Development of a Small Sucker Manipulator for Underwater Surgery Support

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***Abstract*—WaFLES (Water-Filled LaparoEndoscopic Surgery) is an operative method suggested by Igarashi et al., which has several advantages, such as, preventing the drying of inner organs, and being able to use ultrasound devices for real time monitoring. However, grasping of inner organs with usual forceps for move and incision purpose is difficult. Therefore our ultimate goal is to develop a small sucker manipulator for WaFLES support. Experiments were conducted to explore suitable suction cups for underwater application, and suitable structure (cup-to-cup distance, elasticity of binding material, layouts of multiple cups) for a multiple-cup assembly, in terms of adsorption force and tolerance to sideslip. Experiment results showed that 1) the shape of each single suction cup for the underwater application was identified; 2) the structure of the multiple-cup assembly affects the adsorption force and tolerance to sideslip.**

I. INTRODUCTION

Recently, as a minimally invasive treatment process, the number of laparoscopic surgery increases rapidly [1]. WaFLES (Water-Filled LaparoEndoscopic Surgery) is the operative method suggested by Igarashi et al. to cope with problems of the conventional laparoscopic surgery, such as the drying of organs and so on. Instead of pneumoperitoneum gas in usual laparoscopic surgery, WaFLES expands the intra-abdominal space using saline [2]. Besides an advantage of preventing the drying of inner organs, the WaFLES can use ultrasound devices for real time monitoring.

However, in this new surgery modality, grasping of inner organs with usual forceps for move and incision purpose, is difficult due to their flexible and slippery surface, and floating state. Our ultimate goal is to develop a small sucker manipulator, which can adhere to and hold the organ underwater by multiple suction cups with reconfigurable surface distribution to solve the grasping problem.

Most industrialized suction cups were supposed to adsorb rigid objects in the air. A few studies employed suction cups for biological tissue or organs. Heart Lander developed by Cameron et al. is an example [3], which worked on epicardium and enabled injection to heart [4]. Since the aim of the robot is to move on the beating heart, it is not clear whether the suction cups are suitable for the other inner organs, such as a liver. A robot with suction cups for the purpose of adsorption to and movement on peritoneum (abdominal wall) was developed [5], for the purpose of NOTES (Natural Orifice Translumenal Endoscopic Surgery) support. But, movement, and adsorption in the water was not investigated. Moreover, a soft underwater robot [6], imitating octopus, could realize jet propulsion and coiling. However, its stability is under investigation.

In this study, the shape, size, and material of suction cups for underwater application, as well as the effect of surface distribution of multiple suction cups were investigated, in terms of the absorption force and tolerance to sideslip, for the purpose of identifying suitable suction cups and structure for underwater application.

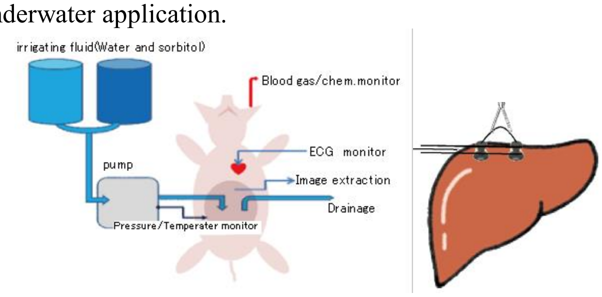

Figure 1. Outline of the WaFLES and manipulator.

II. EXPERIMENT

A. *Determination of most suitable suction cups for underwater application*

In this study, the liver was used as the organ object for different types of experiment. This is because that the liver is slippery, heavy and harder than the other organs in the abdominal cavity, recognized as one of the organs difficult to grasp in the underwater environment [7].

Suction cups (SMC corporation) with different size, material and cap shape, as shown in TABLE I and Fig. 2, were chosen for test.

TABLE I. Dimension, cap shape and material of the suction cups tested

Size[mm]	shape	Material
ϕ 10	Flat with projections	flurine rubber
	Flat with projections	silicon rubber
	Flat with projections	conductive silicon rubber
	Flat with projections	conductive NBR
ϕ 16	Flat	Silicon rubber
	Flat with projections	Silicon rubber
	Thin	Silicon rubber
	Thin with projections	Silicon rubber
	Deep	Silicon rubber
	Bellow	Silicon rubber
ϕ 40	Flat with projection	Silicon rubber
	Bellows	Silicon rubber

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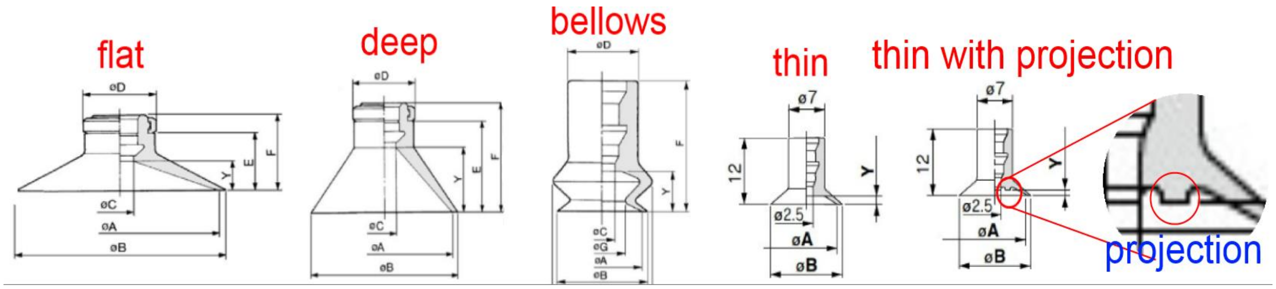


Figure 2. Suction cups tested. [8]

A compressor (0.75LP-7S) with maximum negative pressure 0.69[MPa] was used. The adsorption experiment were done in 3 conditions, i.e., a) to a film in the air, b) to a piece of liver in the air, c) to a piece of liver underwater. The adsorption force perpendicular to the adsorption surface, and the maximal force the adsorbed suction cup could tolerate when pulled horizontally, were measured. The latter corresponds to the static friction, though the two objects tend to move relatively are not solid. The other conditions were listed in TABLE II.

The liver was put into water for 10 minutes, before all the tests began. The purpose of this process is to simulate the real operation situation in WaFLES.

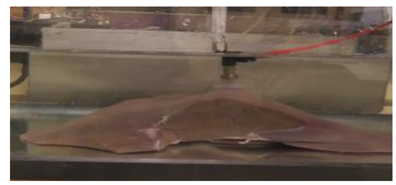


Figure 3. Experiment setup.

TABLE II. Data of the experiment

(a) liver condition

Type	Pig's liver
Weight	942g
Volume	693cm^3
Take out time	Morning of the experiment day
Frozen processing	None

(b) environment condition

Temperature	27℃
Water temperature	27℃
Depth of the water	9cm
Time of underwater leaving	10min

B. A 2-cup suction assembly

It was expected that multiple suction cups could improve both the adsorption force and sideslip tolerance, but the relative position or distribution of the cups, the structure and elasticity of the assembly need to be investigated. Although each single suction cup with its elasticity and shape might adapt to the deformation partially, because, the surface of organ is usually irregular, and the organ deformation subject to the vertical or horizontal pulling force might occur in a wide range, which is difficult to deal with by a single suction cup, the multiple-cup assembly should be able to absorb the distortion caused by non-uniform mass distribution.

In this study, the 2-cup and 3-cup assemblies were built and investigated. In the experiment for this part, self-made suction cups were used. For the 2-cup assembly, the binding materials with different elasticity and dimension were tested. For the 3-cup assembly, 3 different layouts of suction cup distribution were tested.

Fig. 4 shows an illustration of the 2-cup assembly. Types of elastic material used to bind the 2 suction cups were shown in TABLE III. The elastic shear modulus of the binding materials was calculated by applying formula shown in (1) to the data measured in a preliminary experiment.

$$G = F / (\triangle x / x) \quad (1)$$

Here, F is the force, $\triangle x$ is the displacement, and x is the length of the elastic object.

The distance between the suction cups might be another factor to affect the adsorption force and tolerance to sideslip, Four different combination of distance and material length, as illustrated in Fig. 4, {50, 10}, {45, 10}, {40, 10}, {45, 5}, were tested. The unit is mm.

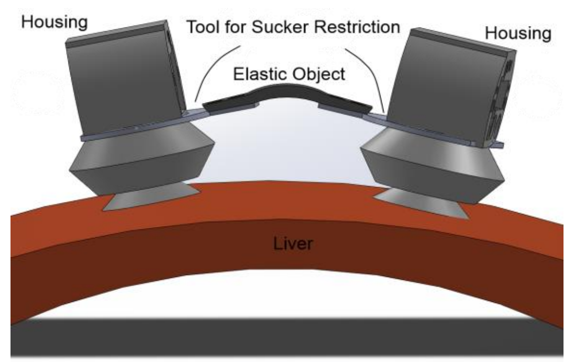


Figure 4. An illustration of 2-cup suction assembly.

TABLE III. Elastic materials

Material	Characteristic	Shear elastic modulus
Wood	Japanese cypress	76.9
	Japanese hemlock	More than 10,000
Plastic	Hard ABS	58.5
	ABS	25.0
Rubber	Wide	11.1
	Narrow	8.33

C. The 3-cup suction assembly

The distance between suction cups were fixed to 30mm. The binding materials length are also 30mm . Both the maximal adsorption force and tolerance to sideslip were measured. The layouts of suction cup distribution tested are a straight line, a right-angle triangle, and an equilateral triangle.

Figure 5. The layouts of 3-cup suction assembly.

III. RESULTS AND DISCUSSION

A. Determination of most suitable sucker characteristic in the water

TABLE IIII shows the maximal adsorption force of the 3 conditions. It is estimated that adsorption force were enough. This is because it was confirmed that the liver can be moved receiving the buoyancy of the water.

By comparing the suction cups with different size, made of silicon rubber, the results of absorption to the film revealed a well-known fact that adsorption force is proportional to the area of a suction cup.

Whereas, in the case of adsorption to the liver, the size is not the only predominant factor. Since the surface of the liver is not a plane, it might be easier for bigger suction cups to have air leakage due to incomplete contact. In addition, the difference in shape of the suction cups resulted in a big change. Firstly, the projection on the sucker part had a remarkable effect on adsorption force. Also, considering both the maximal adsorption force and tolerance to sideslip, bellows type is also an important factor. In summary, suction cups with bellows and projections are suitable for grasping the liver in the water.

B. Results of the 2-cup suction assembly

Fig. 6 shows one situation in the experiment. The liver deformed due to the gravity and pulling force, and a valley occurred. Not only the bellow of the suction cups, but also the elastic binding material determine the adhesion to the deformed organ surface. Fig. 7(a) shows the relationship between adsorption force and between-cup distance for each binding-material. A pink arrow at the top the figure shows the increasing order of elastic shear modulus. Fig. 7(b) shows the relationship between adsorption force and length of the binding-material.

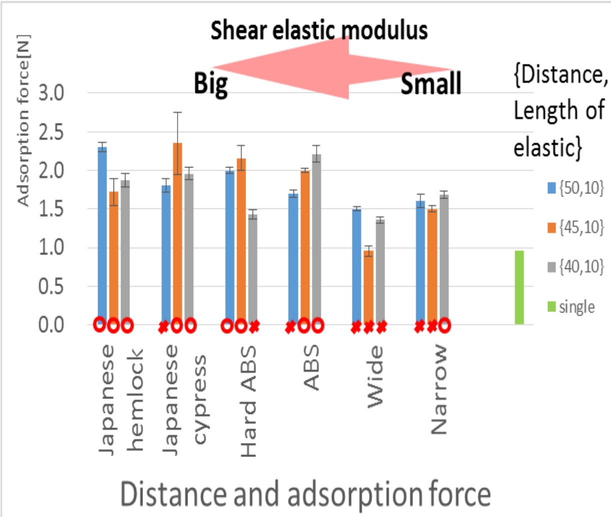
If a valley, as illustrated by a red line in Fig. 6, occurred, an “x” was marked under the bar in Fig. 7. Contrarily, an “o” was marked if there is no valley appeared.

As shown in Fig. 7(a), the longer the distance between two suction cups is, the bigger the adsorption force is. For the liver, shortening the distance between the suction cups could improve the adsorption force. But for the organs with different softness, the optimal distance should be different. This should be further investigated. The occurrence of a valley resulted in weaker adsorption force. The deformation of the organ, the elasticity of the binding material, and the structure (distance between cups, etc.) of the assembly interact to form the final morphology changes, and adsorption results. In this experiment, tolerance to sideslip was not investigated, however, a suitable structure might contribute to the prevention of that.

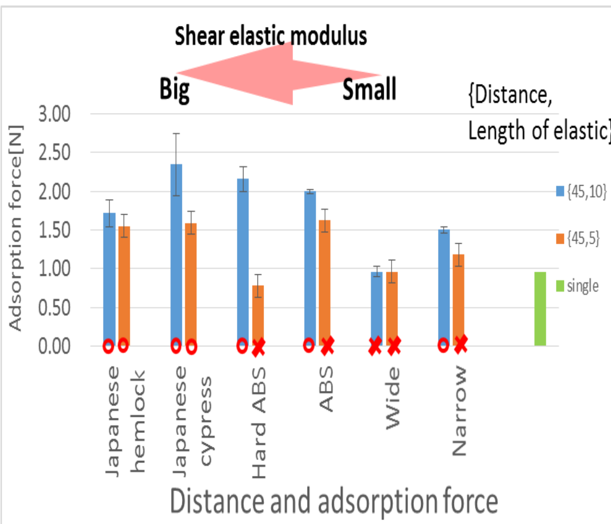
Figure 6. State of the bend.

TABLE IIII. Results of the adsorption force

Size	Shape	Material	Biggest adsorption force on the film[N]	Biggest adsorption force in the air [N]	Biggest adsorption force in the water[N]	Tolerance to sideslip[N]
ϕ 10	Flat with projections	Fluorine rubber	2.0	0.8	0.1	0.5
	Flat with projections	Silicon rubber	4.0	1.1	0.8	0.5
	Flat with projections	Conductive silicon rubber	3.5	0.5	0.1	0.5
	Flat with projections	Conductive NBR	2.7	0.9	0.7	0.5
ϕ 16	Flat	Silicon rubber	9.7	-	0.1	0.0
	Flat with projections	Silicon rubber	10.6	-	-	1.0
	Thin	Silicon rubber	4.6	0.1	-	0.0
	Thin with projections	Silicon rubber	6.6	-	-	0.5
	Deep	Silicon rubber	9.1	2.7	1.8	0.0
	Bellows	Silicon rubber	7.0	1.7	2.7	1.0
ϕ 40	Flat with projections	Silicon rubber	28.0	-	-	2.0
	Bellows	Silicon rubber	30.7	8	-	2.0



(a). Distance and adsorption force.



(b). Length of bind-material and adsorption force

Figure 7. Relations of adsorption force.

C. Results of the 3-cup suction assembly

The results of the 3-cup suction assembly were shown in Fig. 8. As shown in the graph, in terms of maximal adsorption force, there is not remarkable difference between the 2-cup and 3-cup suction assemblies. However, tolerance to sideslip was improved in comparison with the 2-cup suction assembly.

Regarding the 3 layouts, the straight line gave the best results. Triangle was expected to give better adsorption force and tolerance to sideslip, since this could give restriction evenly to the slip of different direction. But the results suggested the opposite. This might be because that the optimal distance between cups, and binding material for the 3-cup suction assembly, especially for the triangle layout, may be different with that of the 2-cup suction assembly. This needs further investigation.

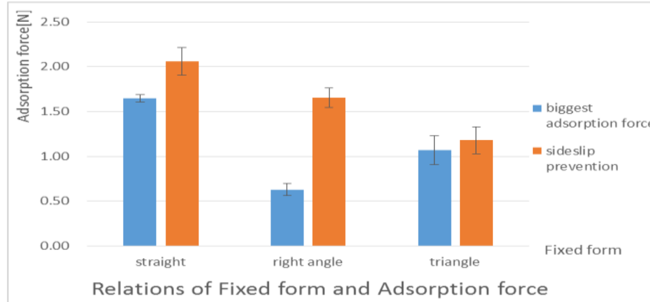


Figure 8. The adsorption force and tolerance to sideslip.

IV. CONCLUSION

In order to develop a small sucker manipulator for WaFLS support, experiments were conducted to determine suitable suction cups for underwater application was accomplished. Using suction cups (SMC corporation) with different size, material and cap shape. The results of the first experiment showed that suction cups with bellows and projections are suitable for grasping the liver in the water. The 2-cup suction assembly was suggested, expecting that the multiple-cup assembly might be able to absorb the effect of distortion. The distance between the suction cups might be an important factor to affect the adsorption force and tolerance to sideslip. The 3-cup suction assembly was also suggested, expecting that, the tolerance to sideslip could be improved. 3 different layouts were tested. Currently, the straight line gave the best results. Since the elastic binding material was not contained in the 3-cup suction assembly, further experiment was required.

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