Magnet Attractive Force Calibration

Methods

The attractive force applied from the electromagnet to the magnetic pistons was calibrated through the use of compressing foam blocks. The first step of calibration was to determine the mechanical properties, specifically Young's Modulus, of foam blocks cut from a polyurethane sponge. This process involved placing 6 polyurethane blocks 3x1.5x1.5 mm within a custom 3D weight drop rig and then dropping 3D printed cubes of known weights on the foam. Pictures of foam compression were taken before and after placement of the weights, and then images were processed in ImageJ to determine the strain experienced by the foam under each weight. Having a calculated strain and knowing the weights of the cubes allowed for calculation of the polyurethane's Young's Modulus.

The second step of calibration was to determine how much compression occurred in polyurethane foam blocks when applying a ramping attractive force from the electromagnet to the magnetic pistons. To do this, 6 polyurethane blocks 3 x 1.5 x 1.5 mm were each placed behind a magnetic piston to be sandwiched between the magnetic piston and well wall at either 16 mm or 30 mm away from the electromagnet. The power supply was then programmed to set the electromagnet's settings to a max of 24 V and then current ramping of 0.1 A, 0.2 A, 0.3 A, 0.4 A, 0.5 A, 0.6 A and 0.7 A. Images of foam blocks were taken before compressing and then after compressing at each current setting. These images were then processed in ImageJ to calculate how much strain occurred in the foam during the compression test at each distance. This strain from the electromagnet compression tests was then paired with the polyurethane's Young's Modulus to determine the force applied by the electromagnet on the magnetic piston at each current setting.

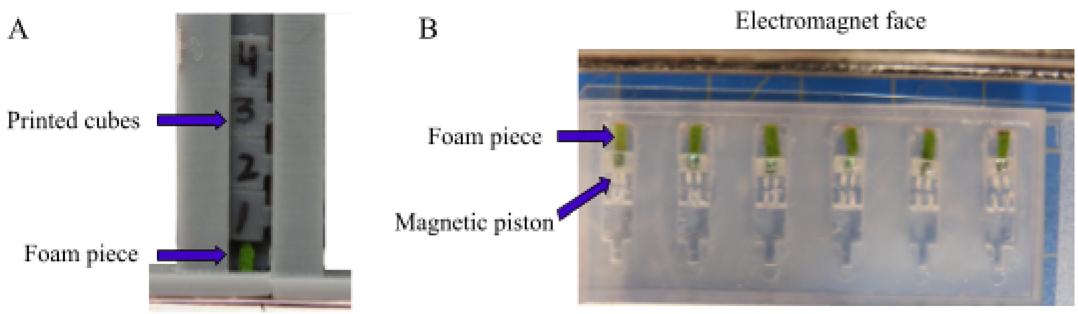


Figure 1. Setup for testing mechanical properties of foam pieces. (A) Compressing foam pieces with 3D printed cubes with a known weight. (B) Compressing foam pieces with the electromagnet attracting magnetic pistons.

Results

Force characterization of the electromagnet's attractive pull began with compressing foam pieces under 3D printed cubes. A total of 10 cubes were printed and weighed, having an average weight of 65.3 mg (Fig 2 A). Cubes were labeled 1-10 and placed on top of a foam piece in ascending order. Images were taken of the foam piece under each weight and processed to determine strain of the foam. A total of 6 foam pieces were observed and strains under each weight were averaged across each foam piece, seen in Fig 2 B. Strains were plotted vs the weight from the cubes and a line of best fit was applied to the data. Taking the equation of the best fit line provided a mathematical relationship for the stiffness of the foam pieces.

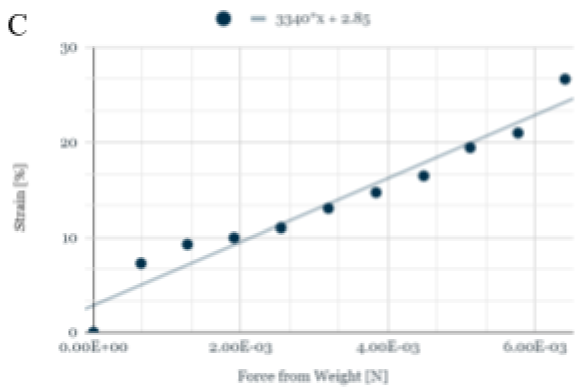
A

Cube #	Mass [mg]
1	65.8
2	64.3
3	64.6
4	65
5	65.6
6	66
7	66
8	64.3
9	66.2
10	65.2

B

Number of Cubes	Average strain
1	7.3
2	9.3
3	10.0
4	11.0
5	13.0
6	14.7
7	16.5
8	19.4
9	21.0
10	26.7

C



D

$$y = 3340*x + 2.85$$

Figure 2. Results from cube drop test. (A) Mass of each labeled 3D printed cube. (B) Average strain for the total number of cubes on top of the foam pieces. (C) Plot of foam strain vs force applied on the foam pieces. (D) Equation for the stiffness relationship of the foam pieces.

The second part of magnet force characterization was compressing 6 polyurethane pieces with the magnetic pistons and electromagnet. 6 pieces of foam were compressed at 16 mm and 32 mm away from the electromagnet at 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, and 0.7 A. Strains were calculated for each piece of foam at each current value at each distance. The average of these strains are shown below in Table 1.

16 mm		32 mm	
Current	Average Strain	Current	Average Strain
0.1	3.3	0.1	2.0
0.2	4.3	0.2	3.0
0.3	6.1	0.3	3.2
0.4	7.8	0.4	5.0
0.5	7.4	0.5	5.5
0.6	9.0	0.6	5.7
0.7	9.6	0.7	6.1

Table 1. Results of foam compression with magnetic pistons. Average strains for 6 foam pieces compressed at two distances away from an electromagnet set to a range of currents.

The reported strains were then plugged into the best fit line from the cube drop test to calculate a force for each current setting at the two distances. These force calculations are shown in Table 2.

Current [A]	16 mm		32 mm	
	Strain (%)	Force (mN)	Strain (%)	Force (mN)
0.1	3.30	0.13	2.04	0.00
0.2	4.27	0.43	3.00	0.05
0.3	6.10	0.97	3.19	0.10
0.4	7.83	1.49	5.02	0.65
0.5	7.39	1.36	5.54	0.81
0.6	8.99	1.84	5.71	0.86
0.7	9.64	2.03	6.11	0.98

Table 2. Force vs strain for each distance from electromagnet. Values for calculating force on the magnetic pistons for each current value at each distance from the electromagnet by utilizing strains from Table 1.

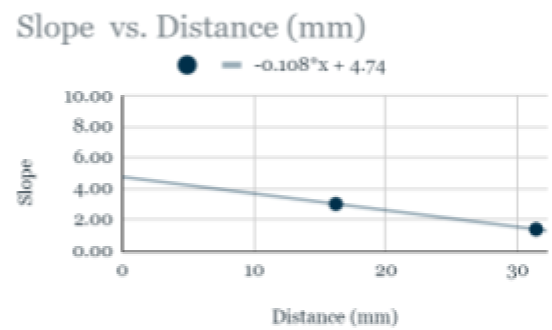
Lastly, the current setting and force for each distance were plotted and fit with a best fit line. The slope of each best fit line was then plotted vs the distance away from the electromagnet. Assuming the magnetic field strength is a linear relationship between the two distances, a best fit line was applied to provide an equation to determine tissue stiffness (y) at different distances from the electromagnet (x) as seen in Figure 3. This equation was then plugged into force = stiffness * current to provide a final force equation for varying distances from the electromagnet set at varying currents.

A

Current vs Force for Both Distances

Current [A]	Force [mN]	
	16 mm	32mm
0	0	0
0.1	0.1336449742	0
0.2	0.4263322231	0.0452657265
0.3	0.9728895457	0.102015591
0.4	1.490994282	0.6486117042
0.5	1.359466553	0.8064766074
0.6	1.838707997	0.8551667062
0.7	2.032705572	0.976491638
Line of best fit D1	2.994819638	0
Line of best fit D2	1.356417842	0

B



C

Slope = -0.108*distance + 4.74
Force = slope*current
Force = ((-0.108*distance)+4.74)*current

Figure 3. Final force equation. (A) Data for best fit lines of Current vs Force at each distance from electromagnet. (B) Plotting slopes of best lines and fitting new best fine line assuming a linear relationship between the magnetic field strength at each distance from electromagnet. (C) Final force equation.