Design of a Force-Controlled Cartilage Bioreactor

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Background & Motivation

Osteoarthritis (OA) impacts 7% of the global population, with that percentage increasing every year [1]. Over 500 million people worldwide live with OA, with that number increasing by nearly 50% in the last twenty years. Figure below depicts future projections of arthritis cases (of which OA comprises ~$\frac{2}{3}$) in the United States.

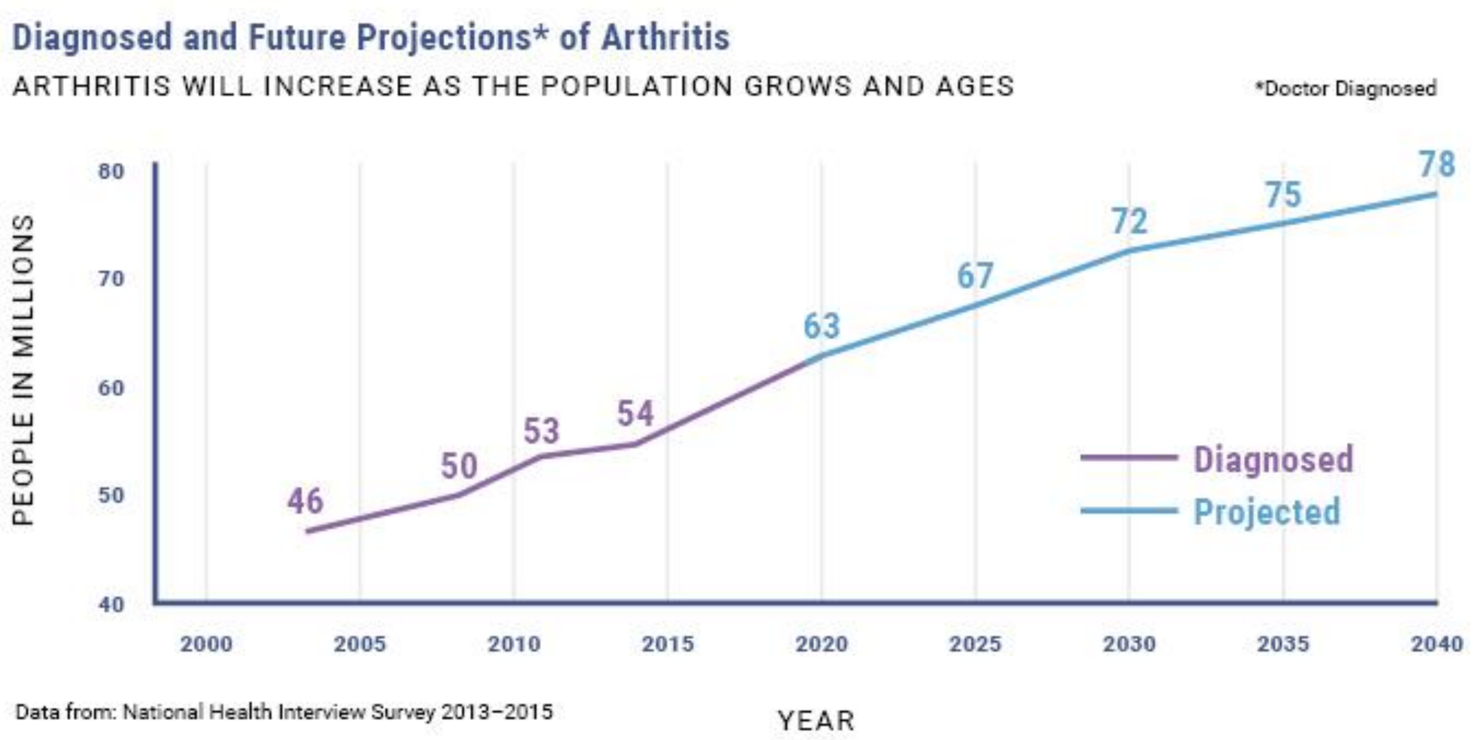
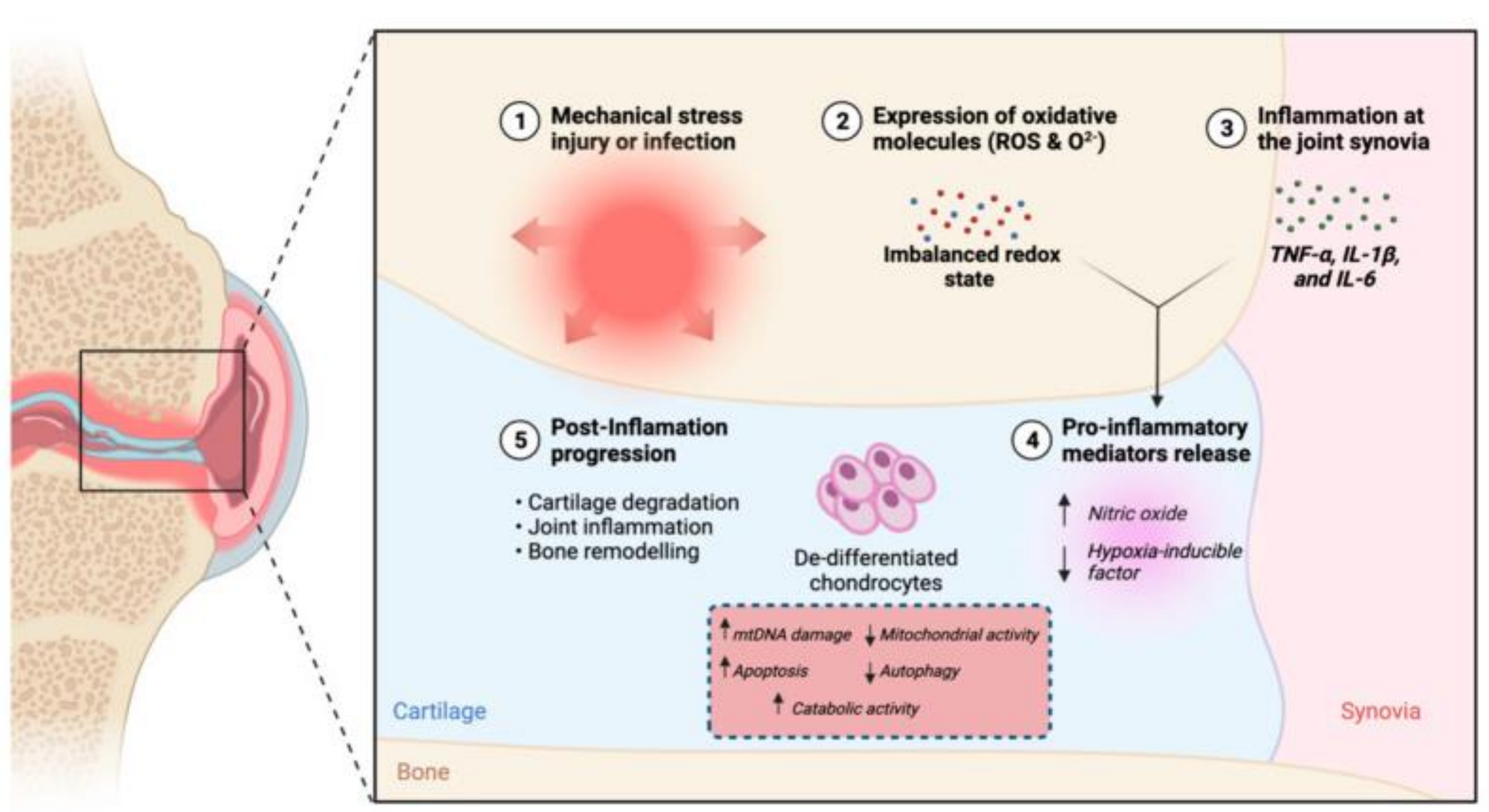


Image sourced from: https://oaaction.unc.edu/oa-module/oa-prevalence-and-burden/



OA is mechanically mediated [2]. Mechanical loading influences cartilage metabolic state, with dysfunction leading to osteoarthritic disease progression (i.e., degradation of articular cartilage).

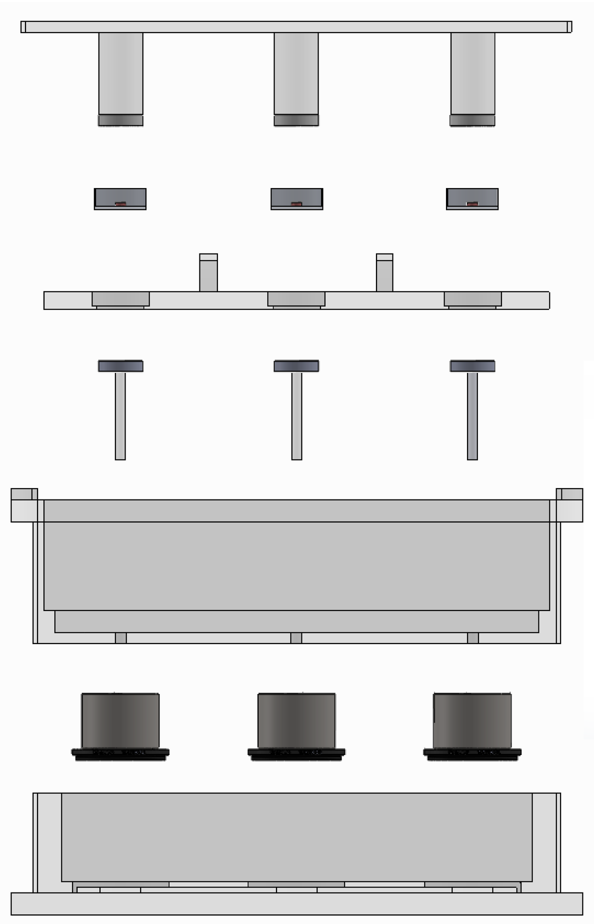
The Henak Lab investigates the relationship between cartilage metabolism (or redox balance) and disease state.

To research the link between long-term mechanical loading and cartilage metabolic balance, **Dr. Henak has requested a device capable of applying cyclic loading* to a cartilage explant culture over several days or weeks.**

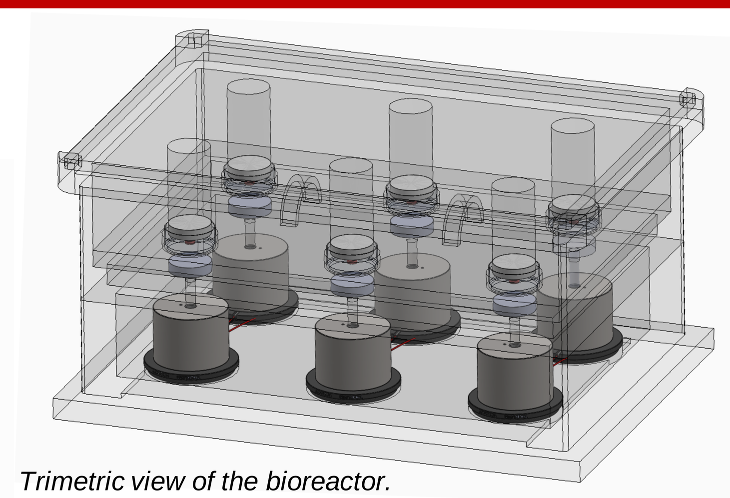
**Due to the poroelastic properties of cartilage, this loading must be force-controlled to avoid sample lift-off.*

Design

Bioreactor Overview and Housing

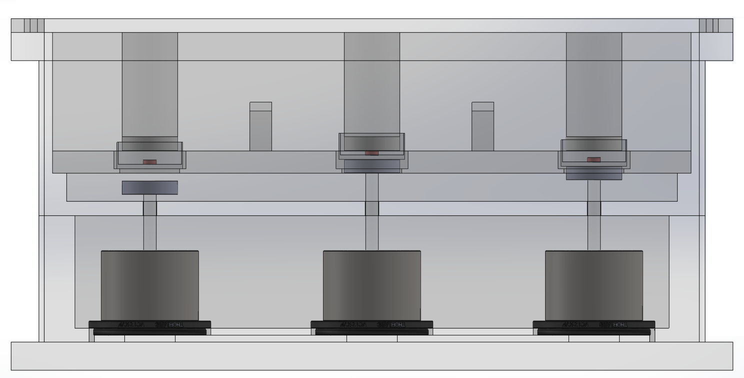


Exploded side view of the bioreactor.



Trimetric view of the bioreactor.

Housing is 3D-printed with biocompatible resin (BioMed Clear V1).



Side view of the device where the left VCA is resting, the middle VCA is fully engaged w the compressive interface, and the right VCA is dropping through the tray to lower the sample.

Actuation: Voice Coil (VCA)

$$\boldsymbol{\sigma_z = \frac{F_{current}}{A_{ref}} = E\varepsilon}$$

$$\mathbf{F \approx 6\,N}$$

$$E = 1\,[MPa]$$

$$\varepsilon = 0.2$$

$$A = \frac{\pi}{4}(6\,mm)^2$$

Cartilage roughly approximated as linear elastic to estimate force order of magnitude.

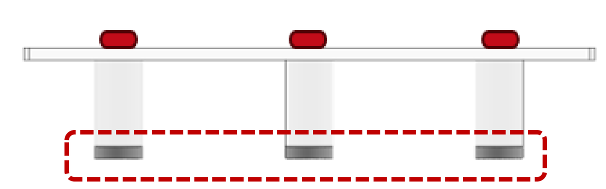
VCA force output is directly linked to current input (F = B x I).

ThorLabs VC125C/M, the VCA to be used in the bioreactor [3]

Force Constant	12.4 N/A
Travel	12.7 mm
Req'd Duty Cycle	50%
Max Operating Temp	230F/110C

Relevant specifications for ThorLabs VC125C/M as they relate to product design specifications [3]

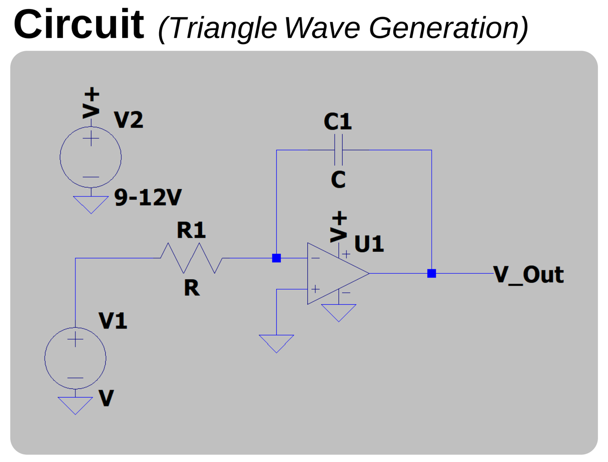
Interface: PTFE (Teflon)



Side view of interface pillar/cover

- **Chemically inert and nontoxic**
- Nonflammable
- **Low coefficient of friction**
  - *Less shear stress on tissue*
- High temperature resistance
  - Melting temp: 635°F/335°C
  - **Autoclave sterilizable**

Circuit *(Triangle Wave Generation)*



General circuit schematic for generating desired wave.

Circuit Overview:
- Input from microcontroller (V1)
- Amplifier Circuit (U1)
  - Utilizes a power op-amp for high voltage and current output
  - Requires different combination of resistor and capacitor for wave output
- Output to Voice Coil actuator (V_{out})

Design Criteria and Support

Incubator-Compatible

1. Fits within 20 x 21 x 25 [in³] space
2. Operates in 37 ºC, humid environment
3. Aseptic Technique Friendly
   1. Capable of adequate sterilization to ensure proper tissue culture

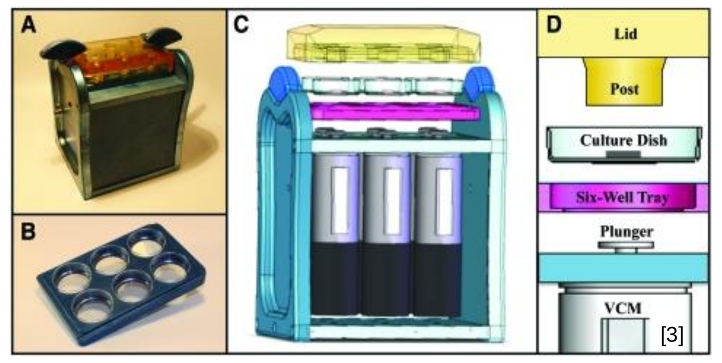
Relevant, Biocompatible Force Application

1. ~ 20% strain on cartilage samples
2. Applied strain must be force-controlled, not displacement-related, due to poroelastic behavior of cartilage
   1. Linear elastic approximation yields ~ 6 N minimum requirement; to ensure client needs are met, actuation needs to apply 12 N
3. Sinusoidal loading profile, ~ 0.1 – 10 [Hz]
4. Low-friction, biocompatible interface contacting sample in compression

Budget

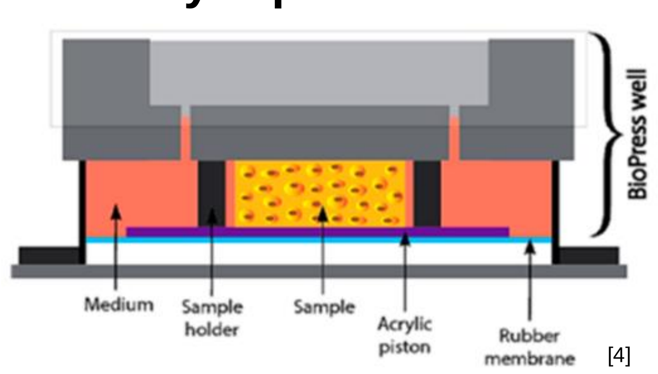
1. ≤ $5000

Scientific Literature



Prior work [4] provides design inspiration. The bioreactor outlined allows for closed-loop force control over uniaxial compression of cartilage explant culture.

Industry Equivalents

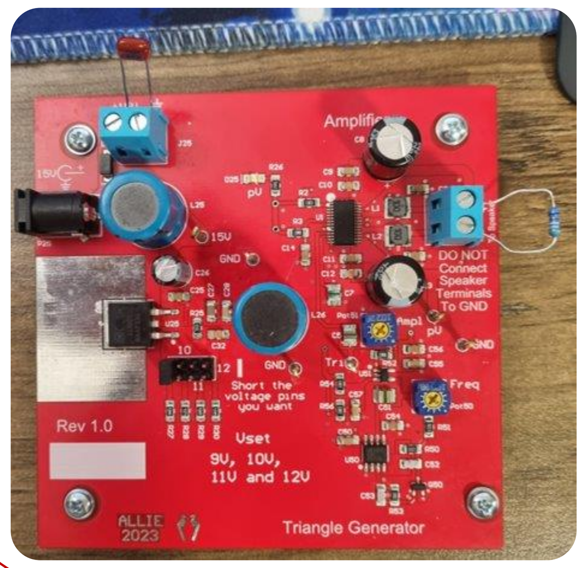


Industry equivalents [5] fail to meet all requirements. Compressive strain field profile is nonuniform.

We aim to build upon prior work to fabricate and validate a closed-loop, force-controlled system.

Planned Testing Procedure

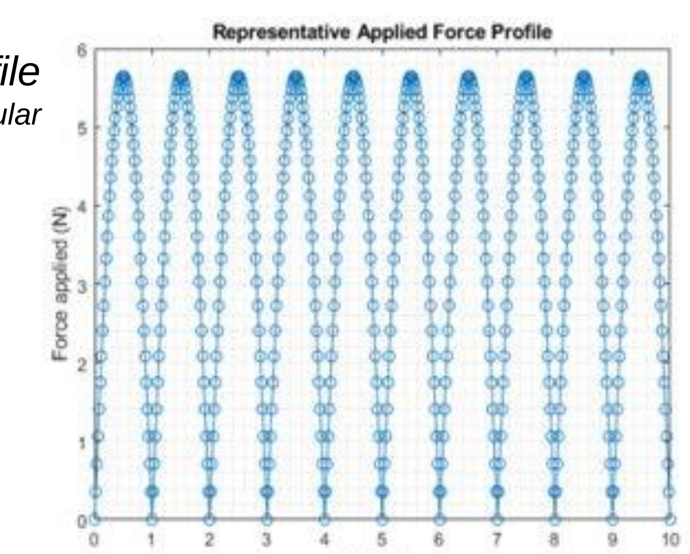
1. *Power circuit via wall adapter*
2. *Connect output terminals to oscilloscope to verify triangular output*
3. *Connect output terminals to voice coil actuator to verify functionality and output frequency*
4. *Validate correct force output using load cell*



Triangular wave generator circuit board

Outputs

Ideal loading profile
**in actuality, triangular*



Future Work and Summary

To complete our final project deliverables, our next steps are to:

- ***Finalize circuitry and validate VCA force output with custom input using Henak Lab load cell(s)***
- ***Finalize and 3D print housing schematics***
- ***Machine PTFE compressive interface and configure within housing***

Our current design allows for closed-loop force control and meets all given design criteria while remaining under $5000.

References

[1] Hunter, D. J., March, L. & Chew, M. Osteoarthritis in 2020 and beyond: a Lancet Commission. *The Lancet* 396, 1711–1712 (2020).

[2] Mohd Yunus, M. H., Lee, Y., Nordin, A., Chua, K. H. & Bt Hj Idrus, R. Remodeling Osteoarthritic Articular Cartilage under Hypoxic Conditions. *International Journal of Molecular Sciences* **23**, 5356 (2022).

[3] "Thorlabs - VC125C/M Voice Coil Actuator, 12.7 mm Travel, SM2 External Thread, Metric," www.thorlabs.com.

[4] Lujan, T. J. *et al.* A novel bioreactor for the dynamic stimulation and mechanical evaluation of multiple tissue-engineered constructs. *Tissue Eng Part C Methods* **17**, 367–374 (2011).

[5] Uzieliene, I. *et al.* Chondroitin Sulfate-Tyramine-Based Hydrogels for Cartilage Tissue Repair. *International Journal of Molecular Sciences* **24**, 3451 (2023).

See our project page for more info!

Poster Contents

At a minimum your poster should have the following information:

- Title
- Authors, Advisor, Client, Date or Semester
- Problem Definition:
    - Motivation
    - Background
- Design Criteria and quantitative specifications
- Final Design
- Testing
- Results
- Future Work
- References

Layout and organization should be logical and easy to follow. Remember that all graphs, charts and diagrams must have a figure legend with axes correctly labeled, and including dimensional units, values, and scale (if any). Ensure that fonts within graphics are legible and conform to the font standards provided above.