xDI - Cartilage Bioreactor

Client: Prof. Corinne Henak
Faculty Consultant: Prof. Corinne Henak (ME); Prof. Paul Campagnola (BME)
Team: Jeffery Guo (ME Admin & Accountant)
Emilio Lim (BME BWIG & BSAC)
Griffin Radtke (ME Operational Leader & Communicator)
Sydney Therien (BME Operational Leader & Communicator)

Status

Report Date: 04/26/2024
Next Milestone: Final Report
Deadline: 04/29/24
Status: on schedule

Technical Summary

This past week, the team fully assembled the final 1D bioreactor which contains all components including the housing, fasteners, VCA, and circuitry. The team also successfully demonstrated its functionality and operation to Dr. Henak. Apart from that, the team extrapolated data from the verification testing to explain the effectiveness and functional operations of the voice coil itself. While the entire bioreactor is assembled, the team did not have time to fully test the force output using a load cell to verify the desired force output. To prepare for the upcoming poster session, the team completed and printed the poster, taking place on 4/26.

New Tasks

Task Name	Description and Concrete Outcome	Owner	Est. Time [hrs]
Assemble the bioreactor	Perform all machining operations related to fabrication and assembly of the final bioreactor device	ST	10+
Work on poster	Work on and revise poster sections corresponding to circuitry design and testing	JG	2
Redesign + print housing	Added necessary through-hole locations as well as wiring slots and created symmetric designs suitable for printing with biocompatible resin (future work).	GR	3
Work on poster + presentation	Created shared templates and worked on poster sections relating to housing, introduction, and design evolution	GR	2
Machine & fit/secure bearing + shaft within	With fully updated CAD, cut aluminum profiles to the length needed to match	GR	2

bioreactor	the distance between VCA & bottom of sample tray. Additionally, assembled bearing + plunger within bioreactor.		
Extrapolate Data	Using the data obtained previously from verification, plot graphs using MATLAB to obtain some numbers.	EL	4

Technical Section

Author: Sydney Therien
Editor: Griffin Radtke

Assemble the bioreactor	Perform all machining operations related to fabrication and assembly of the final bioreactor device.	ST	10+

In order to bring all the work we've done over the course of the semester together, the entire bioreactor had to be assembled. This involved starting and picking up the 3D printed parts, drilling through-holes into the acrylic, and designing/fabricating posts that will allow for the easy and secure attachment and removal of the lid. These posts fit into the corners of the sample tray and have 8/32" threaded rods sticking out of the top. Through-holes in the acrylic lid fit into the threaded rods, which are fitted with wingnuts that secure the lid in a removable but strong way.

Drilling through-holes in the acrylic was done with a standard drill press in the Makerspace and TeamLab (depending on which was open at the time). Successive stepping-up of drill sizes was done to mitigate the chance of the acrylic shattering. The walls of the bioreactor fit together in a tongue-and-groove pattern, which is secured with epoxy purchased from the Makerspace and TeamLab. During a small brain slip, the base was epoxied to the walls. It is not supposed to be attached with epoxy because now a machined aluminum base can't be substituted in without recutting and reassembling the entire bioreactor. This is inconvenient, but all modules of the bioreactor are fortunately still accessible. The bearing module acrylic piece is not epoxied to the walls, so this can be lifted to access the actuators. The sample tray is attached to the acrylic walls with M4 bolts.

Overall, the bioreactor came out nice. There are definitely areas that could be improved, but the team is confident presenting this to the client as a solid preliminary device that can be used in its current state for the Henak lab's important research.

Author: Jeffery Guo
Editor: Emilio Lim

Work on poster	Work on and revise poster sections corresponding to circuitry design and testing	JG	2

Looking ahead to both the BME and ME final poster sessions, my work this week was centered on compiling relevant information pertaining to the circuitry side of the project. This essentially included captions for each prototype design and descriptions of our final circuit and organizing information to be readable and concise while conveying all necessary information. Another aspect pertaining to the electronics side of the project includes load cell testing to validate the force output of the VCA. The results and conclusions from our tests were summarized in the poster.

We also decided not to order the power supply and NI DAQ due to uncertainty on the lead times and expected date of arrival.

Author: Griffin Radtke

Editor: N/A

Work on poster + presentation	Created shared templates and worked on poster sections relating to housing, introduction, and design evolution	GR	2

Templates for both the poster and presentation were created and shared, helping direct work on the respective deliverables. Regarding my contribution to the poster, I modified the introduction, completed an additional section detailing the evolution of our overall design, and completed the section detailing our overall housing design.

Author: Griffin Radtke

Editor: N/A

Machine & fit/secure bearing + shaft within bioreactor	With fully updated CAD, cut aluminum profiles to the length needed to match the distance between VCA & bottom of sample tray. Additionally, assembled bearing + plunger within bioreactor.	GR	2

To fit the ‘plunger’ system properly within the bioreactor, the previously discussed aluminum profiles were cut to, alongside the two 3D-printed mating components, sum to the dimension shown in Figure 3. Profiles were cut with a drop saw, cleaned, and press-fit onto the VCA-mate component. An M6 bolt was then used to fasten the profile + VCA-mate to the VCA; after attachment, the plunger itself (i.e., the cylindrical component in contact with the sample dish) was then press-fit onto the profile.

Figure 3. Required length of aluminum profile + 3D-printed attachments [mm].

Author: Griffin Radtke

Editor: N/A

Redesign + print housing	Added necessary through-hole locations as well as wiring slots and created symmetric designs suitable for printing with biocompatible resin (future work).	GR	3

To resolve the previous issue of the fastening within the bioreactor, Sydney & I discussed and opted to add, more or less, sequential fasteners to each layer of the bioreactor, securing each module to the adjacent; with this, M4 fasteners were selected to balance size and mitigate the risk of potential bolt shearing. Additionally, alongside other small modifications relating to the stability of the print, wiring pass-throughs were added to allow for access to the VCA wiring. Following conclusion of design (Figure 4), all parts were printed with PLA, which is best suited for sterilization with ethanol.

Further, to provide Dr. Henak with further options to improve the biocompatibility of the bioreactor, a symmetric model (intended to be used with ¼“ stainless dowels) was created to allow for printing of the device with biocompatible resins, which would require a printer with a smaller build volume (i.e., thereby requiring a smaller part). Given the note mentioned below and the significant cost discrepancies between PLA & BMC (i.e., ~10-15x), though, this design is offered as a potential suggestion rather than an actual implementation in the final deliverable.

It should be noted that an alternate printing site besides the Makerspace will need to be used if printing with BioMed Clear, as the Makerspace washes all parts in the same IPA (negating the biocompatibility benefits offered by the resin).

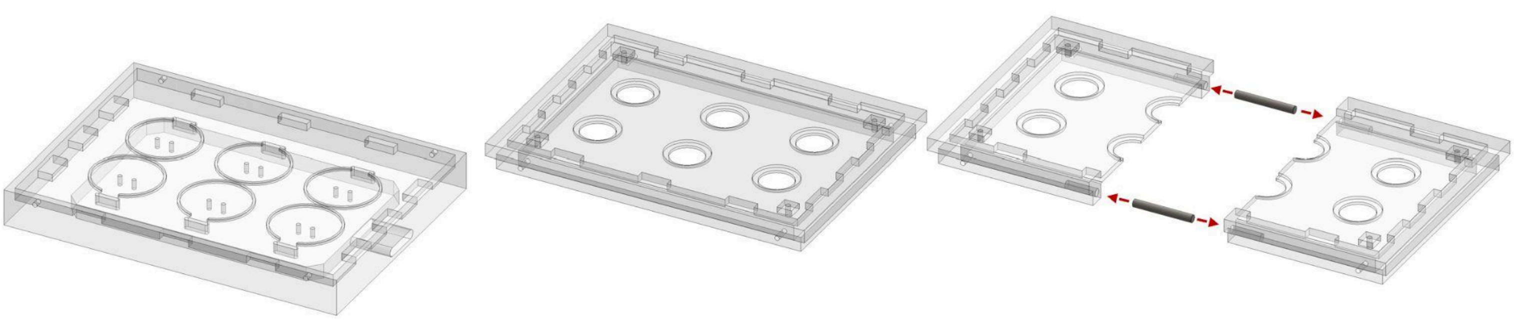


Figure 4: Final CAD schematics of both the full/final and symmetric parts.

Author: Emilio Lim
Editor: N/A

Extrapolate Data	Using the data obtained previously from verification, plot graphs using MATLAB to obtain some numbers.	EL	4

By using the data from testing using the load cell at Dr. Henak's lab, several graphs were plotted to observe the consistency of the force output. The initial first test records the force output over 30 minutes. A FFT graph was then plotted to observe the frequency at which the actuator operated at. The first graph started with a force output of 0N and slowly increased to hit 6N. The voltage was increased simultaneously from 0V and up to 6.33V with a current of approximately 0.7A. From the force output, we noticed that there is an overshoot in the force generated by the actuator. This can be attributed to the voice coil needing to overcome the magnetic attraction force from the base of the machine platform during the testing.

Other data was also collected such at 1Hz, 2Hz, and 0.5Hz. Each of these tests were run with data extrapolated for 15 seconds to make comparisons. It was quite apparent that all of these frequencies have an inherent spike every once in 15 seconds. The cause of this was not identified. The general trend seen was the greater the frequency, the greater the spike is; and the lower the frequency, the more consistent the force output is.

Overall, more verification testing needs to be done before being able to conclude the effectiveness and consistency of the force output by the voice coil. The whole system needs to be verified using a load cell to obtain the voltage output for the desired force output.

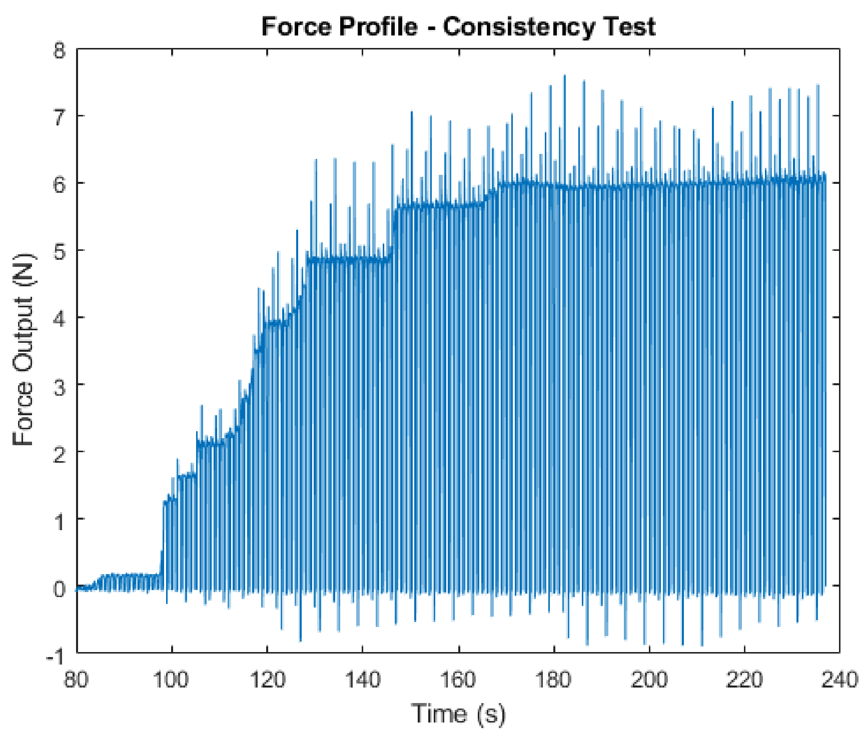


Figure 5: Force profile during consistency testing.

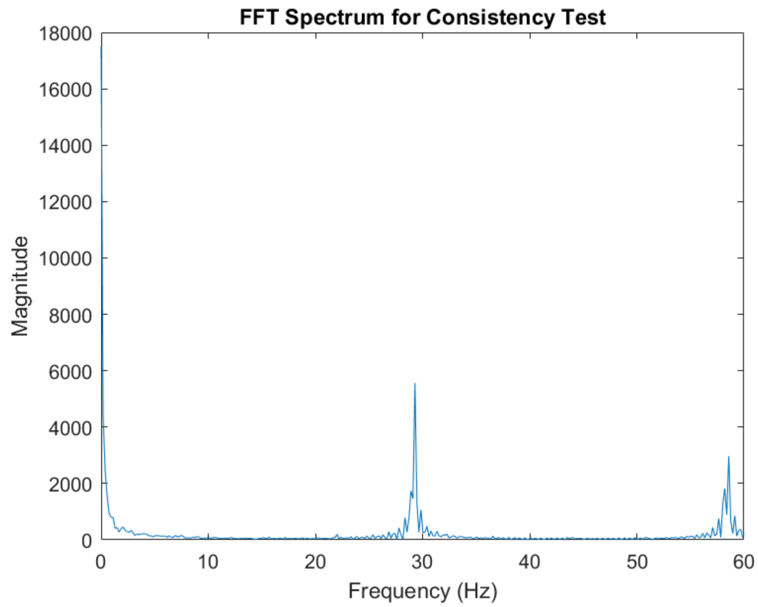


Figure 6: FFT of force profile for the consistency test.

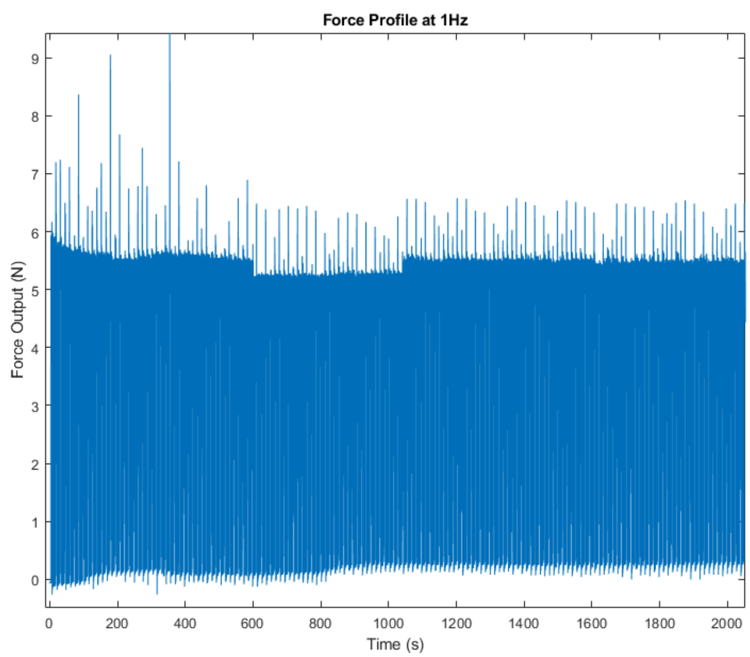


Figure 7: Force profile at 1Hz.

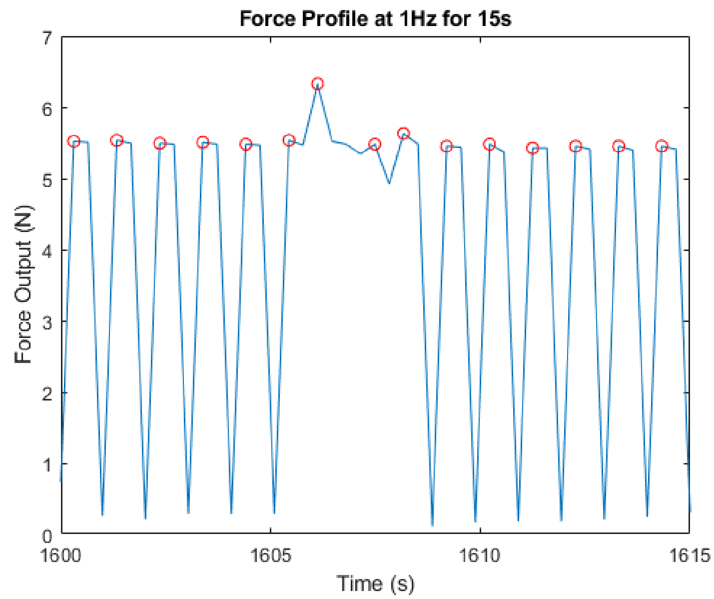


Figure 8: Force profile at 1Hz with a snapshot of 15 seconds.

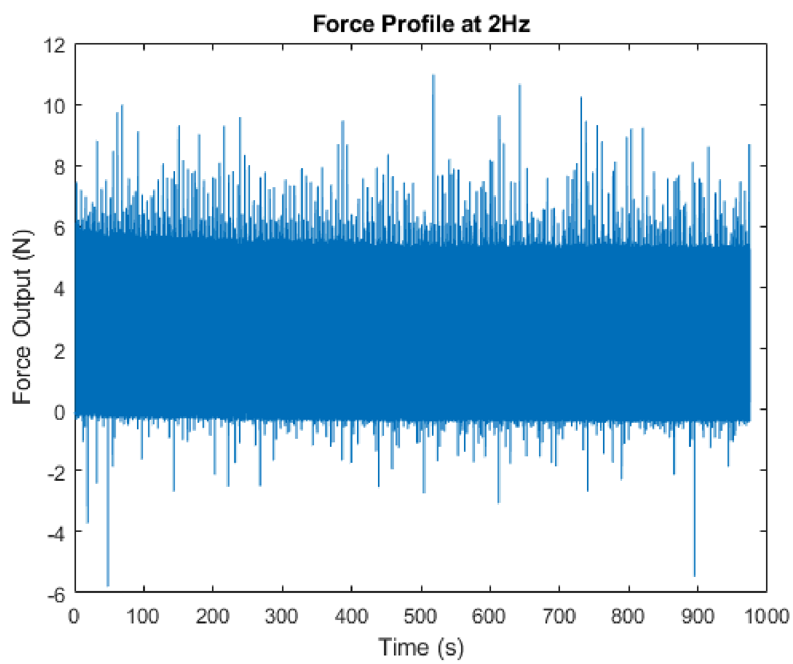


Figure 9: Force profile at 2Hz.

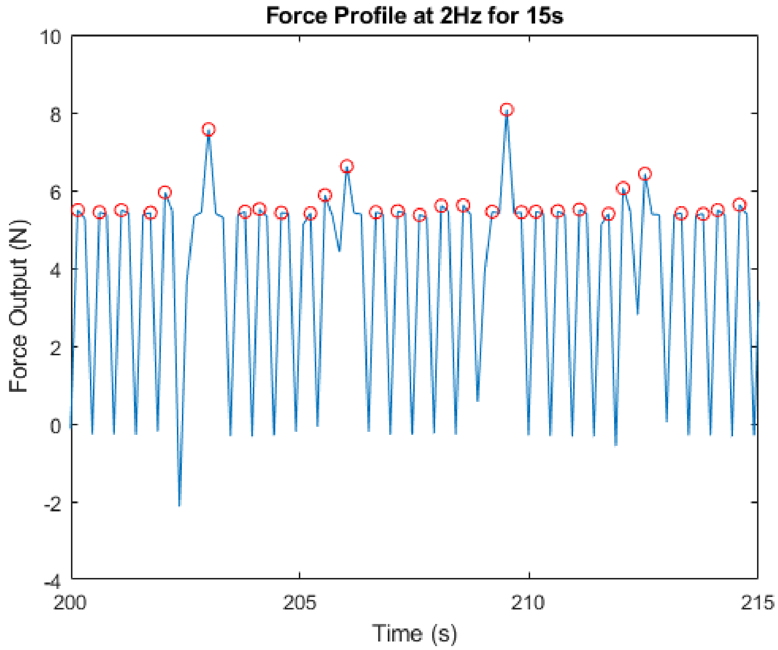


Figure 10: Force profile at 2Hz with a snapshot of 15 seconds.

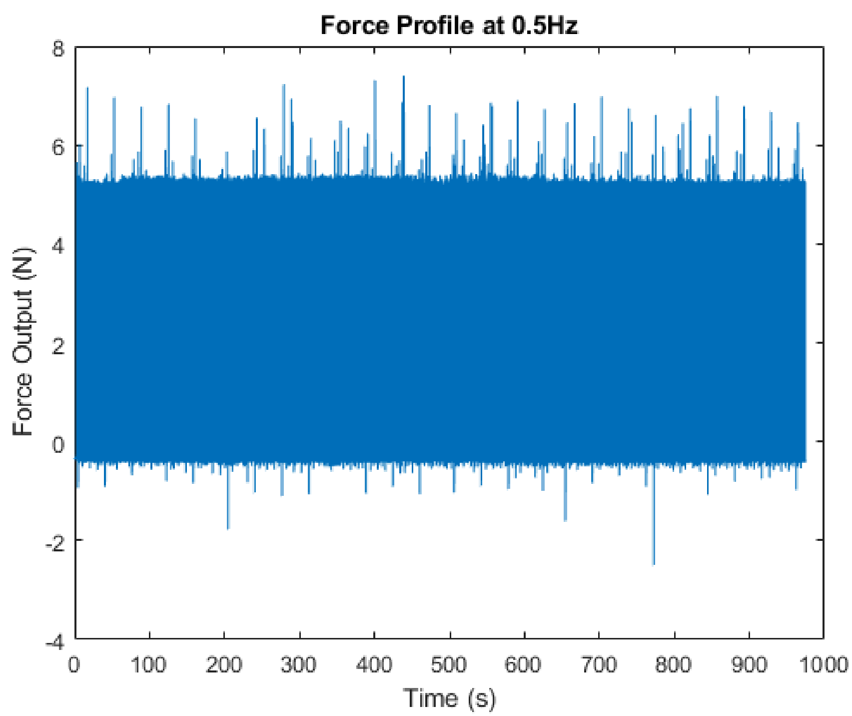


Figure 11: Force profile at 0.5Hz.

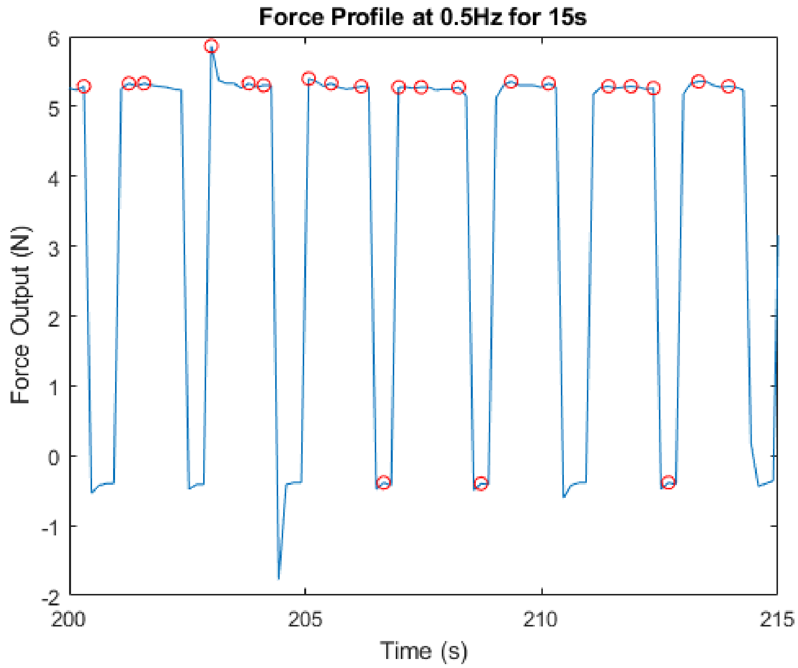


Figure 12: Force profile at 0.5Hz with a snapshot of 15 seconds.

Gantt Chart

Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	Jan		Feb				Mar				Apr				
Task	24	31	7	14	21	28	6	13	20	27	3	10	17	24	1
Individual Presentations					X										
Bioreactor Housing and Bearings															
Control with One VCA								X							
Working Prototype										O					O
Full Bioreactor CAD Model				X											
Fabricated Bioreactor									X						
Circuitry with All Six VCAs															
Final Review										O					O
Design Specification Validation															
Bioreactor Assembly with Circuitry															

X = Completed Tasks, O = Milestone Deadlines

Old Tasks

Task Name	Description and Concrete Outcome	Owner	Est. Time
Finish PTFE fabrication	Threaded the PTFE and obtained the correct fasteners for the cylinders.	ST	1
Ideate sample tray connection/removal strategies	Brainstormed how to best attach the sample tray to the lid in a way that can be secure but also easily removable	ST	2
Complete Breadboard circuit	Design a breadboard circuit diagram for ease of building in future	EL	1
Finish VCA Attachment Components	Made slight additional modifications and 3D-printed press-fit, biocompatible attachments to the bearing shaft.	GR	2
Review load cell test data and order parts	Review last week's testing data from the load cell and get ready to purchase parts	JG	1
Work with Arduino and current regulator	See if some codes of the arduino can be used to generate a sine wave in lieu of the current regulator from the ME library	EL	2
Design consultation with TeamLab regarding fabrication and bearings	Met with TeamLab personnel to ask about the cost/feasibility of fabricating the device and solicited their opinion on what bearings to use.	ST	1
New CAD with fabrication feedback from TeamLab	Turned the TeamLab's recommendations for the bioreactor into a full SolidWorks file which will be possible to machine.	ST	7.5
Estimate 3D-Print Costs	Calculate exact costs of 3D-printing previous model, itemize budget	GR	1
Test and develop working system of circuitry/electronics to operate VCA	Continue experimenting with electronics/other components (e.g., motor controller, H-bridge, power supply, myDAQ, Arduino) to develop functioning system that can operate the VCA	JG/EL	3

Develop rough calibration curve for voltage input and force applied	Create a rough calibration curve for voltage input for the VCA vs. force outputted by the VCA using the triangle PCB	JG/EL	1
Estimate friction and impact of wear for Drylin Q Flange bearing	Pulled numbers from Drylin website and made plots to get a sense of how long the bearing could be in operation and how much of an issue friction would be.	ST	2.5
Continue testing H-bridge	Continue testing H-bridge to get a triangle output	JG/EL	3
Revamp CAD for Machining	Make modifications to existing CAD for machining-purposes	GR	6
Finalize prototype CAD and manufacture prototype parts	Put finishing touches on the actual 3D model and create SolidWorks drawings that can be laser cut. Use Makerspace facilities to 3D print and laser cut the parts for the prototype.	ST	3
Prepare presentation for prototype demonstration	Administrative – working to concisely present physical and analytical work.	All	2+
Continue developing working electronics/circuitry	Continue developing the circuit and electronics to operate the VCA	JG/EL	2
Draw a circuit diagram	Use LTSpice to draw out the circuit diagram	EL	0.25
Temp. Analysis of Compressive Lid	Verified acrylic's stability under thermal expansion at incubator-like conditions.	GR	1.5
Request sample of bearing and shaft from Igus.	Ordered one bearing and 9-12in of hard-anodized aluminum square hollow shaft on a sample form available on Igus.com.	ST	0.5
Modifying CAD for prototype presentation	Added bearings, compressive interface PTFE, and VCAs to the CAD used for prototype fabrication.	ST	1
Finalize circuitry and mode of operation	Finalize the circuit and choose on either using the Arduino or MyDAQ	EL/JG	3

Force Sanity Check	Conducted finite element simulation of cartilage plug sample under loading conditions expected within the bioreactor.	GR	1.5
VCA-Compatible Components	Designed (and will be 3D-printing) components compatible with the drylinQ bearing system.	GR	2
Received bearing and shaft sample from Igus (!)	Unpacked the samples that arrived from Igus over spring break.	ST	0
Machined PTFE (almost complete)	Used a bandsaw and lathe to cut the PTFE pillars, face them, and drill holes that still need to be tapped.	ST	4
Force test	Used a load cell to test the consistency of the force output	EL/JG	2

Previous Work

Author: Sydney Therien
Editor: N/A

Finish PTFE fabrication	Threaded the PTFE and obtained the correct fasteners for the cylinders.	ST	1

In order to finish full fabrication of the PTFE rods, the inside of the drilled holes needed to be threaded. This was accomplished on a lathe using an M6 bit. Additionally, all the fasteners were swapped out to be the same length. As of now, the PTFE is 100% ready to be assembled into the bioreactor housing.

Author: Sydney Therien
Editor: N/A

Ideate sample tray connection/removal strategies	Brainstormed how to best attach the sample tray to the lid in a way that can be secure but also easily removable	ST	2

In order to make the bioreactor's samples easily accessible for imaging by Dr. Henak and her lab personnel, the sample tray needs to be completely removable from the bioreactor. This will require some strategic thought about fastener locations and methods. There were two main ways to do this that came to mind. The first of which requires eight bolts and wingnuts that attach to the lid and base modules, shown in Figure 1 below. Four bolts go into the lid and four go into the base, and a pair of them attaches each corner. The force applied by these bolts would be directly perpendicular to the surface they are drilled through. This method would require the acrylic and sample tray holes to be threaded.

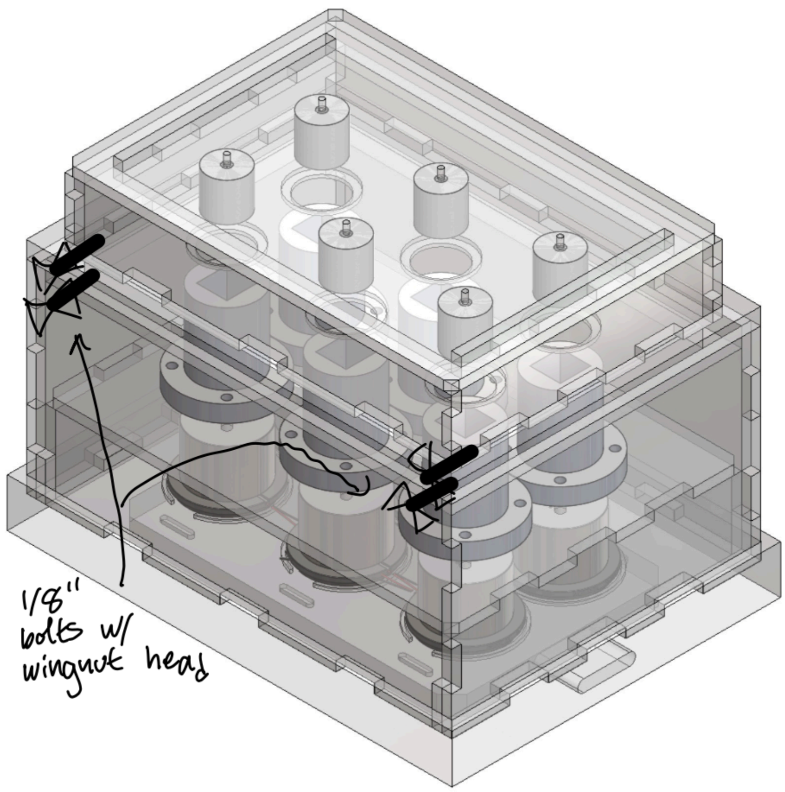


Figure 1: A schematic bioreactor with one face of wingnut attachment shown.

The second method to fasten the lid involves utilizing eight dowels and four cable clamps. The dowels will go in the same (non-threaded this time) holes and stick out for about half an inch. This will provide two points for a Cable Clamp to go around and hold the dowels together. If you are unfamiliar with what a Cable Clamp is, it's essentially a reusable zip-tie. An example can be found in Figure 2. This method would be much faster of an assembly since adding eight dowels and four Cable Clamps would be more easily done than twisting eight wingnuts.

Figure 2: Some examples of Cable Clamps in open and closed configurations.

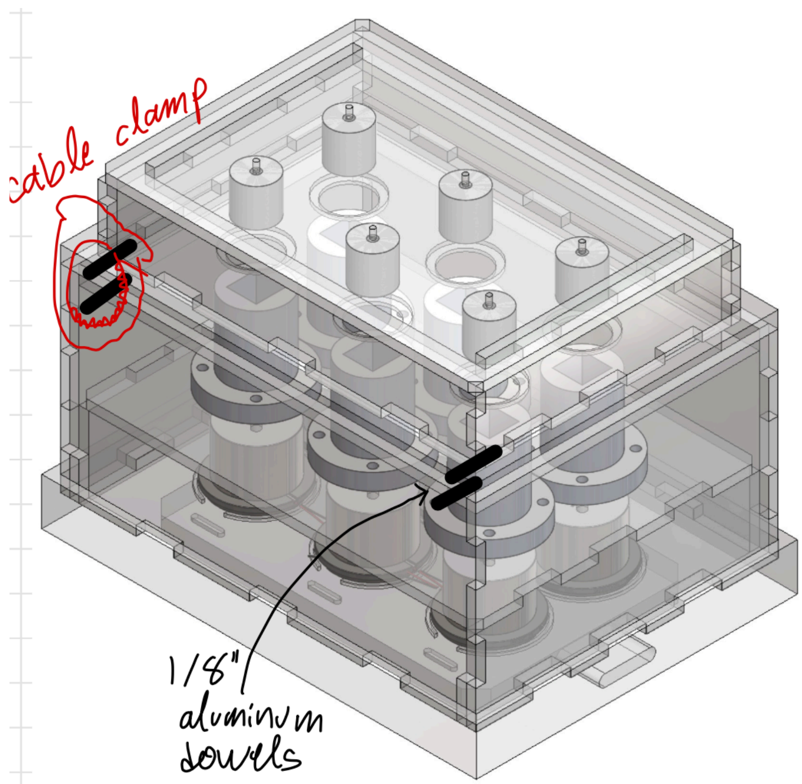


Figure 3: A schematic bioreactor with one face of dowel and Cable Clamp shown.

The potential issue with this design is the bending introduced by the Cable Clamps pulling on the dowels and creating a bending moment. In order to decide what to do moving forward regarding attaching the sample tray, SolidWorks simulations will be run after Sydney and Griffin discuss potential alternate methods of achieving this connection. There were alternatives discussed at this week's client meeting that will need to be evaluated, but the decision on this will be made quickly due to the ever-decreasing amount of time left in the semester.

Author: Emilio Lim
Editor: N/A

Complete Breadboard circuit	Design a breadboard circuit diagram for ease of building in future	EL	1

For the ease of building the circuit in the future, Dr Henak requested a breadboard diagram on top of the LTSpice schematic. The schematic was made using different components as it was not available on the software I was using. From figure 4 below, the 9V battery represents a power supply and the Arduino represents the MyDAQ. The ports of the Arduino and the MyDAQ are exactly the same. Other components include a NMOS transistor, diode, 1kΩ, 1MΩ, and a motor. While the components differ slightly to the actual design, the cable and connections are accurate. During the meeting with Dr Henak, it was explained that the circuit shown below can only power one VCA. To power all 6 VCAs, we would need to duplicate the exact circuit 5 times exactly.

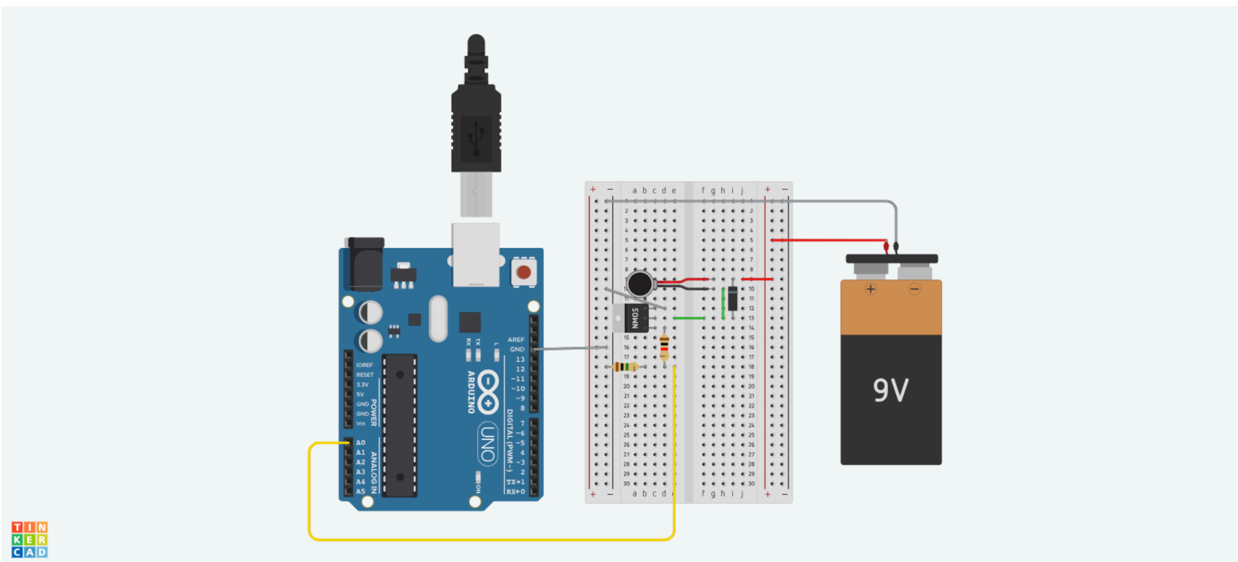


Figure 4: Breadboard circuit schematic.

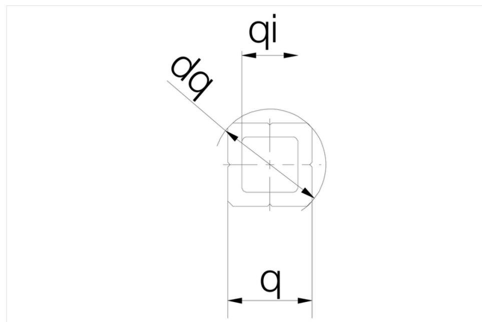
Author: Griffin Radtke

Editor: N/A

Finish VCA Attachment Components	Made slight additional modifications and 3D-printed press-fit, biocompatible attachments to the bearing shaft.	GR	2

As the drawing for the drylinQ aluminum shaft isn't dimensioned particularly well (namely, the inner radius - Figure 5), I made a few slight adjustments to the previous CAD to ensure successful press-fit after receiving the sample parts from Sydney. Following those revisions, both adaptive components (see previous work) were 3D-printed with FL BioMed Clear resin. The plunger component was then press-fit (see Figure 6), with machining of the shaft (i.e., likely with a drop-saw) to the necessary length needed prior to press-fitting of the VCA-shaft/square profile attachment.

drylin® Q square profile



Art.-Nr.	AWMQ-10
q	7.5 mm
Ø dq	10.0 mm
qi	5.0 mm

Figure 5: Note the missing inner radial dimensions (the outer radius is not filleted while the inner is, interestingly enough).

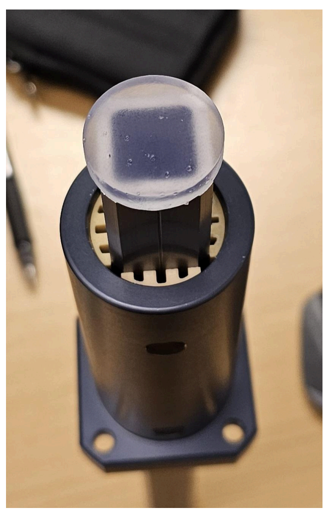


Figure 6: Press-fit plunger (i.e., which will contact the sample dish).

Author: Jeffery Guo
Editor: N/A

Review load cell test data and order parts	Review last week's testing data from the load cell and get ready to purchase parts	JG	1

Last week, Jeff and Emilio ran the VCA under the Henak Lab load cell to analyze the force profile and how it may or may not change over longer test durations. Initial review of the results seems to suggest that there could possibly be minor fluctuations or changes in the load over time scales of 15-30 minutes. More specific results and numbers quantifying behavior such as overshoot, which will be included in the final report and posters. The force profile was a square wave, and its square-like profile could be partially attributed to the base of the load cell being magnetic. We will also prepare to place purchase orders for a NI DAQ, power supply, and circuit components.