2023 IEEE/ASME International Conference on Advanced Intelligent Mechatronics (AIM)
June 28-30, 2023. Seattle, Washington, USA

Development of a Magnetorheological Elastomer Actuator for a Mixed Reality Haptic Glove

Matthew Daniel Christie
School of Mechanical, Materials, Mechatronic, and Biomedical Engineering, University of Wollongong,
Wollongong, Australia
mchristi@uow.edu.au

Taine Fredericksen
School of Mechanical, Materials, Mechatronic, and Biomedical Engineering, University of Wollongong,
Wollongong, Australia
tf688@uowmail.edu.au

Weihua Li
School of Mechanical, Materials, Mechatronic, and Biomedical Engineering, University of Wollongong,
Wollongong, Australia
weihuali@uow.edu.au

***Abstract*— The implementation of wearable haptic devices has enabled fully immersive environments to be implemented in virtual and augmented reality applications. Advances in these technologies utilize various methods and stimuli to develop realistic sensations of touch, with a key focus area on the hands and fingertips. In haptic devices, magnetorheological elastomers (MREs) are yet to be fully explored, providing an opportunity for an application of an MRE haptic actuator to a wearable haptic glove. Through application of established MRE modelling techniques such as magnetic field simulations, a novel design of an MRE haptic actuator is developed. The device is then experimentally characterized, showing a maximum output force of 161 mN, increasing linearly with current supplied to the included electromagnet. Some paths towards optimization are then explored for improving output force and miniaturization before investigation of an experimental approach to integrate with mixed reality technologies.**

Keywords*— *Virtual Reality and Human Interface, Actuators in Mechatronic Systems, Actuators.

I. INTRODUCTION

Haptic mechanisms, paired with visual and audio feedback, enables fully immersive environments to be replicated or developed. Innovative advances in haptic technologies utilize a variety of materials and methods enabling the simulation of realistic touch. These advances have led to a variety of implementations, particularly in technologies for augmented reality (AR) and virtual reality (VR). Such applications include immersive gaming and entertainment, interactive learning, military training, medical rehabilitation and interactive human–machine interfaces [1]. Much of the common haptic interfaces use vibratory sensations, such as those in gaming controllers and mobile phones. Although, efforts are being made in developing technologies that use alternative methods to replicate realistic sensations of touch in a non-invasive way. Much of the haptic feedback from the physical world is interpreted through the mechanoreceptors in hands [1], so wearable haptic devices, such as gloves, are effective at generating compelling virtual sensations.

Extensive developments have been made in smart haptic technologies from conventional electric motors [2], particularly with the introduction of skin-integrated interfaces such as soft pneumatic, piezoelectric, and electromagnetic actuators [1]. These are designed to stimulate mechanoreceptors, relying on direct skin contact to achieve realistic touch sensations. For these technologies, results can vary due to changes in hydration levels of the skin, sweating, and the presence of dead skin cells [1, 3]. This has led to further developments with mechanical actuators that focus on cutaneous haptics. Importance is placed on these actuators to conform with the natural shape of a limb, whilst limiting potential obstruction of other body parts through their regular motion.

Controlled stimulation of the skin can be categorized as vibration, normal indentation, or lateral stretching [4]. To conform with the requirements of the device being discrete, accurate, and realistic, the use of soft actuators has been widely researched. The aforementioned skin-integrated interfaces are able to produce vibrational feedback, whereas lateral stretching usually requires the use of electric motors that tend to be bulky and require larger power consumption. Less work has been done on the use of soft actuators in achieving normal indentation, which can be attributed to the issues associated to its discrete integration [3]. Normal indentation, as outlined by Greenspan, requires forces ranging from 6.76 mN to 100 mN throughout specific areas of the hand [5]. Similar results are reported by Yin et al., showing that stimuli in the range of 10 mN to 100 mN at a depth of 0.01 mm to 0.1 mm are typical detection thresholds for the skin. In particular, a threshold of 32.8 mN is outlined for fingers, with some variability noted between sexes [3]. To achieve these skin indentation detection thresholds, magnetorheological (MR) materials have been established as viable candidates.

Magnetorheological materials are composite smart materials with dispersed micron-scale ferromagnetic particles suspended in a non-magnetic matrix [6]. The rheological properties are controllable and reversible with the application of a magnetic field. First developed in the 1940s [7], MR fluid (MRF) is a suspension of magnetic particles in a liquid carrier, offering controllable viscosity with the application of a magnetic field. More recently, MR elastomer (MRE) has taken the stage as a rubber-based suspension of magnetic particles, offering actuation capabilities when a magnetic field is applied.

Applications of MRF in haptic feedback gloves have been reported by multiple groups [8-10]. Limited development has been made, however, in the use of MRE to provide haptic feedback in a similar scenario for AR/VR applications. MREs prove to be a practical alternative to MRFs in a variety of contexts due to stiffness tunability and being without any sealing or storage issues [11]. Moreover, the actuation capabilities of MRE with applied magnetic fields makes it a prime candidate for haptics. Adding to the difficulty in producing accurate sensations of touch is that stimuli in the fingertips can be discretely perceived 2 mm apart and within a receptive field of 1-2 mm in diameter [12]. This challenge can readily be overcome by indentation achieved through out-of-plane deformation of MRE.

To explore the use of MRE in a wearable haptics application, this work proposes a miniature MRE actuator which is characterized and experimentally investigated through rudimentary haptics testing. The remainder of this paper is structured as follows: (II) Device Design and Magnetic Field Analysis, (III) Experimental Characterization, (IV) Optimization and Future Work, and (V) Conclusions.

II. Device Design and Magnetic Field Analysis

A. *Design Concept and Working Mechanism*

Taking inspiration from one of the proposed linear MRE actuator designs presented by Böse et al. in [13], the miniaturized design here is illustrated in Fig. 1. This design features a steel yoke (1020 low carbon steel) which surrounds a solenoid coil of 0.5 mm copper wire with 90 turns. The yoke forms part of the magnetic circuit, allowing the induced magnetic field to pass through it and the attached 2 mm disc of MRE. This MRE is fabricated with a 7:2:1 mass ratio of carbonyl iron particles type C3518 (Sigma-Aldrich Pty. Ltd), silicone rubber (Selleys Pty. Ltd), and silicone oil (type 378364, Sigma-Aldrich Pty. Ltd), respectively. The overall dimensions of the MRE actuator are Ø25 mm by 17 mm, with a piston stroke of 2 mm and tip diameter of Ø1 mm.

As supplied coil current is increased, this causes the MRE to deform from its resting state as it is attracted to the inner-yoke, stiffening in the process. This then depresses the non-magnetic aluminum piston while the coil is active, with the tip of the piston protruding through the bottom of the actuator. When the coil is switched off, the MRE returns to its undeformed softened state. This allows for a continuously controllable output force with input coil current, localized to a small point. For the proposed haptics application, the piston tip could then depress through the epidermis to the dermal layer of skin at a point on the hand to stimulate the sensation of touch.

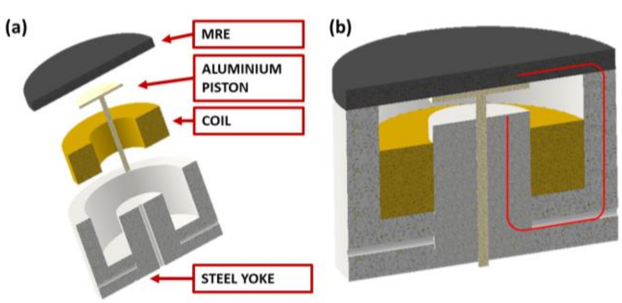

Fig. 1. Proposed MRE actuator design (a) exploded view, and (b) sectional view.

B. *Magnetic Field Study*

To assist with design and for better understand the magnetic flux path within the proposed MRE actuator design, a stationary magnetic field study (2D axisymmetric) was conducted using COMSOL Multiphysics 5.5. To produce a close representation of the magnetic behavior of the actuator, the magnetic properties of aluminum, copper, and 1020 low carbon steel were defined using built-in material data. For aluminum and copper, these refer to relative magnetic permeabilities of 1, whereas the steel follows a B-H curve, making it subject to magnetic saturation. The MRE is set to follow a relative magnetic permeability of 300, as this has been demonstrated to be reasonable for this 7:2:1 ratio used [14]. The copper coil was defined as cylindrical, i.e. a solenoid, with 90 turns.

Two states of the actuator were investigated, those being the undeformed MRE state and deformed MRE state, as illustrated in Fig. 2. When the coil is subject to electric current, the actuator tends rapidly to the deformed MRE state, with the magnetization of the MRE towards the inner-yoke. To assess the magnetic flux density within the MRE, a line through the midspan of the cross-section was analyzed for a range of coil currents from 0.5 A to 4.0 A. As per the magnetic flux densities included in Fig. 3, these tend to be consistent through the depth of the material at the midspan. These vary from 0.13 T to 0.99 T at a 1 mm depth over the tested current range.

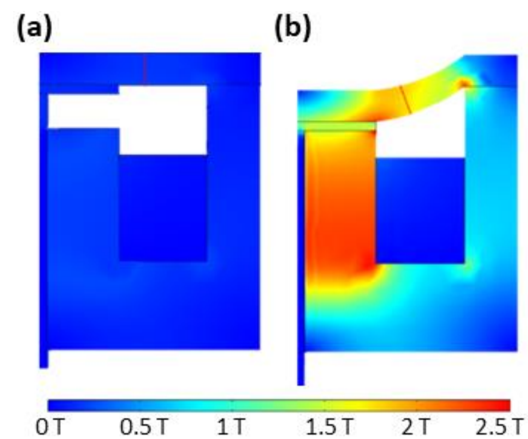

Fig. 2. Magnetic field study results for (a) 0 A current with undeformed MRE, and (b) 4 A current with deformed MRE.

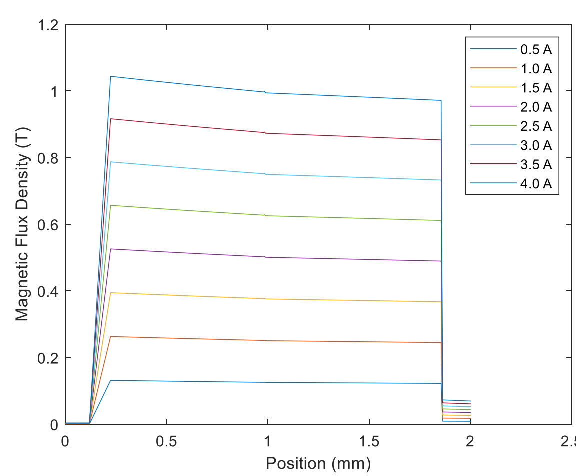

Fig. 3. Flux density through midspan of deformed MRE under varied coil currents.

III. Experimental Characterization

A. Experimental Setup and Methodology

The experimental setup for force characterization of the prototype MRE actuator is shown in Fig. 4, with key aspects annotated. To test the linear force output of the actuator, it was fixed above a force sensitive resistor (FSR) sensor (400 Series Round FSR). This sensor was driven by a circuit featuring an INA126 operational amplifier, providing an appropriate output voltage to an NI myRIO-1900 for data acquisition. For visualization and control of the test system, a PC running NI LabVIEW was connected to the myRIO during testing. To control the MRE actuator, a DC power supply was used to provide electric current to the included solenoid coil.

A set of tests were conducted first to calibrate the FSR sensor and characterize actuator force output. The FSR sensor was calibrated with an appropriate gain found through a linear relationship between output voltage and the application of known masses to the sensor. The output force of the actuator was then characterized through supply of constant currents over a 1 A to 4.6 A range, with steady-state output force measured by the FSR sensor.

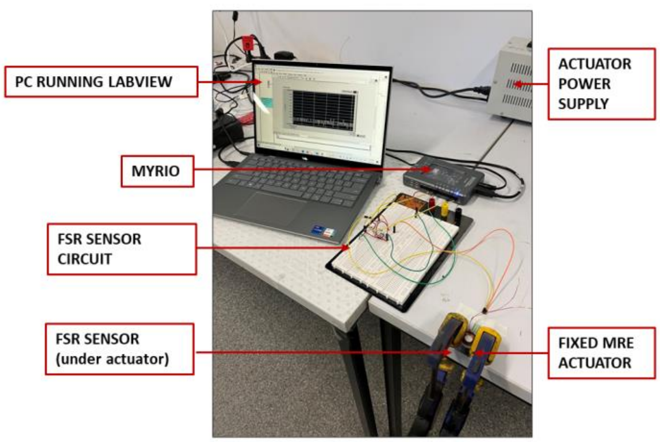

Fig. 4. Force characterization experimental setup.

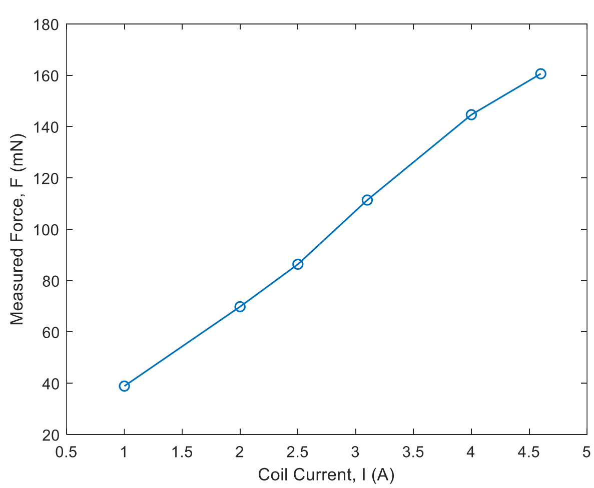

Fig. 5. Force characterization results.

B. Results and Discussion

As illustrated in Fig. 5, the prototype MRE actuator has quite a linear output force over the tested coil current range. This measured force was found to range from 39 mN at 1 A coil current to a maximum of 161 mN at 4.6 A coil current. Of great significance to the proposed haptics application of this actuator, the finger skin detection threshold force of 32.8 mN [3] is surpassed with 1 A of coil current. Furthermore, the maximum detection threshold for human skin of 100 mN is adequately surpassed with at least 3 A of current supplied. This demonstrates the prototype MRE actuator satisfies the force threshold for rudimentary haptics testing.

IV. Optimization and Future Work

A. Force Optimization

A key requirement for wearable haptic feedback devices is weight minimization to facilitate maneuverability. This is a common challenge faced by designers of MR-related technologies, given magnetic field strength requirements are difficult to satisfy without a low-reluctance magnetic circuit. Almost universally, this means a ferrous yoke for solenoid electromagnets is required for MR devices. Furthermore, with the magnetic saturation of steels, this poses a significant challenge for miniaturization where reduced yoke volume quickly leads to reduced field strength. As such, a first stage in miniaturization efforts for this MRE actuator design was to optimize the current prototype for force output, trading yoke volume for more coil turns, as illustrated in Fig. 6. A good balance was found with an almost 300% increase in coil sectional area, allowing for a coil of 250 turns of 0.5 mm wire.

Based on further magnetic field studies conducted for this force-optimized design, output force was predicted through correlation of magnetic field strength of the prototype design with the measured output force. With the results of this reported in Fig. 7, the expected output force of the force-optimized design ranges from 109 mN to 267 mN over a 1 A to 4 A coil current range. This represents a substantial improvement in output force from the prototype, indicating that with a reduction

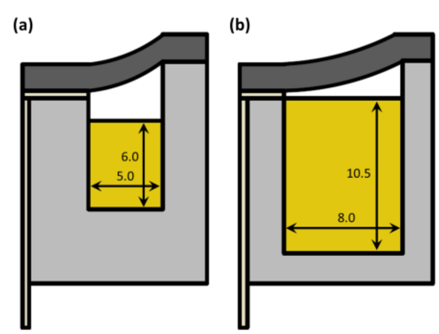

Fig. 6. Coil geometry of the (a) prototype, and (b) force-optimized design of the MRE actuator. Indicated dimensional units in mm.

in volume of up to about 65%, the actuator should be able to still satisfy finger skin detection threshold forces, assuming a squared reduction in output force with volume. Fabrication and characterization of the force-optimized design will be required to validate the predicted results before proceeding with miniaturization efforts.

B. *Mixed Reality Experiments*

Before attempting to fabricate further prototype designs, a basic haptics experiment was conducted using the fabricated prototype. As outlined in Fig. 8, the MRE actuator was attached to the finger of a test subject along with a hall effect sensor attached arbitrarily close to the actuator. Using an electromagnet, the finger was brought into its proximity, with the actuator controlled to depress its tip depending on the measured field strength. This served as a proof of concept for the haptic glove application without the immediate need for full hand tracking. This demonstrated in a rudimentary way that the prototype could produce haptic stimulation, however, with limited fidelity of applied pressure for different current levels. Further testing in a similar arrangement of later prototypes will, as such, be conducted.

With miniaturization of the design and numerous actuators fabricated, an array of actuators is planned to be fitted to the palmar side of a glove. This could then readily be adapted to feature servo-motor-based force feedback on the dorsal side of the glove in later studies. In combination with camera-based hand tracking, this will facilitate comprehensive mixed reality experimentation.

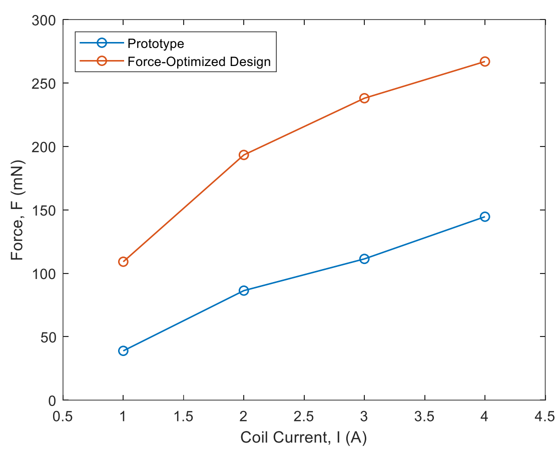

Fig. 7. Current-force relationship for alternative MRE actuator designs.

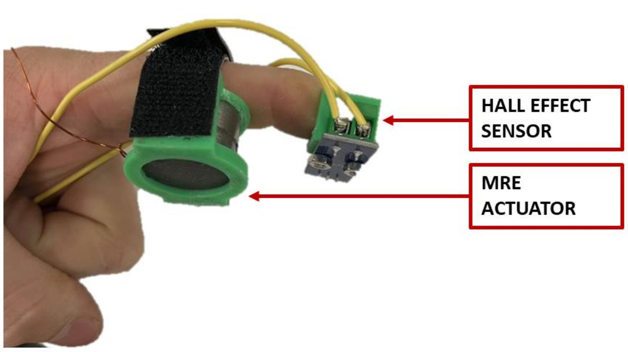

Fig. 8. Experimental arrangement for haptic feedback testing.

V. CONCLUSIONS

Addressing the growing application of haptic feedback wearable devices, this work presented a small-scale MRE-based haptic actuator of dimensions Ø25 mm by 17 mm. Through force characterization, this actuator was found to produce a maximum output force of 161 mN, satisfying human hand skin detection thresholds. Rudimentary haptics testing shows the device can produce haptic stimulation for the finger, however, the fidelity of applied pressure is limited with the current prototype. While further efforts are required for miniaturization, force-optimization of the design indicates the actuator can be feasibly reduced in volume to haptic glove appropriate size.

REFERENCES

[1] Y. H. Jung, J. H. Kim, and J. A. Rogers, "Skin‐Integrated Vibrohaptic Interfaces for Virtual and Augmented Reality," *Advanced Functional Materials,* p. 2008805, 2020.

[2] J. Blake and H. B. Gurocak, "Haptic Glove With MR Brakes for Virtual Reality," *IEEE/ASME Transactions on Mechatronics,* vol. 14, no. 5, pp. 606-615, 2009.

[3] J. Yin, R. Hinchet, H. Shea, and C. Majidi, "Wearable Soft Technologies for Haptic Sensing and Feedback," *Advanced Functional Materials,* p. 2007428, 2020.

[4] C. Pacchierotti, S. Sinclair, M. Solazzi, A. Frisoli, V. Hayward, and D. Prattichizzo, "Wearable Haptic Systems for the Fingertip and the Hand: Taxonomy, Review, and Perspectives," *IEEE Transactions on Haptics,* vol. 10, no. 4, pp. 580-600, 2017.

[5] J. D. Greenspan, "A Comparison of Force and Depth of Skin Indentation upon Psychophysical Functions of Tactile Intensity," *Somatosensory Research,* vol. 2, no. 1, pp. 33-48, 1984.

[6] W. Li and X. Zhang, "Research and applications of MR elastomers," *Recent Patents on Mechanical Engineering,* vol. 1, no. 3, pp. 161-166, 2008.

[7] B. Spencer, S. Dyke, M. Sain, and J. Carlson, "Phenomenological Model of a Magnetorheological Damper," *Journal of Engineering Mechanics-asce - J ENG MECH-ASCE,* vol. 123, 03/01 1997.

[8] S. Winter and M. Bouzit, "A Haptic Force Feedback Glove Using Magnetorheological Fluid," 2006.

[9] C. Bullion and H. Gurocak, "Haptic Glove with MR Brakes for Distributed Finger Force Feedback," *Presence: Teleoperators and Virtual Environments,* vol. 18, no. 6, pp. 421-433, 2009.

[10] N. Sgambelluri, E. P. Scilingo, R. Rizzo, and A. Bicchi, "A Free-Hand Haptic Interface Based on Magnetorheological Fluids," in *The Sense of Touch and its Rendering: Progress in Haptics Research*, A. Bicchi, M. Buss, M. O. Ernst, and A. Peer, Eds. Berlin, Heidelberg: Springer Berlin Heidelberg, 2008, pp. 155-178.

[11] Y. Li, J. Li, W. Li, and H. Du, "A state-of-the-art review on magnetorheological elastomer devices," *Smart Materials and Structures,* vol. 23, p. 123001, 2014.

[12] A. G. Purves D, Fitzpatrick D, et al, *Differences in Mechanosensory Discrimination Across the Body Surface*, 2nd edition ed. (Neuroscience). Sunderland (MA): Sinauer Associates, 2001.

[13] H. Böse, T. Gerlach, and J. Ehrlich, "Magnetorheological elastomers — An underestimated class of soft actuator materials," *Journal of Intelligent Material Systems and Structures,* p. 1045389X21990888, 2021.

[14] M. D. Christie, S. S. Sun, D. H. Ning, H. Du, S. W. Zhang, and W. H. Li, "A torsional MRE joint for a C-shaped robotic leg," *Smart Materials and Structures,* Article vol. 26, no. 1, 2017, Art. no. 015002.