Development of a Magnetically Induced Stiffening Soft Robotic Glove for Effective Motor Rehabilitation

Susanna Aufrichtig[1,2], Deniz Albayrak[2], Leah Gaeta[2], Tommaso Ranzani[2]

Palo Alto Senior High School, 50 Embarcadero Rd, Palo Alto, CA 94301[1],

Boston University Morphable Biorobotics Lab, 730 Commonwealth Avenue, Boston, MA 02446[2]

MBL Morphable Biorobotics Lab

BOSTON UNIVERSITY

Introduction

Background

- Stroke can cause difficulties in hand movement and coordination[1]. Robotic devices can help patients perform repetitive and controlled rehabilitative exercises to facilitate the relearning of motor skills.
- Due to their compliance, soft robots can conform to the human body, providing increased comfort and freedom of motion compared to traditional rigid robots.

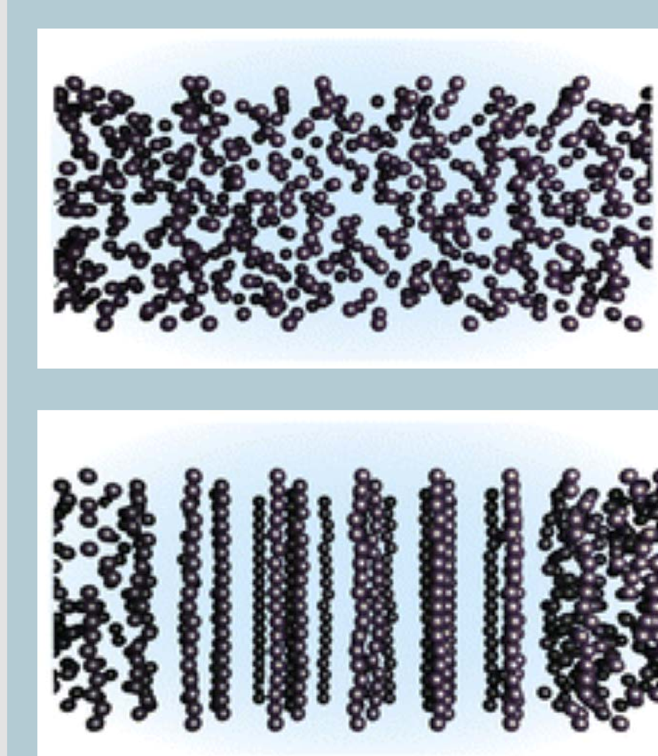
Magnetically Induced Stiffening

- Variable stiffening methods are necessary for soft robots to transmit sufficient force to manipulate biological structures[2]
- Magnetorheological (MR) fluids can rapidly solidify when experiencing a magnetic field
  - Composed of micron-scale iron particles suspended in a carrier fluid (often water or oil with stabilizing agents)
  - Iron particles arrange along magnetic field lines, increasing stiffness
  - Stiffness an be adjusted based on the strength of the magnetic field applied

Electropermanent magnets (EPMs) can control MR fluid effects electronically[3]

- Produce magnetic fields comparable to permanent magnets and do not require continued power to maintain their magnetic field
- Increases portability compared to conventional pneumatic stiffening that often requires bulky equipment such as pumps[2]

Figure 1: Magnetorheological fluid particles without (top) and with (bottom) applied magnetic field[2]



Goal

Implement MR fluid stiffening technology in a rehabilitative soft robotic glove prototype for stroke patients.

Methodology

Pouch Fabrication

- 2D layering of laser cut TPE (thermoplastic elastomer) and PTFE (Teflon) sheets
- Carver Heated Lab Press heats (285°C) and applies pressure (1,500lbs) for 10-minutes to adhere TPE layers in an accordion finger joint structure
- PTFE layers prevent bonding in unwanted areas, allowing for a continuous channel throughout the finger in which MR fluid is injected

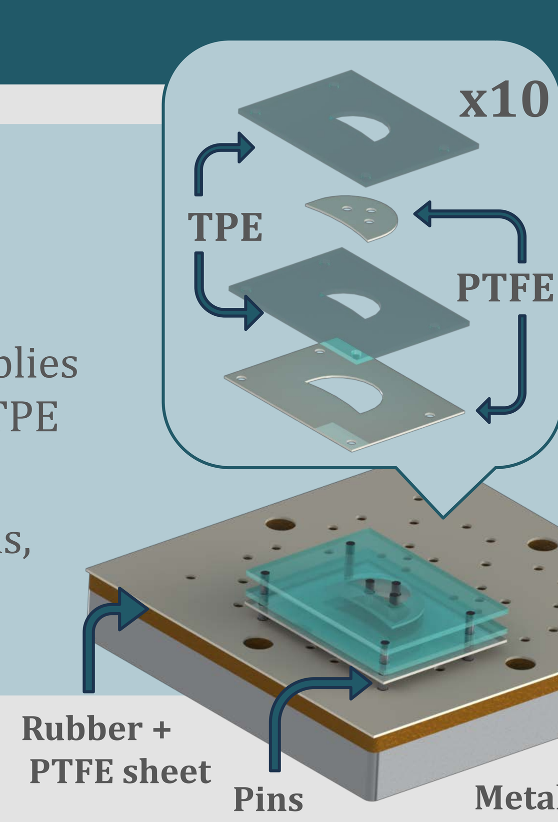


Figure 2: Fabrication of accordion structure. TPE and PTFE layers demonstrated in an exploded view with heat plate setup.

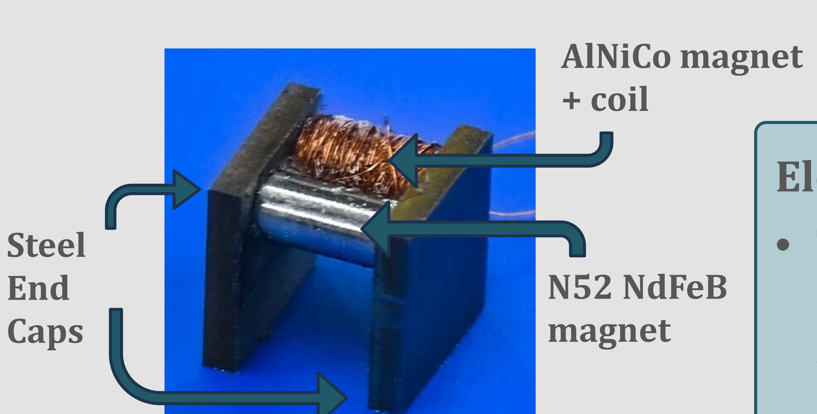


Figure 3: EPM with labeled components[3]

Electropermanent Magnets

- Two adjacent permanent magnets, one Neodymium (N52 NdFeB) and one AlNiCo, and an electromagnet, contained between two steel end caps[3]
- Hard (N52 NdFeB) and soft (AlNiCo 7) magnet pair allows to easily magnetize and demagnetize the EPM
- A pulse from the electromagnet reorients the magnetic field of the AlNiCo magnet, forming a magnetic field around the steel end caps

Testing

- A three-point bend test protocol comparing force (mN) vs. displacement (mm) measured stiffness of the MR fluid in the glove accordions when a magnetic field was absent vs. present
- An accordion rested on custom 3D printed support beams and an anvil structure was attached to an Instron 5943 tensile testing machine
- The bend test routine was run for two conditions, (1) magnets affixed to the sides of the accordion vs. (2) no magnets present. Four trials were performed per condition

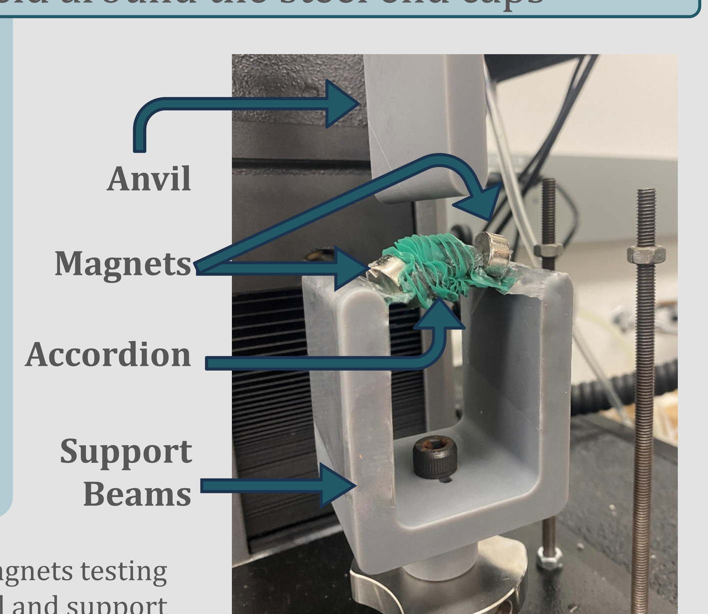


Figure 4: Accordion with magnets testing setup on Instron 5943. Anvil and support base attached.

References

Chen, Y.; Tan, X.; Yan, D.; Zhang, Z.; Gong, Y. A Composite Fabric-Based Soft Rehabilitation Glove with Soft Joint for Dementia in Parkinson's Disease. *IEEE Journal of Translational Engineering in Health and Medicine* **2020**, *8*, 1–10. DOI:10.1109/jtehm.2020.2981926.

Gaeta, L. T.; McDonald, K. J.; Kinnicutt, L.; Le, M.; Wilkinson-Flicker, S.; Jiang, Y.; Atakuru, T.; Samur, E.; Ranzani, T. Magnetically Induced Stiffening for Soft Robotics. *Soft Matter* **2023**, *19* (14), 2623–2636. DOI:10.1039/d2sm01390h.

McDonald, K. J.; Kinnicutt, L.; Moran, A. M.; Ranzani, T. Modulation of Magnetorheological Fluid Flow in Soft Robots Using Electropermanent Magnets. *IEEE Robotics and Automation Letters* **2022**, *7* (2), 3914–3921. DOI:10.1109/lra.2022.3147873.

Results

Graph

- Accordion stiffness with magnetic field present was 85 mN/mm, roughly four times higher than stiffness with no field present (21 mN/mm)
- Force required for maximum deflection of the accordion with a magnetic field present was 425 mN, while force required with no field is significantly smaller at 136 mN

Three-point-bend test protocol used

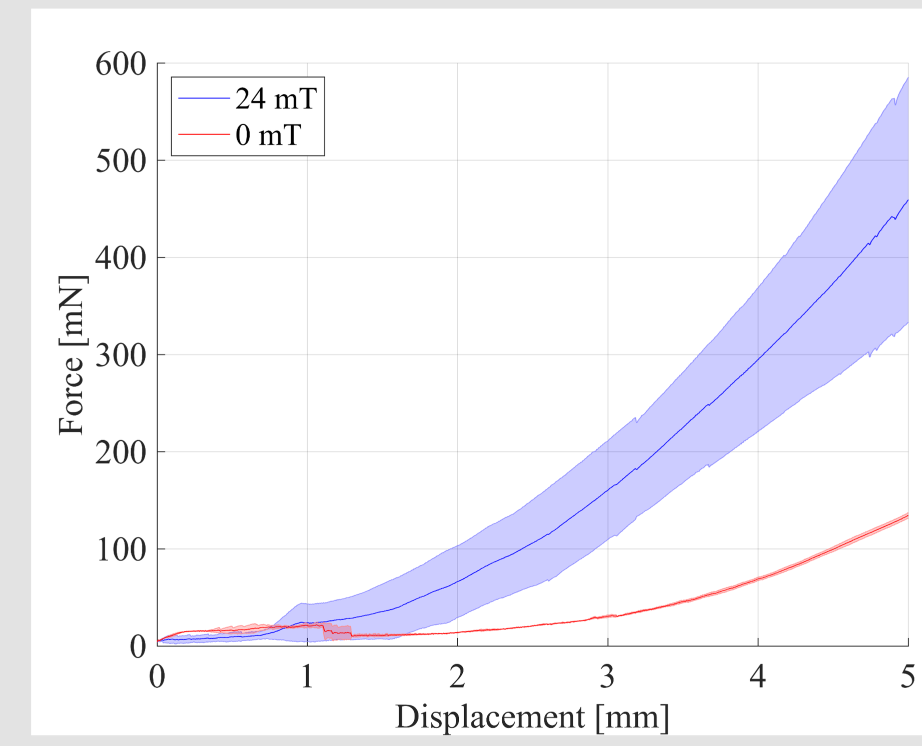


Figure 5: Applied force on accordion (mN) vs. displacement of anvil (mm) during three-point-bend test routine when magnets are present/absent

A

Equation for stiffness (k) is derived from the Euler-Bernoulli theory with three-point-bend test boundary conditions, taking into account the frictional shear stress induced by the magnetic field on the MR fluid

$$k \propto \frac{F + bh\tau_f}{w}.$$

B

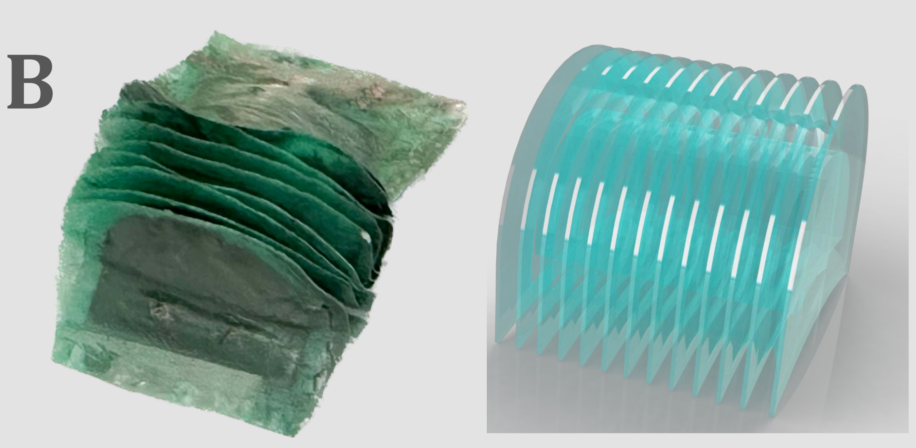


Figure 6: (A) Fully assembled finger pouch on hand. (B) MR fluid filled accordion (left) with accordion CAD model (right)

Discussion

- The integration of MR stiffening in a soft robotic glove holds promise for advancing the field of stroke rehabilitation. Patients with stroke-induced hand impairments can benefit from repetitive exercises to facilitate motor skill relearning. Soft robots, due to their ability to deform to delicate structures, present an ideal platform for such rehabilitation devices.[1]
- By controlling the strength of applied magnetic fields, MR fluids can tailor stiffness to the specific needs of stroke patients, accommodating different levels of impairment and progress in motor recovery.
- The integration of EPMs, which do not require a continuous energy source, allows for quick adjustments in stiffness through electronic means and eliminates the need for cumbersome external components. This feature enhances patient compliance by making the robotic glove less obtrusive.
- Accordion observes a four-fold increase in stiffness when a magnetic field is applied

The goal of implementing MR fluid stiffening technology in a prototype of a rehabilitative soft robotic glove for stroke patients is to bridge the gap between recent research and practical clinical applications.

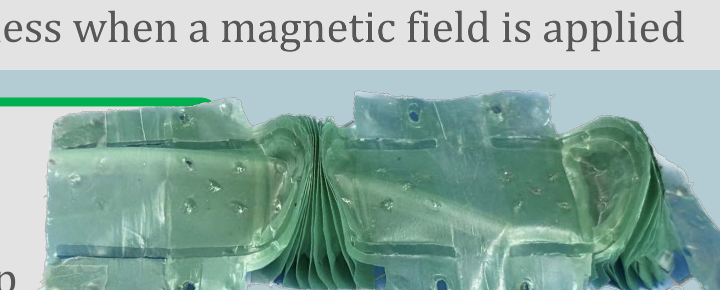


Figure 7: Inflated continuous finger

Future Directions

- Implement silicone oil-based MR fluid recipe to prevent water evaporation. Incorporate iron nanoparticles to increase friction between the iron microparticles to limit sedimentation
- Fabricate complete hand
- Communicate with clinicians about rehabilitative exercises in which glove assistance is beneficial. Experiment with pouch and EPM placement to allow for such requests

Acknowledgements

I would like to express my sincere gratitude to Professor Ranzani and the members of the Morphable Biorobotics Lab for providing me with the invaluable opportunity to delve into the world of soft robotics, gaining not only hands-on experience but also exposure to cutting-edge research in the field. I am truly thankful for the guidance, mentorship, and support extended particularly by my mentors, Leah and Deniz, whose expertise and enthusiasm made me feel instantly welcomed within the lab and inspire me to pursue further exploration in this field.