1. Detailed Actuator Design & Fabrication

Initial inspiration for the SEMA setup was similar to the one shown in **Figure 1**. However, the configuration would not be feasible for the design of an armband containing SEMAs. The magnets used (cylindrical 6 mm x 6 mm) were too small to produce a uniform magnetic field that the SEMA was situated in. Even if the ideal magnetic field were achievable using this configuration, the configuration in **Figure 1** was awkward and would be difficult to integrate into an arm band. Therefore, two more designs of SEMAs were proposed and further investigated to finalize the haptic glove (**Figure 3** and **Figure 4**).

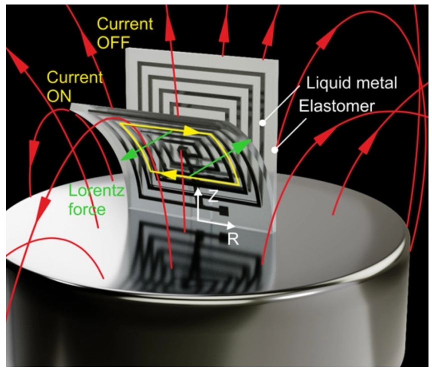


Figure 1. *A soft electromagnetic actuator (SEMA) experiences electromagnetic force and bends as it sits inside a magnetic field while current is applied. The liquid metal acts as a flexible wire. Figure from [7].*

Both designs utilized thin copper wires of 0.5mm in diameter to ensure a product that was easy to fabricate and safe to handle within the lab setting. This would provide an alternative to liquid metals and acts as the best choice for SEMA fabrication in terms of flexibility. They also involved embedding copper wires in Ecoflex 00-30. In the first design, the SEMAs were fabricated using a rectangular coil design, inspired by Mao *et al.* [7]. To fit on fingertips, the SEMAs were produced as 20mm x 20mm x 3mm in size. **Figure 3** shows the layout of the SEMA with rectangular coil design. **Figure 3** shows the schematic of the magnets and SEMA. In the second design, the SEMAs would be fabricated using a solenoid coil design with a diameter of 15mm. The design schematic is shown in **Figure 4**.

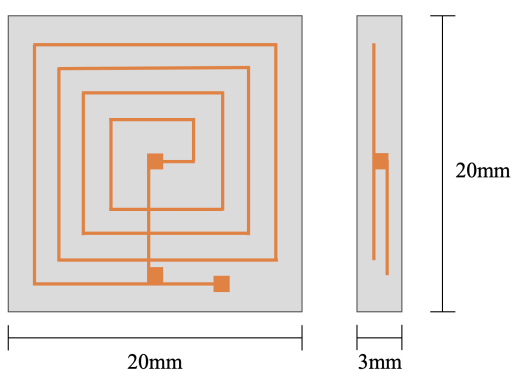


Figure 2*. 20mm x 20mm x 3mm SEMA made of copper wire and Ecoflex.*

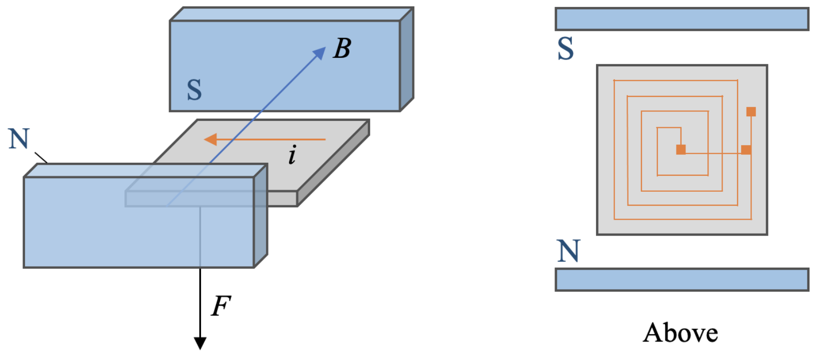


Figure 3. *SEMA with rectangular coil design*

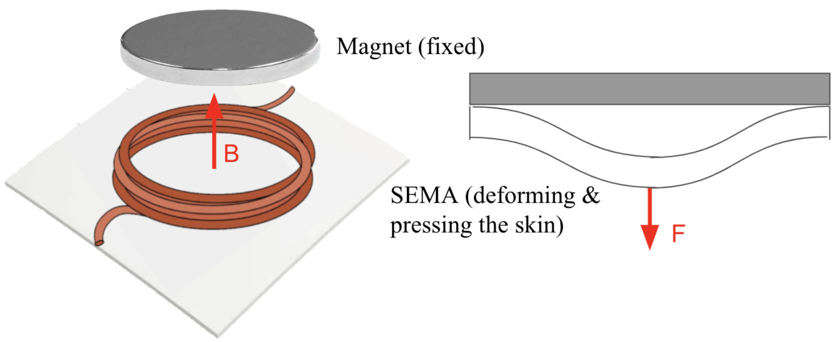
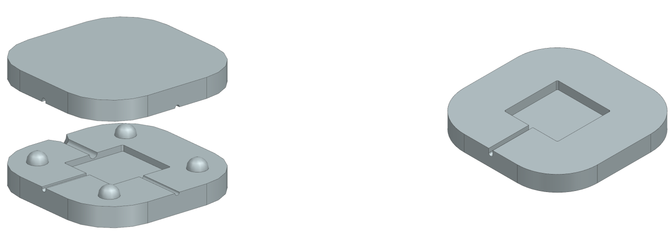
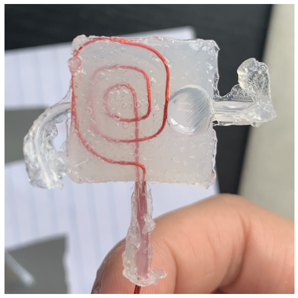


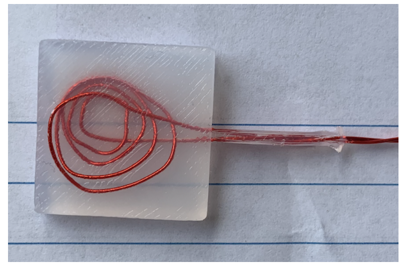
Figure 4. *SEMA with solenoid coil design made of copper wire and Ecoflex*

For the first fabrication, the design with the square spiral was chosen. To fabricate the SEMAs, a mold of the desired size was made using CAD and 3D printing. **Figure 5** shows two versions of molds that were tested and their results. Copper wire was prepared to the correct structure, making sure that the coils were as straight as possible and elbows at 90 degrees. After mixing the two Ecoflex parts, the copper wire was inserted in place, and the Ecoflex was poured and cured. To actuate the SEMA, multiple 10mm x 5mm x 3mm magnets with its North and South poles facing each other were used to create a uniform magnetic field across the SEMA as shown in **Figure 3**. Then, a current was applied through the wire.



(a) (b)





(c) (d)

Figure 5. *(a) CAD of the two piece injection mold. Injection starts from the largest channel while excess air and Ecoflex exit from the opposite channel. The middle channel provides an out for the wire. (b) CAD of the one piece mold has one channel for the wire. (c) The result of the first attempt using Mold 1. (d) The result of the first attempt using Mold 2.*

Because lab limitations resulted in the use of copper wire instead of liquid gallium, the project saw a rise in problems associated with the wire. The success of the SEMA depended on the square spiral being perfectly perpendicular to the magnetic field. However, the copper wire was found to be too difficult to bend to the correct shape. Thinner wire also did not maintain a coiled shape well. Additionally, there was the concern of consistency; the hand bending process resulted in coils that were not uniform across productions. Lastly, the rigidity of the SEMA was heavily affected by the thickness of the wire. Much thicker wire allowed for greater current and maintained its shape, but hindered the ability of the SEMA to flex and move. **Figure 6** shows the result of the SEMA fabricated in the lab.

Figure 6*. The open pour mold was used to fabricate an SEMA.*

1. Solenoid Design and Fabrication

Unfortunately, the force exerted by the first iteration of SEMAs was not sufficiently strong to be felt. The square spiral proved to be too difficult to manufacture and did not provide a sufficient electromagnetic field. This was a turning point because the project design needed to be altered. The actuator needed to rely on a circular coil or solenoid shape instead of the square spiral to strengthen the electromagnetic field. The design from **Figure 4** was revisited for this reason. The reconsideration sprouted two new design ideas: a flat coil (**Figure 7)** inspired by Bugeja [8] and a soft solenoid (**Figure 8)** inspired by Johnson *et al.* [9].

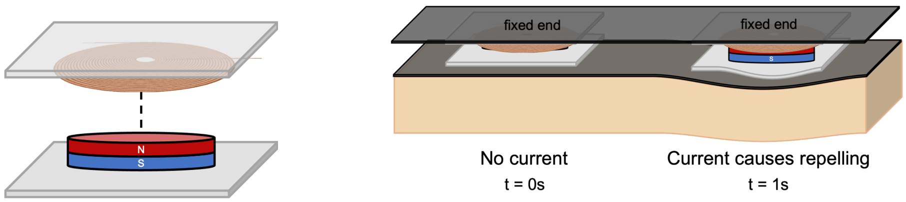


Figure 7. *Flat coil and permanent magnet sandwiched between two Ecoflex layers.*

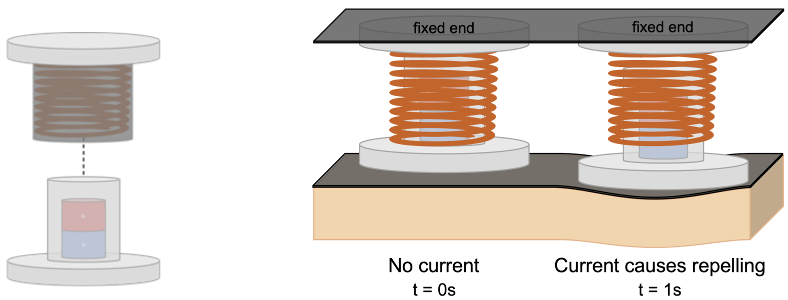


Figure 8. *Two-half assembly following Johnson et al [2].*

More tests were carried out to evaluate the magnetic field strength of flat coils fabricated using varying wire thickness (**Figure 9**). A solenoid using the 0.45 mm copper wire was also tested. A current of 3 A was sent through the wires. It was concluded that while the flat coils were able to generate a magnetic field, the solenoid was stronger despite using less turns. The solenoid was able to hold a magnet (cylindrical 6 mm x 6 mm) suspended in the air, and the flat coils could not. Thus, the project evolved to be inspired by the design from Johnson *et al.* [9] but with modifications to suit the project needs and reflect the group's own ideas.

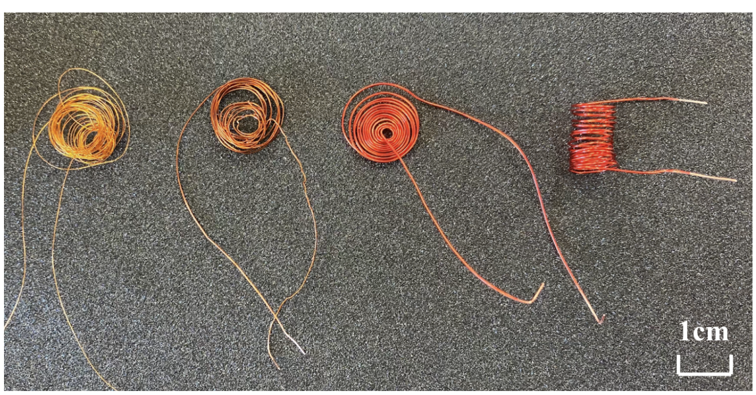


Figure 9. *Wires of various thickness were tested to evaluate the magnetic field strength.*

The new design incorporated a threaded pipe nipple to house the magnet (**Figure 10**). The copper wire was wound around the pipe nipple such that a solenoid was created. The benefits of having this design was that the threads acted as a guide for the wire and a lock nut would hold the actuator in place on the arm band. In order to ensure that the magnet remained in the pipe nipple, a 3D printed cap or insert was manufactured. Most of the elements were commercially available, and the manufacturing of this electromagnetic actuator (EA) was repeatable.

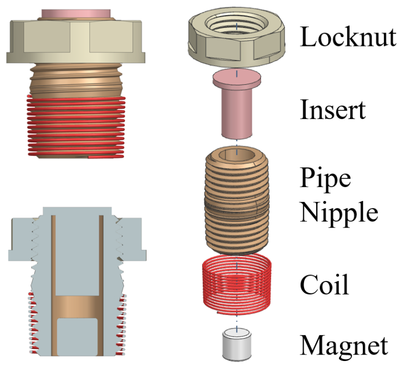


Figure 10*. Iteration 1 of the in-house electromagnetic actuator, in assembled and exploded view.*

The intent of iteration 1 was for the magnet to be repelled by the copper coil when current was applied to the coil. When EA iteration 1 was placed on a human user's arm, the intent was that the repelling force would be felt by the user (as demonstrated in **Figure 11**). Despite iteration 1 of the EA being successfully integrated into the circuit and fully functional in actuating, two issues arose concerning the EA. Although the magnet was visibly repelled by the electromagnetic field of the coil supplied by 3 A, users were unable to sense a pressure on their arm from the EA. Current through the coil was increased from a range up to 9 A to increase electromagnetic force on the magnet. The pressure applied by the EA was still deemed to be not tangible.

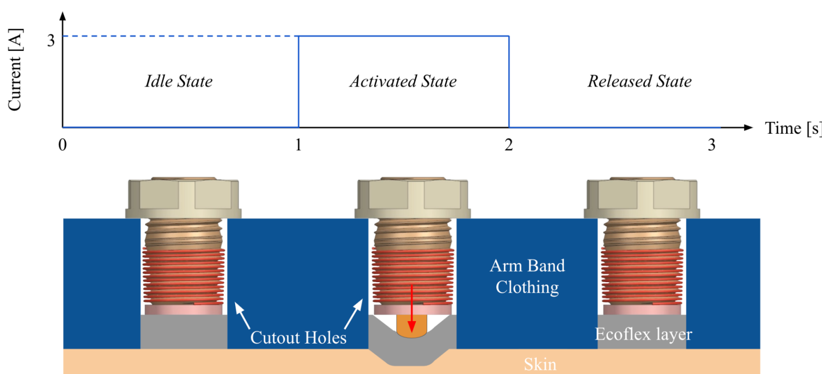


Figure 11. *The intent of EA iteration 1 was for a magnet to be repelled onto the skin for as long as current was supplied to the coil, with a layer of Ecoflex acting as a cushion.*

A second iteration was created to address the lack of tangible pressure. Iteration 2 used magnetism to increase pressure. A flat magnet was fixed at one end of the coil. The electromagnetic field produced by the coil would repel the free shaft magnet toward the fixed magnet (shown in **Figure 12a**). In turn, the fixed magnet would repel the shaft magnet back toward the skin (shown in **Figure 12b**). The pressure applied was noticeably tangible by all members of the team. However, there was strong magnetism between the fixed magnet and free shaft magnet. Even without the electromagnetic field of the coil, the magnetic fields of the two magnets were constantly interacting, and a pressure could be felt *without* activation of the sensor.

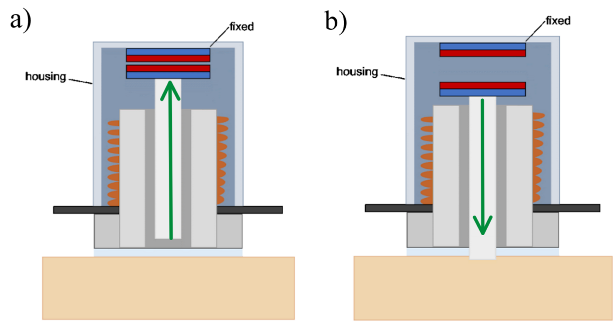


Figure 12. *Iteration 2 of the in-house electromagnetic actuator. (a) Expectations were that current applied to the coil would cause the shaft magnet to repel towards the fixed magnet. (b) Expectations were that the fixed magnet would repel the shaft magnet towards the wearer's arm.*