)	Available (filling)

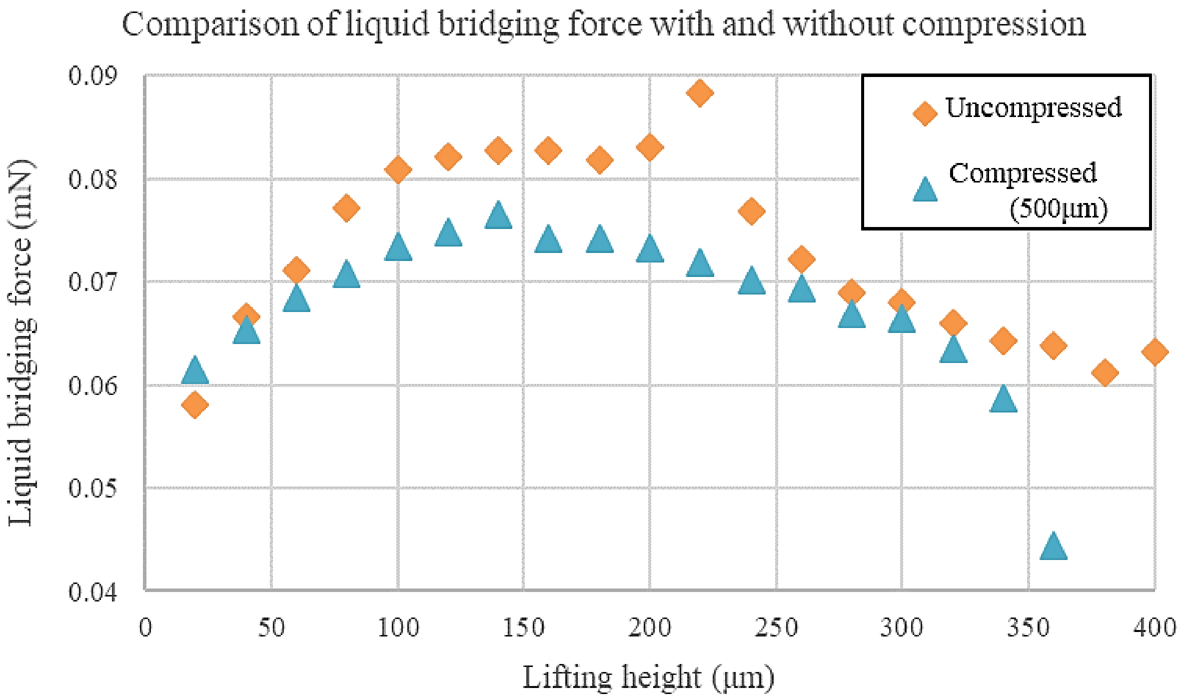


Fig. 4. Measurement Results of liquid bridging force (between object and floor)

Based on the theory of capillary action described in section 2, the equation of the capillary force in the groove of the functional floor is obtained. The width of the groove is *d*. The depth to the bottom of the groove is *l*. (Eq. (4))

$$h = \frac{(2l + d)\sigma \cos\theta}{\rho d l g} \tag{4}$$

As the width of the groove decreases, the depth of the bottom surface of the groove increases. However, the rate of increase in the depth to the bottom surface of the groove is small. Therefore, the smaller the width of the groove is, the greater the capillary phenomenon becomes. Therefore, the experimental results are theoretically correct.

Liquid is then supplied into a groove by capillary action. This allows the liquid to be supplied without being affected by the direction of the floor surface (groove). The fluid filled by capillary action is not lost when the groove width is reduced to the size of the base. Therefore, the function of the main floor may be useful when micro devices are to be assembled three-dimensionally.

Next, the measurement experiment of the liquid bridging force is described. By comparing the values between a non-compressing and compressing liquid bridging force, the former tends to be larger at any pulling height. At an uncompressed state, the maximum bridging force is 0.0828mN. Under 500μm compression, the maximum liquid bridging force is 0.0765mN. This is because, the element that constitutes the liquid bridge generated between the microbeads and floor surface changes by widening the width of the groove. As the width of the groove changes, the value of r' in Eq. (3), and the value of the liquid bridging force will also change (Fig. 5). More specifically, the larger the size of the groove that provides the liquid bridge to the object, the greater the liquid bridge force. These experimental results align with the theoretical results.

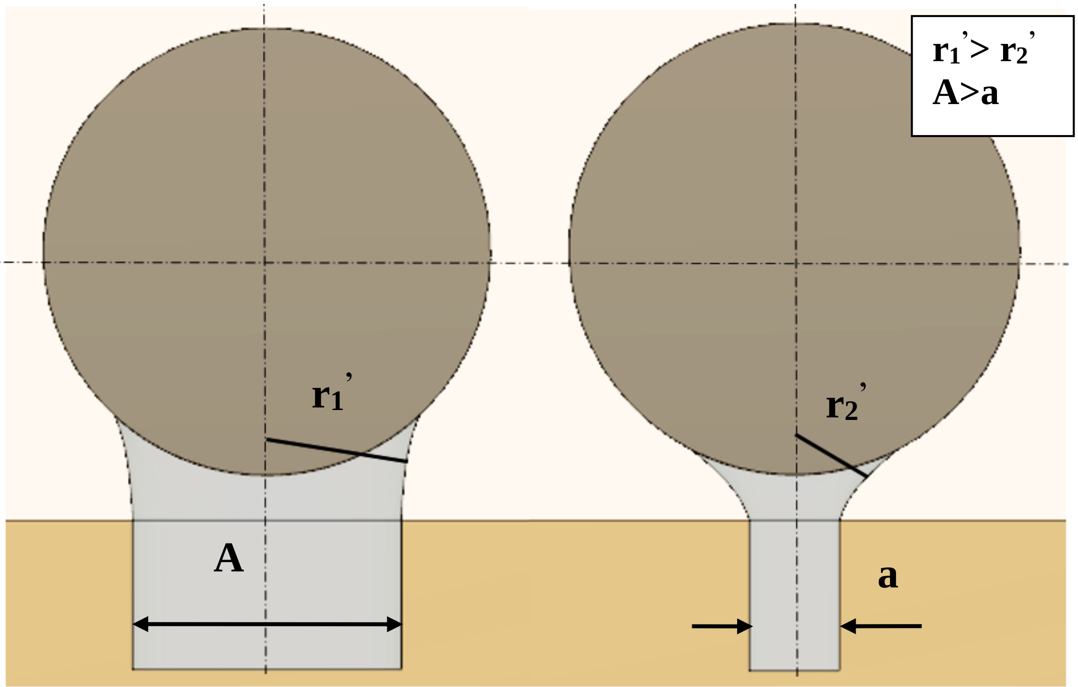


Fig. 5. Relationship between the width of the groove and the radius of curvature inside the liquid surface (r_1': wide, r_2': narrow)

The difference between the maximum compressed and non-compressed liquid bridging strength is 0.00632mN. The extent this effect is under investigation. However, the minute change of each element becomes remarkable in the micro-scale. Thus, the difference in the maximum liquid bridging force works effectively. It is proven that the larger the size of the groove, the stronger the liquid bridging force. Conversely, if an object too large for the size of a minute object is used in the groove, it may enter the inside of the groove. In some cases, it may move and flow randomly in the groove filled with liquid. Here, by making the width of the groove match the size of the object, a large liquid bridging force can be generated while avoiding such a risk.

7. Conclusion

This study proposes a functional floor that can supply liquid through capillary action by changing the width of the groove. Capillary forces can be increased by compressing the grooves of proposed the functional surface to reduce their width. By increasing the capillary forces, liquid is supplied to the groove in which the liquid was not originally supplied. The supplied liquid continues to remain after the groove width returns. That is, the liquid can be supplied from the outside of the functional floor surface, and the bridging force can be switched between ON and OFF. It is found that the compressive width of the floor surface necessary to provide sufficient capillary force to the functional floor surface is 500μm. The probability of occurrence of capillary action at a compression width of 500μm is 80%. When the capillary phenomenon does not occur, the process can be repeated until capillary action occurs. By changing the width of the groove, the liquid bridging force can be changed, thereby enabling the suitability of the place work for the size of the object. The liquid bridging force increases as the liquid area in contact with the object increases. Therefore, the larger the groove, the stronger the liquid bridging force obtained. However, if the object becomes smaller than the width of the groove, the object sinks into the groove. Future problems include the bottom of the groove being a triangle, and not a flat surface. In this case, the effect of the capillary phenomenon becomes stronger toward the bottom. Therefore, in the future, a more precise formula will be established to calculate a value closer to the result of the experiment and provide a stronger theoretical proof. In addition, although a clamp was used when compressing, there are still concerns about uniform compressing. Therefore, it will be necessary to produce a device capable of uniformly compressing the floor surface. Finally, it will also be necessary to clarify specifically how much the functional floor contributes to micromanipulation work.

NOMENCLATURE

r_s	[N/m]	solid-gas interfacial tension
r_l	[N/m]	liquid-gas interfacial tension
r_{sl}	[N/m]	solid-liquid interfacial tension
θ	[°]	contact angle
r	[m]	the inner diameter of the tube
h	[m]	the height of the raised liquid level
ρ	[kg/m^3]	density
g	[m/s^2]	the gravitational acceleration
σ	[N/m]	the surface tension of a liquid
p_L	[kg/m^3]	the negative pressure in the liquid bridge
r_0	[m]	the particle radius
r'	[m]	the radius of curvature from the inside of the liquid surface
F_L	[N]	the liquid bridging force
P_L	[-]	$=r_0 p_L/\sigma$
d	[m]	the width of the groove
l	[m]	the depth to the bottom of the groove

REFERENCES

[1] Sonia, L. and Aurelio, S. Design of an electro-thermally actuated cell microgripper, Microsystem Technologies, Vol. 20, 2014, pp. 869-877.

[2] Shigeki, S., Hideo, H. and Kunio, T. Electrostatic detachment of an adhering particle from a micromanipulated probe, Journal of Applied Physics, Vol. 93, 2003, pp. 2219-2224.

[3] Shoiti, N., Hemthavy, Pa., Kunio, T. and Shigeki, S. Micromanipulation of liquid bridging force under scanning electron microscopy, The Japan Society for Precision Engineering, 2015, pp. 803-804.

[4] Kishan, D., Peter, R. and Min, G. Optical micromanipulation, The Royal Society of Chemistry, Vol. 37, 2008, pp. 42-55.

[5] Chen, T., Wang, Y., Yang, Z., Liu, H., Liu, J. and Sun, L. A PZT actuated triple-finger gripper for multi-target micromanipulation, Micromachines, Vol. 8, 2017, pp. 33.

[6] Daigo, M., Ryuhei, K., Satoshi, N. and Shigeomi, K. Use of AR/VR in micro manipulation support system for recognition of monocular microscopic images, International Journal of Automation Technology, Vol. 5, 2011, pp. 886-874.

[7] Daigo, M., Syuhei, Y. and Kyuhei T. Fabricating the active functional surface for micromanipulation, paper presented in the Proceeding of the 8th International Conference on Positioning Technology, 2018, Kaohsiung, Taiwan.

[8] Kaiji, S., Kentaro, I., Seiichi, H. and Akira, S. Self-alignment of microparts using liquid surface tension-behavior of micropart and alignment characteristics, Precision Engineering, Vol. 27, 2003, pp. 42-50.

[9] Katsuo, M., Shungo, A. Naoki, T., Tomoya, I. and Tohru, N. Electrowetting on dielectric (EWOD) device with dimple structures for highly accurate droplet manipulation, Applied Science, Vol. 9, 2019, pp. 1-9.

[10] Nobuyuki, M. Surface function based on microstructure, 2011, Morikita Publishing, Japan.

[11] Shu, O. Surface tension, 1980, Iitate Publishing, Japan.

[12] Yoshiyuki, E., Yasuo, K. and Yasunobu, N. Analysis of liquid bridging adhesion between two particles, The Society of Chemical Engineers, Japan, Vol. 19, 1993, pp. 55-61.