Design of tactile device for medical application using magnetorheological fluid

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Abstract. For the tactile recognition of human organ in minimally invasive surgery (MIS), this paper presents a novel tactile device that incorporates with magnetorheological (MR fluid). The MR fluid is contained by diaphragm and several pins. The operator for MIS can feel different force (or stiffness) from the proposed tactile device by applying different magnetic field or current. In order to generate required force from the device, the repulsive force from the human body is measured as reference data and an appropriate size of tactile device is designed and manufactured. It has been demonstrated via experiment that the repulsive force corresponding to the human body can be achieved by applying proper control input current. In addition, it has been shown that we can control the repulsive force by dividing the tactile device by several sections.

1. Introduction
Tactile sensation means to realize contact sensation and stimulate the skin, especially on fingertips. Beginning purpose of such devices is visual information transmission for blind person [1]. However, their potential is exploited, so numerous ranges of new application such as virtual object, training, game, rehabilitation and minimally invasive surgery (MIS) have appeared. Among them, application of MIS is urgently required. MIS is a procedure carried out through the skin or anatomical opening. So, the MIS systems only send back visual information. There is no information about viscosity and stiffness of the touched tissue or organ. This causes the surgeon not to feel what is happening inside patient. Therefore, it is essential to develop the tactile device.

Various mechanisms of tactile device have been researched; pin-arrays utilizing piezoelectric actuators [2], shape memory alloys [3], piezoelectric ceramics [4], ionic conductive polymer gel films [5], polymer fabrics [6], electric motors [7] and MR fluid. The rheological properties of MR fluid are reversibly and instantaneously changed by applying magnetic field to the fluid domain [8]. This behaviour can represent the compliance, damping and sliding feeling of flexible objects of the different materials [9]. Since then, many researches have continued to focus on the MR fluid applied in tactile applications. Scilingo et al. proposed a MR application able to mimic the compliance of biological tissues manipulated by surgical tools [10]. In another line of research, Liu et al. investigated

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the surface force response of a MR fluid-based haptic display with different electro-magnets in single cells, and their results provided a preliminary basis for future developments of this area [11].

The main objective of this research is to propose a new type of tactile device. The purpose of tactile device is to mimic a wide variety of tactile sensations during the minimally invasive surgery. Proposed tactile device consists of diaphragm which filled by MR fluid and movable pins. The magnetic circuit is installed between diaphragm and pin. When diaphragm is compressed by operator, the operator can feel the tactile sensation of MR fluid. The tactile sensation can be controlled by magnetic field. In order to determine design parameters of magnetic circuit, finite elements analysis of magnetic field is conducted and tactile device has been manufactured. In order to evaluate the performance of tactile device, the repulsive force measurement experiment has been conducted. From experimental results, it has successfully been demonstrated that the proposed tactile device can be effectively applied to MIS robot system.

2. Investigation on the human tissue

Recently, several attempts to realize tactile recognition was tried, there has been no successful results. This is because quantification of tactile recognition is very difficult. There are many physical indexes related with tactile recognition, but how these indexes can be affected to tactile recognition has not yet been investigated. So, in order to simplify the procedure, the repulsive force is only utilized for tactile recognition index. Subsequently, the reflection force of human is measured by force sensor. As shown in Figure 1, force sensor is connected with servomotor. So, measurement condition is controlled: 10 mms⁻¹. Measured force is resulted in table 1. From table 1, the objective range of repulsive force is between 0.6 N and 1.3 N.

![Figure 1. Measurement equipment for repulsive force.](image)

| Table 1. Repulsive force of human body. |
|----------------------------------------|
| **Body Part** | **Repulsive Force [N]** |
| Hand         | 0.6–0.9               |
| Neck         | 0.6–1.2              |
| Abdomen      | 0.4–1.3              |
| Thigh        | 0.7–1.2              |
| Back         | 1.0–1.3              |
3. MR tactile device
In order to realize the tactile recognition, the MR tactile device which consists of MR fluid and several pins is devised. MR fluid which can change its rheological properties by the external magnetic field is utilized to mimic a wide variety of tactile sensations. MR fluid is assumed to behaves as Bingham model given by

\[
\tau = \eta \dot{\gamma} + \tau_Y(H)
\]

\[
\tau_Y(H) = \alpha H^\beta
\]

where \(\tau\) is the shear stress, \(\eta\) is the dynamic viscosity, \(\dot{\gamma}\) is the shear rate, and \(\tau_Y(H)\) is the dynamic yield stress of the MR fluid. Dynamic yield stress of MR fluid is a function of the magnetic field, \(H\), and increases with respect to magnetic field. The parameters \(\alpha\) and \(\beta\) are characteristic values of the MR fluid. The measured yield stress of the employed MR fluid (MRF-132DG, LORD Corp.) is 0.0922\(H^{1.236}\) kPa and shown in Figure 2. The schematic configuration of tactile device is shown in Figure 3. MR fluid is inserted into diaphragm. MR diaphragm is supported by several pins. The pin consists of washer, nut and coil. The washer and nut is utilized for sealing of MR fluid. The bottom of MR diaphragm is connected to coil. By applying input current to coil, rheological properties of MR fluid is changed. Using this smart material, we can control the tactile recognition of surface of MR diaphragm. With this configuration, several sections of tactile device can realize diverse tactile sensations at same times.

![Figure 2. Yield stress of MR fluid.](image2)

![Figure 3. Schematic configuration of tactile device.](image3)
However, because magnetic field is developed at the bottom of the MR diaphragm, it is very difficult to dynamic modelling of the tactile device and design process of magnetic circuit. So, in order to get required magnetic flux density, experimental method is implemented as shown in figure 4. When permanent magnet is added at the bottom of the diaphragm, the repulsive force and magnetic flux density is measured. In order to generate 1.5 N, required magnetic flux density is 12 mTesla. Also, the number of coil turns is 400 and maximum input current is assumed as 3 A.

![Figure 4. MR diaphragm with permanent magnet.](image)

Next step is to confirm the performance of magnetic circuit. FEM analysis for magnetic circuit is conducted as shown in Figure 5. From Figure 5, it is confirmed that required magnetic flux density is successfully generated. The maximum magnetic flux density is 14 mTesla. As first phase of research, the tactile device has been manufactured with 4 pins and MR diaphragm. As second phase of research, the tactile device will be researched with 16 pins; then, it can represent more diverse tactile recognition.

![Figure 5. Magnetic analysis results of tactile device.](image)

4. Performance evaluation of MR tactile device
In order to evaluate the performance of tactile device, an experimental setup is established as shown in Figure 6. Because input current is applied to coil, input case is four. So, repulsive force is measured at 2 points (Area1 & Area 5) as shown in Figure 6; Area 1, 2, 3 and 4 are geometrically identical. Figures 7 - 10 present the experiment results of tactile device. From Figure 7, maximum measured force is
1.43 N. So, this result is bigger than repulsive force of human body. But, other results are some smaller than repulsive force of human body.

**Figure 6.** Experimental apparatus for MR tactile device.

**Figure 7.** Experiment results at Area 1 (Pin 1&Pin 2).

**Figure 8.** Experiment results at Area 5 (Pin 1).

**Figure 9.** Experiment results at Area 5 (Pin1&Pin 2).

**Figure 10.** Experiment results at Area 5 (Pin1&Pin 3).
In order to apply experiment results to real applications, the relationship of repulsive force is experimentally obtained as follows:

\[ F_1 = 0.4 + 0.04 \cdot I_1 + 0.015 \cdot I_1^2 + 0.024 \cdot I_2 + 0.046 \cdot I_1 \cdot I_2 + 0.022 \cdot I_2^2 \quad (\text{Area 1,2,3,4}) \]

\[ F_2 = 0.4 + 0.09 \cdot I_1 + 0.057 \cdot I_2 + 0.012 \cdot I_1 \cdot I_2 + 0.058 \cdot I_3 - 0.01 \cdot I_1 \cdot I_3 \]

\[ + 0.059 \cdot I_4 - 0.012 \cdot I_1 \cdot I_4 \quad (\text{Area 5}) \]

where \( I_1, I_2, I_3 \) and \( I_4 \) are applied current of each pins.

5. Conclusion
In this study, a new type of tactile device was proposed using MR fluid and performance of the proposed tactile device was evaluated. The proposed tactile device consists of diaphragm which filled by MR fluid and several pins. Using MR fluid, tactile device can mimic a wide variety of tactile sensations. Thus, the proposed tactile device can provide repulsive information of the organ to surgeon. In order to determine design parameters of magnetic circuit, finite elements analysis of magnetic field has been conducted and tactile device has been manufactured. Repulsive force experiments have been conducted to evaluate performance on the tactile rendering of the proposed device. From these results, the practical feasibility of the proposed tactile device has been investigated. The proposed tactile device is quite satisfactory for the application of MIS robot system.

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