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A new tactile device using magneto-rheological sponge cells for medical applications: Experimental investigation

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ABSTRACT

This work proposes a new tactile device that uses a single magneto-rheological (MR) sponge cell to realize the viscoelastic sensation of real organs. The proposed MR sponge cell can be usefully applied to medical fields to provide tactile information to surgeons who perform robotic surgery and doctors who receive training for practicing surgery with a computer-based simulator. In order to demonstrate the effectiveness of the proposed MR sponge cell, a 3-axis robot is designed and manufactured as an experimental apparatus. Using the robot, the relaxation times and repulsive forces of the MR sponge cell are measured and compared among three animal specimens: pork, pork rind, and pork heart. It is noted that the specimens represent the soft or/and hard tissues of human organs. The relaxation times are obtained from exponential equations based on the measurement data according to the properties of the viscoelastic material. The repulsive forces, normal force, tangential force, and bending moment are determined on the basis of comparison criteria of the beam bundle model (BBM). It is shown that the proposed MR sponge cell can effectively represent different feeling of the sensation of the specimens by applying different magnetic intensity to the cell domain.

1. Introduction

Robot technology is enhancing several fields such as space exploration, manufacturing and construction. Recently, the medical market is also being greatly influenced by robot technology [1]. Robot-assisted minimally invasive surgery (RMIS) is commonly performed using surgical robots such as the da Vinci™ robot [2], which is controlled by a surgeon. Numerous studies related to RMIS have been undertaken so far. Mack [3] introduced advances in surgery, especially minimally invasive and robotic surgery. Oh et al. [4] presented a 4-degree-of-freedom surgical master in cyberspace for RMIS. Choi et al. [5] developed a surgical master with image processing for RMIS. However, in these research works the surgical robot does not offer haptic sensation to the surgeon. Therefore, the surgeon cannot distinguish between normal organs and cancer cells. This limitation may cause medical accidents. Hence, a tactile device which is directly connected to the surgeon is very essential to operate safe and accurate robotic surgery.

When a tactile application is introduced, it is very helpful for doctors to feel organs in training and to distinguish between soft and hard tissues. Generally, the doctors in training period practice various simulations through a realistic computer-based simulator for surgery. Even though the doctors in training process repeat simulation motion numerous times, they cannot easily encounter the sensation of real tissues in those simulations. A number of attempts have been made to provide medical applications with haptic sensation. Franks et al. [6] developed a pneumatic balloon-based system for tactile feedback in robotic surgery. Nowlin et al. [7] patented a new method using grip strength with tactile feedback. Shelton et al. [8] patented a motor-driven surgical instrument for cutting and fastening with tactile position feedback. Goethals et al. [9] presented a tactile display based on micro-hydraulic actuators. Despite many research works on the tactile devices for medical application, it is hard to simulate the sensation of separate organs because each human organ has different properties.

In this regard, a magneto-rheological (MR) fluid has been effectively employed to generate the repulsive forces of an organ during robotic surgery. It is well known that MR fluid is a smart material which features controllable rheological characteristics by the magnetic intensity. The MR fluid can change from a liquid-like state to a solid-like state, and vice versa depending on the magnetic field. This

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is achieved by the transition of iron particles when controlling the strength of applied the magnetic fields. Liu et al. [10] developed a prototype tactile display incorporating MR fluid. Scilingo et al. [11] proposed two different haptic display prototypes using pinch-grasp and whole-hand immersive exploration. Another MR haptic system applying force feedback control for telerobotic surgery was modeled by Ahmadkhanlou et al. [12]. Recently, Oh et al. [13] presented a novel tactile device containing a diaphragm and several pins. Bachman and Milecki [14] proposed a one-axis haptic joystick using MR brake. Blake and Gurocak [15] built a force feedback MR glove using six MR brakes, and Nguyen and Choi [16] developed a bi-directional MR brake for the haptic master. Liu et al. [17] and Li et al. [18] investigated the performance of a MR actuator as a joystick in virtual reality. Reed and Book [19] also introduced a new dissipative passive haptic display that uses magneto-rheological (MR) brakes as actuators. As mentioned above, MR fluid is a smart fluid that can change its phase depending on the magnetic fields. However, it is not easy to realize the viscoelastic sensation of organs perfectly because MR fluid has no elastic property. The combination of elastomeric matrices with MR fluids has been researched intensely in the last few years. MR foams are a new kind of magnetic field-responsive smart material. The foams are loaded with MR fluids and have potential advantages due to their elasticity. Open-celled polyurethane foam is usually used in MR foams. Because of its porous structure, the foam leads to complicated magnetic and mechanical properties. Schumann et al. [20] studied the effect of magnetic particles on the pores in soft polyurethane foams. The mechanical properties of foams strengthened by iron particles were studied by Goods et al. [21]. However, it has been identified that the sensation realization corresponding to the human organs is very hard using the field-dependent polyurethane foams only [20,21].

Consequently, the research objective of this work is to propose a novel type of a tactile sensing device which can effectively represent the human organs which consist of soft and hard tissues. In order to achieve this goal, a new tactile device using an MR sponge cell is proposed to represent the viscoelastic feelings of organs. In contrast to other tactile devices using MR fluid only, the proposed MR sponge cell can realize the elasticity as well as the viscosity of the organs. Thus, the MR sponge cell proposed in this work is innovative in this aspect. The effectiveness of the MR sponge cell is evaluated by its relaxation time and reaction forces by operating a 3-axis robot. The specimens used in this work are pork, pork rind and pork heart those can represent the soft and hard tissues of the human organs. It is well known that porcine organs have similar properties to human organs for physiological and structural aspects through several researches. Groenen et al. have presented the assembly and analysis of the genome sequence of a female domestic Duroc pig and identified that pig genome is very similar to human genome in terms of the shape of tissues and organs [22]. Furthermore, it has been demonstrated that all data obtained from both human and porcine organ show similar tendency [23–25]. Therefore, it can be regarded that the MR sponge cell realizes the sensation of human organs when the experiments with porcine organs are successful. The specimens are tested and their results on the relaxation and reaction force properties are compared at different magnetic field strength. In order to clearly explain the application of the MR sponge cell in the robotic surgery, a schematic diagram for RMIS is here presented as shown in Fig. 1. As seen from the figure, the surgeon can feel the sensations of organs through the MR sponge cell. These sensations are quantified as reaction forces obtained from a force sensor connected to the end effector of the surgical robot. Then, the MR sponge cell is affected by the magnetic fields corresponding to the reaction forces. Therefore, the MR sponge cell which is a tactile sensing device is very effective for the surgeons in RMIS because it prevents medical accidents which can be occurred without any information about sensations of organs.

Table 1
Properties of open celled polyurethane foam.

Property	Value
λ	1.256–1.281
$\frac{\rho^*}{\rho}$ (%)	2.36–2.44
$\frac{E^*}{E}$ (%)	0.200–0.215
(kPa)	4.9–5.8
σ_{1P} (kPa)	4.8–5.7

2. MR sponge cell

MR fluid belongs to a group of rheological materials with phases that are changed under magnetic fields. Regular MR fluids consist of ferromagnetic or paramagnetic particles dispersed in a carrier fluid. The particles are solid, micron-sized and highly magnetizable and the particles can occupy up to 50% of the MR fluid volume. The carrier fluids are mineral and silicon oils and synthetic hydrocarbons.

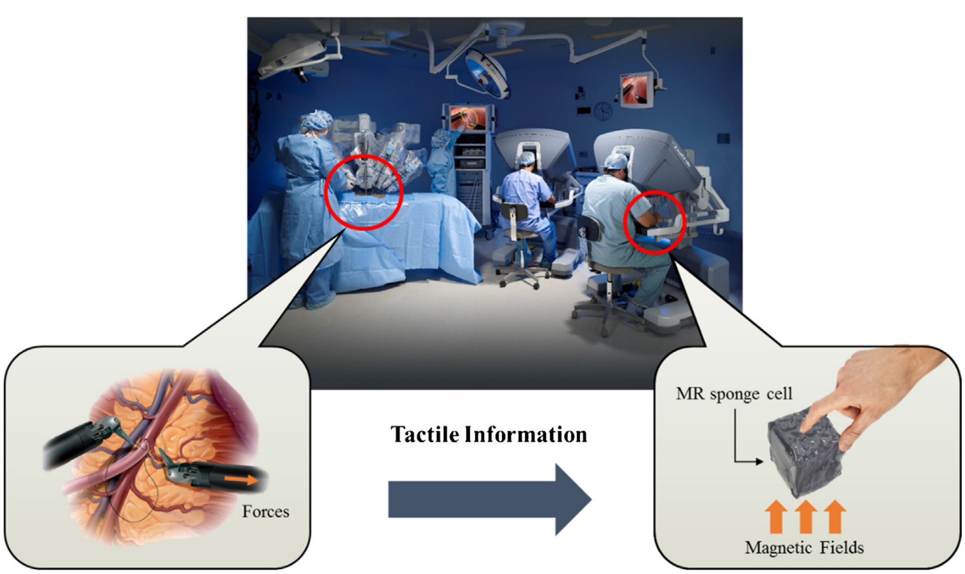

Fig. 1. RMIS using MR sponge cell as a tactile sensor.