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Development of Hydraulic-Driven Devices Using Additive Manufacturing

Tohru Sasaki[1], Yudai Fujiwara[1], Naotoshi Matsumoto[1], Masao Hebisawa[1], Takashi Naraoka[1], Kenji Terabayashi[1], Mitsuru Jindai[1], Kuniaki Dohda[2] & Satoshi Kuroda[3]

[1] *Department of Mechanical and Intellectual Systems Engineering, University of Toyama*
[2] *Department of Mechanical Engineering, Northwestern University*
[3] *Department of Neurosurgery, University of Toyama*

tsasaki@eng.u-toyama.ac.jp

Abstract
We developed hydraulically driven micro-forceps that can measure force when holding an object. The system uses Pascal's principle to measure small forces acting on the tips of the forceps. The holding force is calculated by determining changes in the internal pressure of the forceps. The trial-production forceps can measure very small forces, and surgeons using them can feel a force response when holding a model blood vessel. Previously developed forceps were not able to measure holding force accurately over a long period of time. The previous system used a syringe to supply water to the forceps. The syringe structure was suitable for supplying water with precision, but there was a gap between the cylinder and plunger. A leak occurred when the syringe supplied water to the forceps, causing the internal pressure acting on the forceps to decrease. The new system prevents leaking by suppling water with a bellows structure. The bellows were produced with a 3D printer that used light shaping. The structure, which was made through additive manufacturing, does not have a gap between the cyclinder and plunger, and it correctly measured internal pressure because there was no water leak. The new system can measure force with precision for an extended period of time when the forceps hold an object. This report describes the new water-supply system that was made through additive manufacturing and the results of our evaluation of its measurement precision and durability. This work was supported by JSPS KAKENHI Grant Number 15K05891.

Sensor, Actuator, Hydrostatic, Accuracy

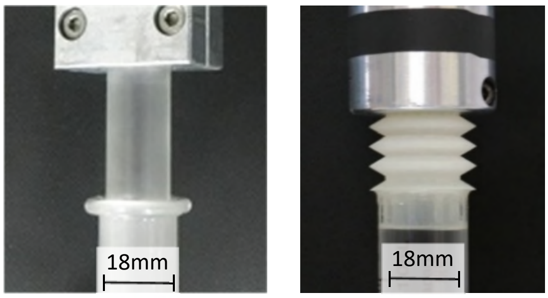
1. Introduction

Surgical manipulators, especially robot systems such as the da Vinci surgical system, are widely used to support human operations [1]. Existing manipulator systems are suitable for careful work, but they are not equipped with haptic sensing functions. Therefore, the surgeon must know advanced techniques for visually assessing physical contact during surgery. A force-sensing probe for use with the da Vinci tools was developed [2]. Such haptic sensing functions need to be incorporated into surgical manipulators.

For this reason, we developed hydraulically driven micro forceps that can measure force when holding an object. The developed system uses Pascal's principle to measure small forces acting on the tips of the forceps. The holding force is calculated by determining changes in the internal pressure of the forceps [3]. A previous system, which used a syringe to supply water to the forceps, was not able to measure holding force accurately over a long period of time. Using the syringe caused a leak when the syringe supplied water to the forceps, and the internal pressure acting on the forceps decreased. The new system prevents leaking by supplying water with a bellows structure, which was produced with a 3D printer that uses light shaping. The structure, which is made through additive manufacturing, did not have a gap between the cylinder and plunger, so it measured internal pressure correctly and had no water leak. The new system can measure force with precision for an extended period of time when the forceps hold an object. In this report, we describe the new water-supply system that was made through additive manufacturing and the results of our evaluation of its measurement precision and durability.

2. Development using additive manufacturing

Figure 1 shows the previous water-supply system that consists of a cylinder structure and the new one that consists of a bellows-pump structure. The new water-supply machine uses a bellows structure to prevent leaking. The bellows structure was produced with a 3D printer that uses light shaping. Specifically, we used 3D Systems' ProJet 3510 HD Plus (net build volume: 298 x 185 x 203 mm, resolution: 375 x 375 x 790 DPI, 32µ layers, material: VisiJet S300). Figure 2 shows the design of the bellows-pump. The outer diameter is 22 mm, and the valley diameter is 15 mm. The plate thickness of the bellows part is 0.2 mm, and that of the other parts is 1 mm. The distance between the bellows' valleys is 4 mm. Young's modulus in the design is approximately 2200 MPa.



(a) Previous (cylinder) **(b)** New (bellows-pump)
Figure 1. Altered part of water supply machine

3. Hydraulically driven system

Figure 3 shows the hydraulically driven system. A bellows pump is moved perpendicularly using a linear actuator. The water supply is delivered by a syringe 15 mm in diameter at a 0.221-μl resolution. A force sensor is attached between the plunger and the actuator rod of the linear actuator. The force sensor measures the amount of force acting on the plunger, which enables the internal pressure inside the syringe to be determined. The measured internal pressure is compared with the displaced-fluid pressure of the forceps, and the difference in quantity is measured as the holding force [4].

4. Forceps-drive experiment

In the forceps-drive experiment, the forceps closed without an object to hold. The linear actuator moved the syringe in accordance with a position command issued from a personal computer, and the syringe supplied water to the bellows tube of the forceps. Figure 4 shows the changes in internal pressure. The internal pressure of the previous mechanism decreased over time. However, the internal pressure of the new one decreased only slightly over time; it kept an approximately constant value in a steady state. This result shows that the new mechanism prevents water leakage. Thus, when the forceps hold an object, the mechanism can get an accurate measurement of the internal pressure of the forceps.

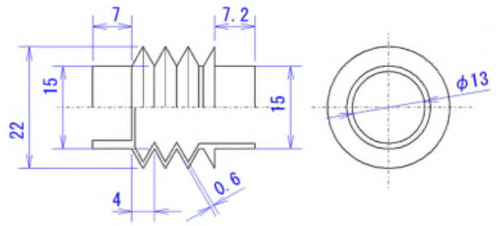


Fig.2 Design of bellows pump

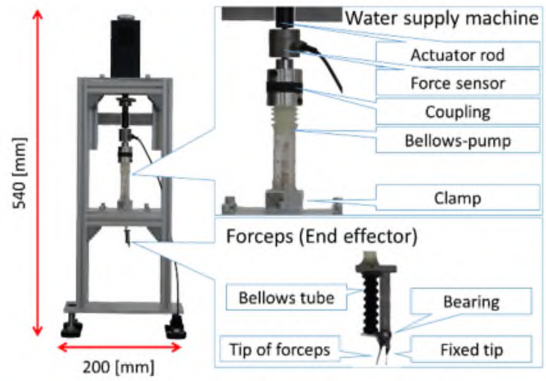


Figure 3. Hydraulic-Driven Devices

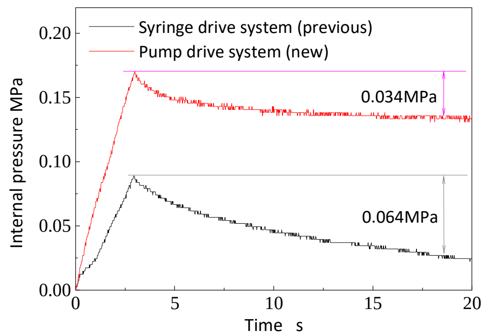


Figure 4. Comparison of water leakage

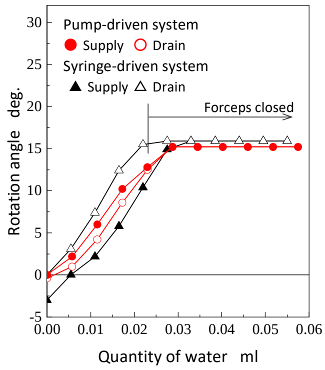


Figure 5. Forceps' angles

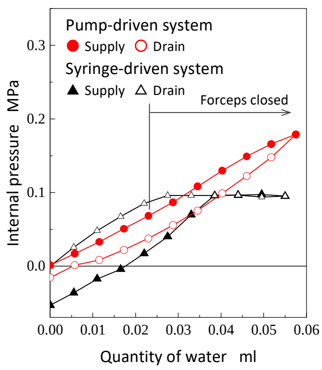


Figure 6. Internal pressure

5. Object-gripping experiment

The forceps held a model blood vessel and measured the forceps' angle and changes in pressure. The model blood vessel was 1 mm in diameter and made of silicon rubber. Figure 5 shows the changes in the rotary angle based on the quantity of water. The rotary angles linearly increased as the quantity of water increased until the forceps closed. With the previous mechanism, the syringe-driven system, the relationship between the rotary angle and the pressure exhibits significant hysteresis. However, because the new mechanism, the pump-driven system, has no water leak, it exhibits less hysteresis. Figure 6 shows the changes in internal pressure, which is based on the quantity of water. The internal pressure of the syringe system increased linearly as the quantity of water increased until the forceps closed. However, because the syringe-driven system had a water leak, its internal pressure did not change after the forceps closed. The internal pressure of the pump-driven system, however, increased linearly as the quantity of water increased after the forceps were closed. Therefore, the pump-driven system can measure changes in internal pressure when the forceps are gripping an object, enabling the gripping force of the forceps to be determined.

6. Summary

(1) We improved the water-supply machine by replacing the syringe-driven system with a pump-driven system to prevent water leaking.

(2) The pump-driven system, which was made using additive manufacturing i.e. 3D printing, was able to completely prevent water leaking.

(3) The pump-driven system exhibits less hysteresis than the syringe-driven system because the pump-driven system prevents water leaking.

(4) Because the internal pressure of the pump-driven system increases linearly as the quantity of water increases after the forceps close, the pump driven system can measure changes in internal pressure when the forceps are gripping an object, enabling the gripping force of forceps to be determined.

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