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Design of a Haptic Brake Based on Magnetorheological Fluid for VR-based Laparoscopic Training

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Abstract

This study proposes the design of a compact haptic actuator that can be integrated into laparoscopic scissors. In laparoscopic surgery, surgical proficiency is crucial owing to visual and spatial constraints, and a haptic feedback device with diverse force profiles can significantly contribute to skill improvement. Active actuators like AC or DC motors are too bulky for handheld devices like haptic laparoscopic scissors and suffer from instability issues that disrupt the interaction with the physical environment. To address these constraints, we designed a haptic brake based on the properties of magnetorheological (MR) fluid. The proposed haptic brake can generate a torque of up to 78.4 N··mm using the viscosity change of MR fluid under a magnetic field, with a power consumption of 1.5 W. Simulation results and theoretical calculations were used to derive the optimum design variables, enabling the implementation of a compact and efficient haptic feedback mechanism. This study is expected to contribute to enhancing the performance of laparoscopic-surgery simulators, thereby improving the realism and user experience of virtual surgical training by providing effective haptic feedback in actual laparoscopic surgical environments.

Keywords: *Magnetorheological Fluid, Laparoscopic Surgery, Haptic Scissors, Haptic Feedback*

1. Introduction

Laparoscopic surgery is a minimally invasive procedure that offers various advantages such as expedited patient recovery and a reduced risk of postoperative complications. However, owing to its visual and spatial constraints, this surgical method is substantially influenced by the surgeons' proficiency [1,2]. Surgical simulations in virtual environments are vital for enhancing proficiency and surgical skills [3]. Previous studies

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have employed active actuators based on direct current (DC) motors to deliver various haptic feedback during cutting procedures, thereby facilitating the replication of the relevant tissue characteristics [4,5]. The motor used in this paper has a power consumption of 20W, a rated voltage of 24V, and a height of 54.4mm, making it not only large for one-handed operation but also relatively high in power consumption and voltage. Additionally, one study employed a hybrid actuator by integrating a DC motor with a magnetorheological (MR) brake [6]. Existing devices based on active actuators, such as alternating current (AC) or DC motors, are too bulky to be incorporated into handheld devices, such as haptic laparoscopic scissors. Moreover, these devices based on active actuators suffer from instability issues that shatter the illusion of interaction with the physical environment. [7-9]. Therefore, this paper presents a compact haptic brake designed to efficiently provide various force feedback profiles for scissoring during laparoscopic surgery. The haptic brake uses MR fluid, whose viscosity can be altered based on the magnetic field. This enables precise resistance (or torque) control with low power consumption, compact structure, and fast response speed. Specifically, we designed a haptic brake that efficiently reproduces a wide range of torques and a compact system that can replicate the force profile of various surgical environments. This MR-fluid-based haptic brake can enhance the immersion and efficiency of virtual-reality (VR)-based laparoscopic-surgery training. The following section describes the overall structure and key components of the proposed haptic actuator, including a performance evaluation through simulation analysis to determine the optimal parameters. Additionally, simulations based on the housing thickness were conducted to achieve an optimal balance between the actuator performance and durability.

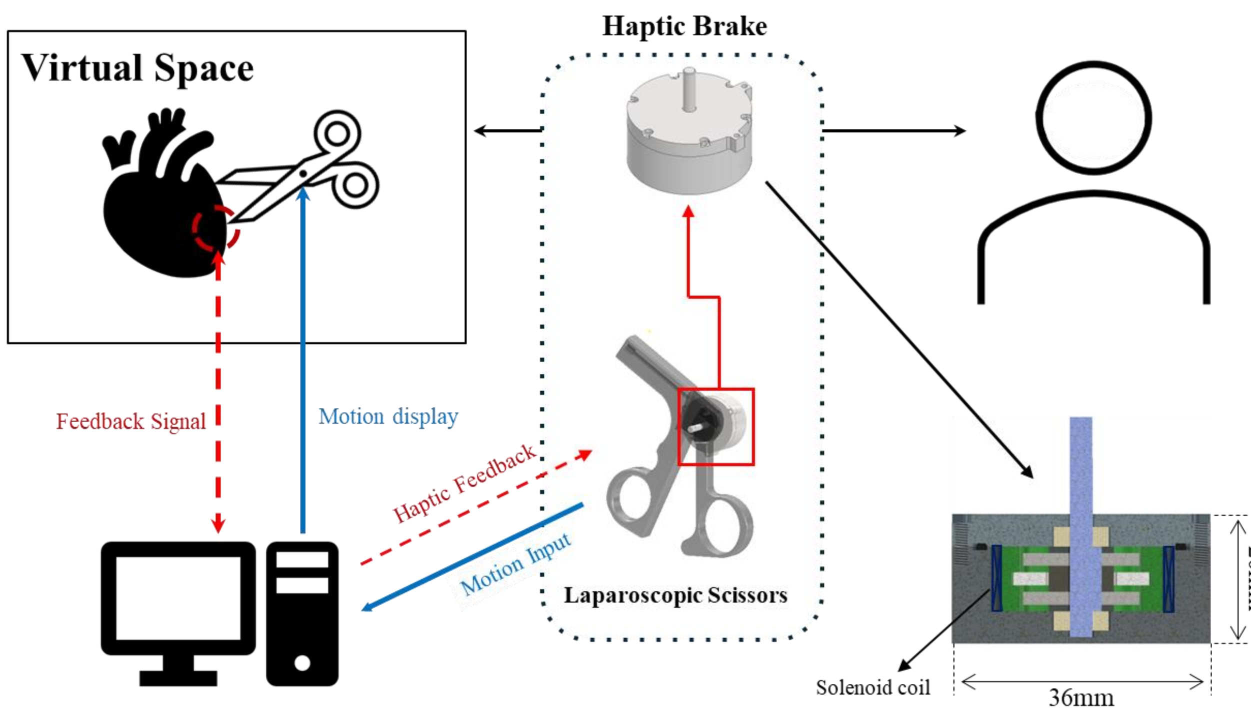

Figure 1. Conceptual design of the proposed haptic feedback system for laparoscopic scissors

2. Proposed haptic-actuator design

This section details the overall structure of the proposed haptic actuator, including its design rationale and key components, as well as the optimization process implemented for enhancing its performance and efficiency.

Subsequently, a simulation analysis was conducted to validate its performance and the results were used to refine its parameters.

2.1 Overall structure

MR fluid comprises three main components: magnetic particles, a carrier fluid, and additives. The application of a magnetic field aligns these particles along the magnetic induction lines, thereby increasing the inter-particle attraction and instantly altering the viscosity of the fluid [10]. Generally, MR fluids operate in three modes: flow, shear, and squeeze [11]. This study employed the shear mode, wherein the fluid flows between two relatively moving plates. By leveraging the magnetic-field-based variable-viscosity characteristics of MR fluids, resistance is applied to a rotating disc to modulate its rotational speed (Figure 2) [12].

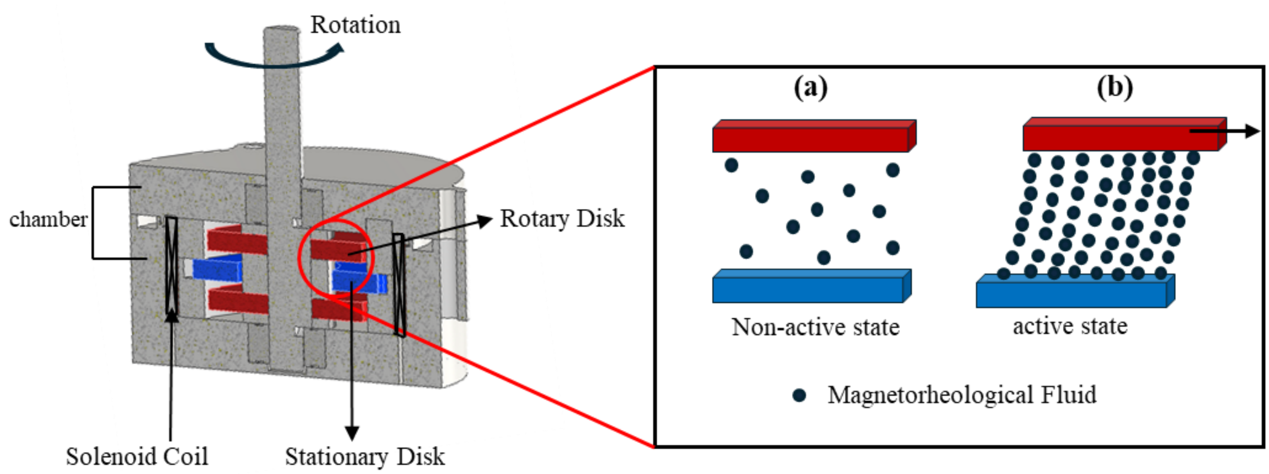

Figure 2. Working principle of the haptic brake: MR fluid particles in the (a) absence of a magnetic field and their (b) alignment in the presence of a magnetic field, resulting in shear-mode operation

As shown in Figure 3, the proposed haptic brake comprises eight components: housing case and body, shaft, disc driven, sus-stationary-top, sus-stationary-bottom, sus-shaft ender, and disc stationary. A solenoid coil is inserted into the housing case and the MR fluid is injected between the discs wi thin the housing case. These discs are attached to the rotating shaft and a rubber O-ring is included to prevent fluid leakage. As the shaft rotates, the applied magnetic field changes the viscosity of the MR fluid, thereby generating resistance during rotation. To maximize resistance while maintainin g compactness, finite element (FEM) analysis was employed to enhance the efficiency of the MR brake. Additionally, to ensure that the brake did not interfere with the cutting action, its initial size was constrained to 40 mm and the housing thickness was varied. Ultimately, 4 mm was selected as the optimal thickness to maintain efficiency.

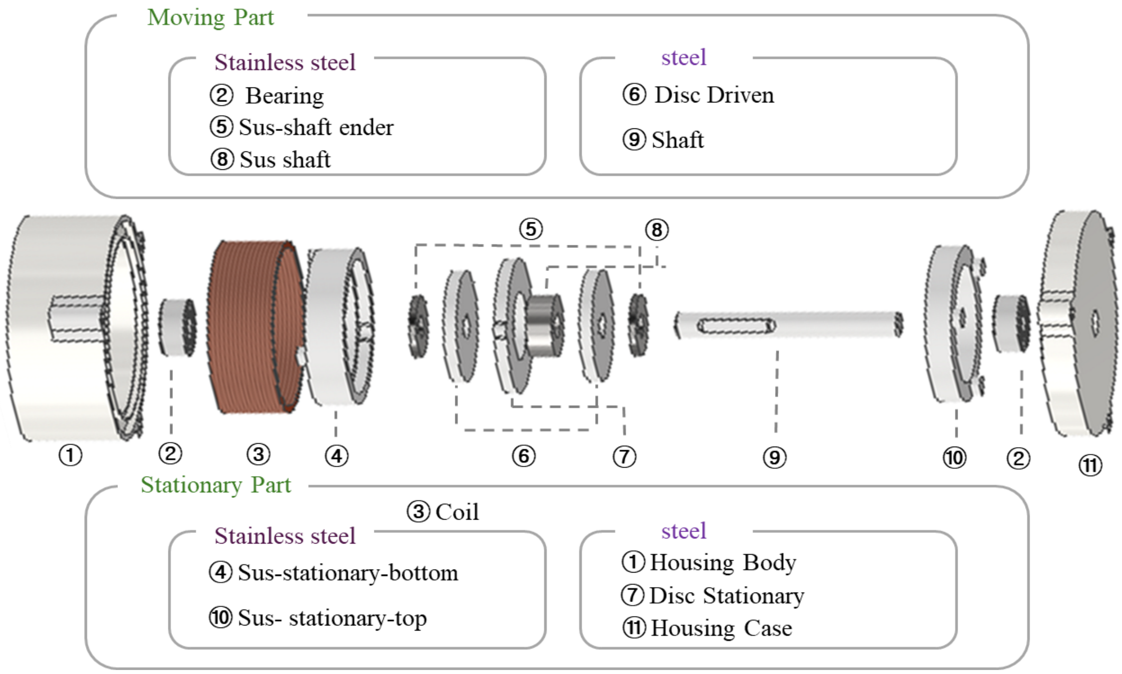

Figure 3. Schematic of the haptic brake, illustrating its individual components

2.2 Simulation-based analysis

In the initial variable design, the magnetomotive force of the coil was determined based on the size and power-consumption constraints. The relationship between the magnetomotive force generated by the solenoid coil and the applied voltage, based on the working principle of the brake illustrated in Figure 2 [12], allows calculating both the magnetomotive force and power consumption. As shown in Figure 4, the maximum magnetomotive force can be determined by varying the wire diameter, with the intersection of the curves representing the point of maximum magnetomotive force for the solenoid coil. Additionally, a graph was plotted to illustrate the variations in coil diameter with reductions in the housing thickness within the specified size constraints, as shown in Figure 4.To miniaturize the haptic actuator, the maximum power consumption was limited to approximately 1.5 W and based on the calculation results shown in Figure 4 (b), a wire thickness of 0.18 mm in the coil was determined to be appropriate. Subsequently, the determined maximum magnetomotive force was applied to the FEM simulations to analyze the magnetic-flux density (B) within the gaps of the haptic-actuator discs. Figure 4(c) presents the torque values calculated based on (a) and (b), achieved by reducing the thickness of the outer housing while adhering to the 40 mm design constraint for the haptic brake. As the housing thickness was decreased in 1 mm increments, FEM simulation results showed that the Magnetic flux density (B) did not significantly diminish, and the torque values exhibited a similar pattern. However, to prevent leakage, additional space for an O-ring was necessary, requiring a 2 mm reduction in housing thickness. This adjustment reduced the overall diameter of the haptic brake to 36 mm, enabling a more compact and lightweight design.

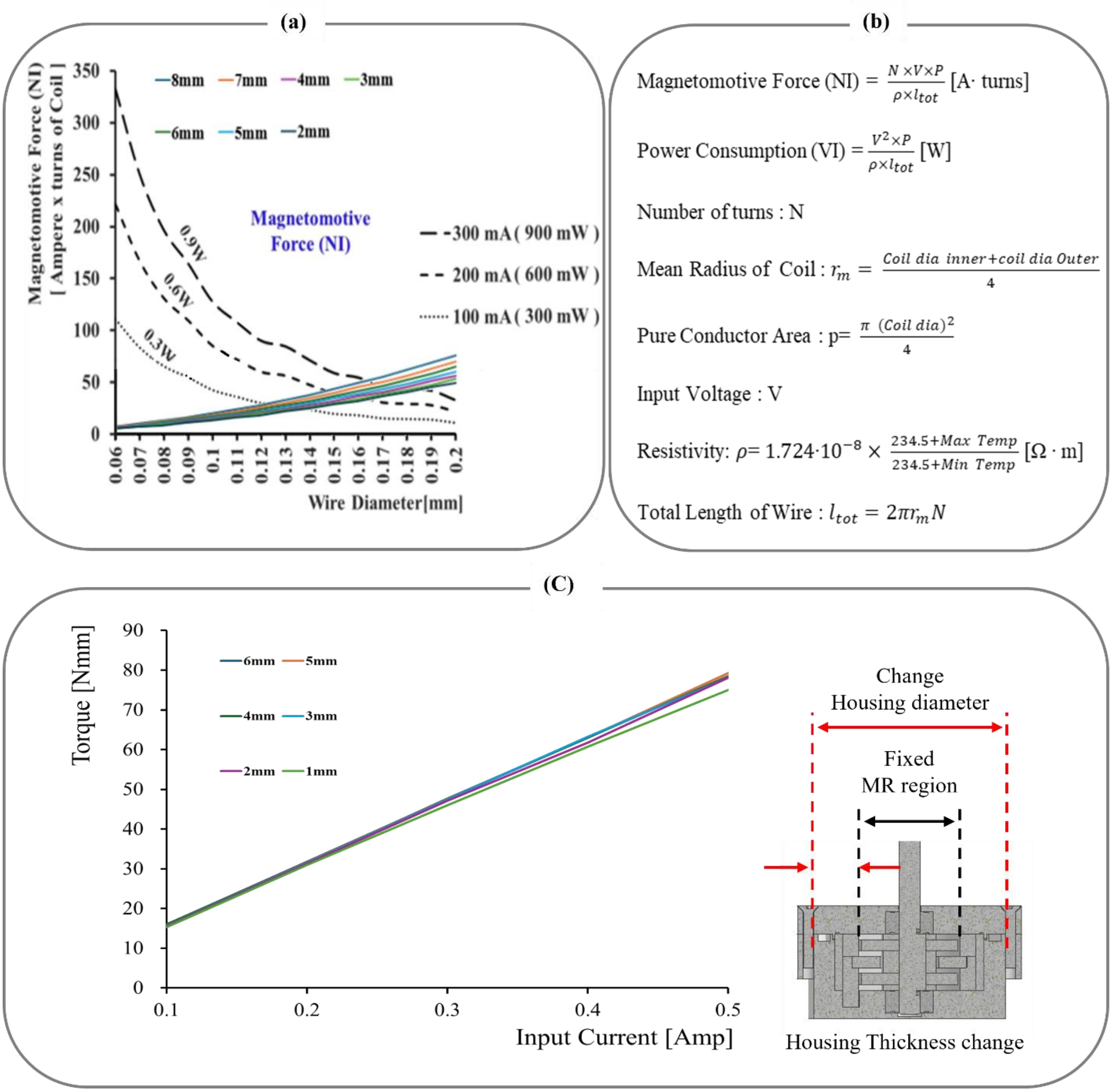

Figure 4. Parametric study for the solenoid coil: (a) Magnetomotive force variation with wire diameter (b) Formulas for calculating the magnetomotive force (C) Torque Calculation Based on Housing Thickness Variation and Current Input

Figure 5 illustrates the design and performance evaluation process of the haptic brake. The first step, shown in Figure 5(a), involves optimizing the housing height to minimize the overall dimensions while maintaining functionality. Next, as shown in Figure 5(b), the magnetomotive force is calculated using the equations shown in Figure 4 by determining the number of coil turns based on the wire diameter and considering the current and power-supply limitation, which affect the viscosity of the MR fluid and play a key role in influencing the magnetic-flux density. Thereafter, as shown in Figure 5(c), an FEM simulation is conducted to calculate the magnetic-flux density within the haptic actuator based on the determined magnetomotive force**.** As shown in Figure 5(d), the calculated magnetic-flux density is used to compute the yield stress acting on the MR fluid through empirical formulas, as elucidated by Ryu et al. [14]. Yield stress represents the behavior of a fluid under the influence of a magnetic field. In Figure 5(c), Φ is the article volume percentage (Φ =40), is the permeability of free space (μ_0=$4\pi \times 10^{-7} T \cdot m/A$), and H is the magnetic field strength (A/m). Finally, as shown in Figure 5(e), the resistive torque and force generated by the actuator are calculated using the yield stress, where N, $R_0, R_i, \omega, T_s, h, \mu$ are the number of gaps, outer radius, inner radius, angular velocity, frictional torque, gap size, and dynamic viscosity, respectively [15]. This step quantitatively determines the maximum resistive torque and force that the actuator can generate based on the yield stress of the MR fluid and magnetic flux density. The graphs illustrate the variations in torque and force according to the housing-body thickness, aiding in performance evaluation and design optimization. Each of these steps represents a crucial phase in the design and performance evaluation of the haptic actuator. The entire process aims to quantify the performance differences based on the current and housing-body thickness, enabling the selection of optimal design parameters for achieving best possible haptic feedback.

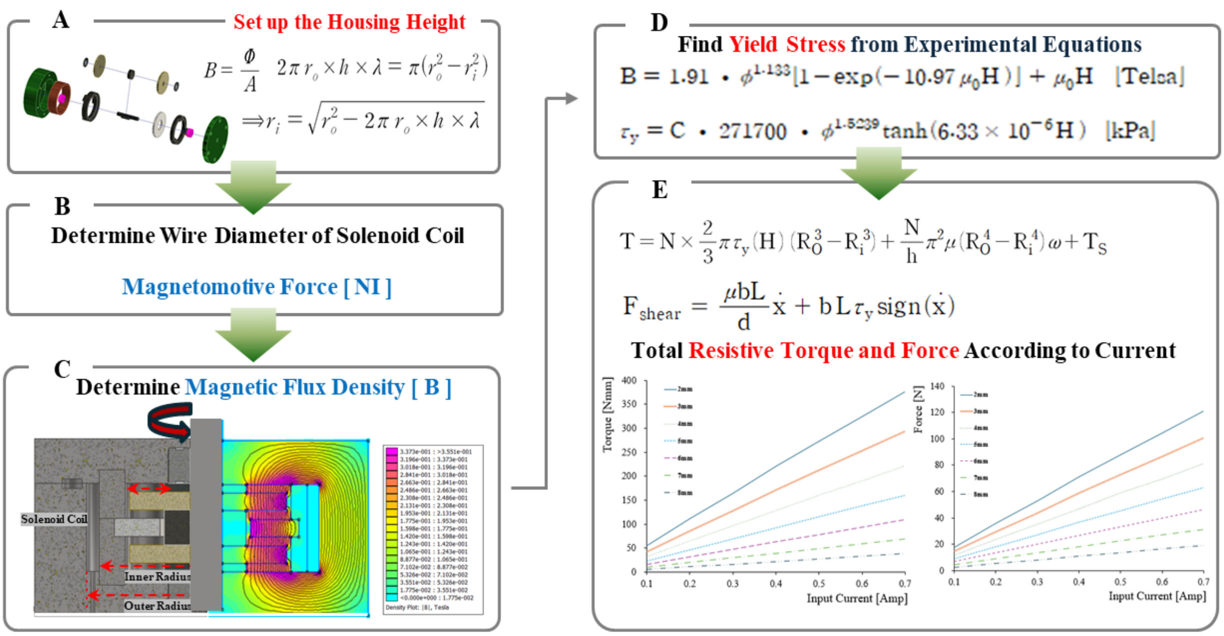

Figure 5. Simulation analysis of the haptic brake: (a) Basic design of haptic actuator, (b) parametric design, (c) FEM analysis, (d) yield stress calculation, (e) resistive force and torque with analytical force equations

The MR fluid (MRF-1400CG) was obtained from Lord Corporation. The torque was calculated based on the housing thickness, using the equations presented in Figure. 5. For a housing thickness of 4 mm and maximum power consumption of 1.5 W, a torque of 78.4 N·mm was obtained. Table 1 summarizes the values and characteristics of the main components used for fabricating the haptic actuator. The calculation results showed that when the magnetomotive force was between 30 and 150 A·turn, the torque ranged from 15.9 N·mm to 78.4 N·mm.

Table 1. Determined parameters used for fabricating the haptic actuator

Component	Design Parameters	Unit	Value
Solenoid Coil	Height	mm	10
	Inner diameter	mm	25.4

	Outer diameter	mm	27.6
	Wire Diameter	mm	0.16
	Maximum Power Consumption	W	1.5
	Input Voltage	V	3
	Number of Turns	turns	300
Physical Constant	Resistivity	Ω/m	$2 \cdot 10^{-8}$
	MR Fluid Viscosity	μ/m^2	0.28
	Wall Thickness	mm	4
	Radius	mm	36
Housing	Height	mm	20
	Top Thickness	mm	5
	Bottom Thickness	mm	5
Output	Magnetomotive Force	A·turn	30~150
	Torque	N·mm	15.9~78.4

3. Conclusion

This paper presented the design of a compact haptic actuator that can be integrated with laparoscopic scissors. To achieve miniaturization, the housing thickness was reduced while ensuring adequate resistance. Performance evaluation through a simulation model showed that the proposed haptic actuator could generate a torque of 78.4 N·mm with a power consumption of 1.5 W, utilizing the shear mode of the MR fluid.

In future research, a haptic actuator will be fabricated and compared with a simulation model to validate its performance. Subsequently, it will be applied to actual laparoscopic scissors and the cutting patterns will be analyzed. By implementing the actuator in a virtual environment and controlling the magnetic field to drive it and provide haptic feedback during the cutting of virtual tissue, the generated feedback can be compared with actual cutting conditions to assess its effectiveness.

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References

[1] A. Buia, F. Stockhausen, and E. Hanisch, “Laparoscopic Surgery: A Qualified Systematic Review.,” *World Journal of Methodology*, Vol. 5, No. 4, pp. 238–254, December 2015. DOI: https://doi.org/10.5662/wjm.v5.i4.238

[2] T. Mori, H. Endo, T. Misawa S. Yamaguchi, Y. Sakamoto, M. Inomata, Y. Sakai, Y. Kakeji, H. Miyata, Y. Kitagawa, and M. Watanabe, “Involvement of a Skill-Qualified Surgeon Favorably Influences Outcomes of Laparoscopic Cholecystectomy Performed for Acute Cholecystitis,” *Surgical Endoscopy*, Vol. 36, No. 8, pp. 5956–5963, August 2022. DOI: https://doi.org/10.1007/s00464-022-09045-9

[3] R. M. Satava, “Virtual Reality Surgical Simulator: The First Steps,” *Surgical Endoscopy*, Vol. 7, No. 3, pp. 203–205, May 1993.

[4] Ben-Ur, E., *Development of a Force-Feedback Laparoscopic Surgery Simulator*, SM Thesis. Massachusetts Institute of Technology, Cambridge, MA, USA., 1999.

[5] S. Greenish, V. Hayward, V. Chial, A. Okamura, and T. Steffen, “Measurement, Analysis, and Display of Haptic Signals During Surgical Cutting,” *Presence: Teleoperators and Virtual Environments*, Vol. 11, No. 6, pp. 626–651, December 2002. DOI: https://doi.org/10.1162/105474602321050749

[6] B. Gonenc and H. Gurocak, “Virtual Tissue Cutting with Haptic Feedback Using a Hybrid Actuator with DC Servomotor and Magnetorheological Brake,” *Journal of Computing and Information Science in Engineering*, Vol. 16, No. 3, p. 030902, June 2016. DOI: https://doi.org/10.1115/1.4033046

[7] R. J. Adams, M. R. Moreyra, and B. Hannaford, “Stability and Performance of Haptic Displays: Theory and Experiments,” in *Proc. ASME International Mechanical Engineering Congress and Exhibition*, pp. 227-234, Nov. 15-20, 1998. DOI: https://doi.org/10.1115/IMECE1998-0259

[8] J. E. Colgate, P. E. Grafing, M. C. Stanley, and G. Schenkel, “Implementation of Stiff Virtual Walls in Force-Reflecting Interfaces,” in *Proc. IEEE Virtual Reality Annual International Symposium*, pp. 202–208, Sep. 18-22, 1993. DOI: https://doi.org/10.1109/VRAIS.1993.380777

[9] J.-U. An, *Stability and Performance of Haptic Interface with Active/Passive Actuators*, Ph.D. Thesis. Korea Advanced Institute of Science and Technology, Daejeon, South Korea, 2005.

[10] Y. Song, L. Li, Y. Tian, Z. Li, and X. Yin, “A Novel Master–Slave Interventional Surgery Robot with Force Feedback and Collaborative Operation,” *Sensors*, Vol. 23, No. 7, p. 3584, January 2023. DOI: https://doi.org/10.3390/s23073584

[11] G. Lo Sciuto, P. Kowol, and G. Capizzi, “Modeling and Experimental Characterization of a Clutch Control Strategy Using a Magnetorheological Fluid,” *Fluids*, Vol. 8, Bo. 5, p. 145, May 2023. DOI: https://doi.org/10.3390/fluids8050145

[12] T.-H. Yang, H. Son, S. Byeon, H. J. Gil, I. W. Hwang, G. Jo, S. Choi, S-Y. Kim, and J. R. Kim, “Magnetorheological Fluid Haptic Shoes for Walking in VR,” *IEEE Transactions on Haptics*, Vol. 14, No. 1, pp. 83–94, January 2021. DOI: https://doi.org/10.1109/TOH.2020.3017099

[13] S. M. Kalikate, S. R. Patil, and S. M. Sawant, “Design and Simulation of Magneto-Rheological (MR) Brake for Automotive Application,” SAE International, Warrendale, PA, SAE Technical Paper 2014-28–0042, April 2014. DOI: https://doi.org/10.4271/2014-28-0042

[14] S. Ryu, J.-H. Koo, T.-H. Yang, et al., “Design, Simulation, and Testing of a Magnetorheological Fluid–Based Haptic Actuator for Mobile Applications,” *Journal of Intelligent Material Systems and Structures*, Vol. 26, No. 13, pp. 1670–1678, September 2015. DOI: https://doi.org/10.1177/1045389X14536009

[15] S.-B. Choi, S.-R. Hong, C.-C. Cheong, and Y.-K. Park, “Comparison of Field-Controlled Characteristics between ER and MR Clutches,” *Journal of Intelligent Material Systems and Structures*, Vol. 10, No. 8, pp. 615–619, August 1999. DOI: https://doi.org/10.1106/217G-CEUN-Q710-AB60