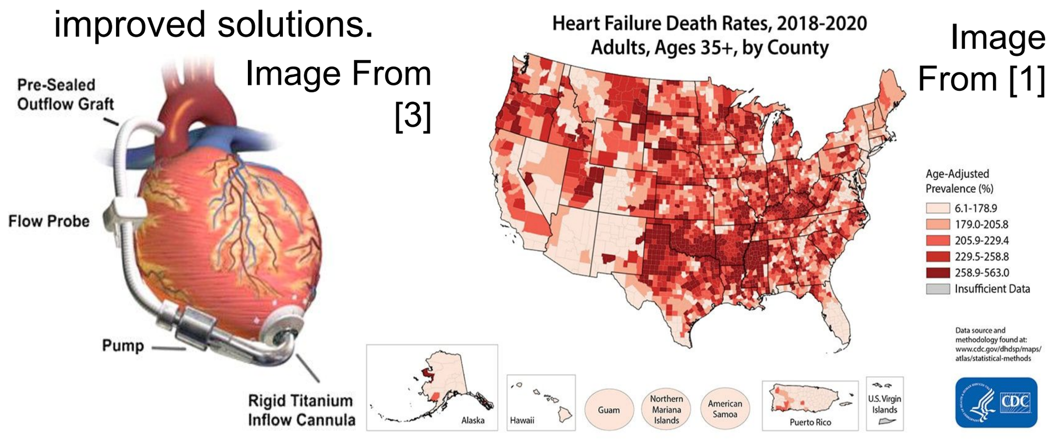
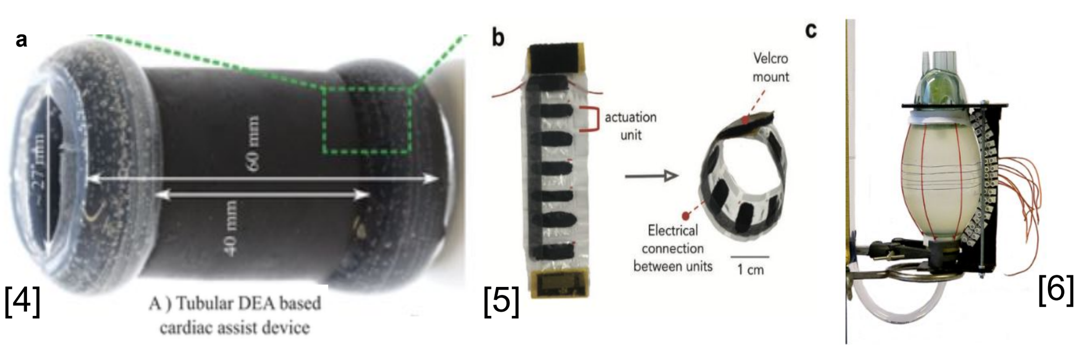
AI-Driven Artificial Muscle for Cardiac Assist using Hydraulically Amplified Self-Healing Electrostatic Actuators

Issue Statement

- Heart Failure (HF) occurs when the heart is unable to pump sufficient blood and oxygen to meet the body's needs, leading to severe health complications.
- It is a major global health crisis, responsible for 17.9 million deaths and affecting 60 million people worldwide each year, making it the leading cause of death worldwide.
- Ventricular Assist Devices (VADs) serve as life-saving interventions for patients ineligible for heart transplants.
- Traditional VADs present significant challenges. These include high rehospitalization rates, mechanical failures, and long-term complications, highlighting the need for improved solutions.



Previous Research



Rigid VADs (Ventricular Assist Devices) have been implemented, but stiff structure causes limited biocompatibility and high rehospitalization rates (37%) with further complications.

A. DEA Based VAD - Durability limitations and complete failure after dielectric breakdown. Safety concerns due to actuation geometry with expansion under voltage rather than contraction which risks over-tightening around the heart.
B. HASEL Based VAD - Lower power output and no real-time control implementation
C. Pneumatic VAD - Risk of driveline infections due to hydraulic drivelines and poor controllability. Low actuation frequencies.

Research Gap

High rehospitalization and complications with rigid VADs	Self-healing, soft HASEL actuators improve biocompatibility
Pneumatic drivelines and Limited control of soft devices	Electronically driven HASELs eliminate pneumatic drivelines
Poor durability of soft electrically actuated devices	Liquid dielectric allows self-repair after breakdown
Complex, nonlinear control of soft actuators	Complex, nonlinear control of soft actuators
Fabrication challenges in soft actuator design	Machine learning enables real-time force prediction
Lack of real-time control in realistic environments	Tested on phantom heart, integrated pressure sensor

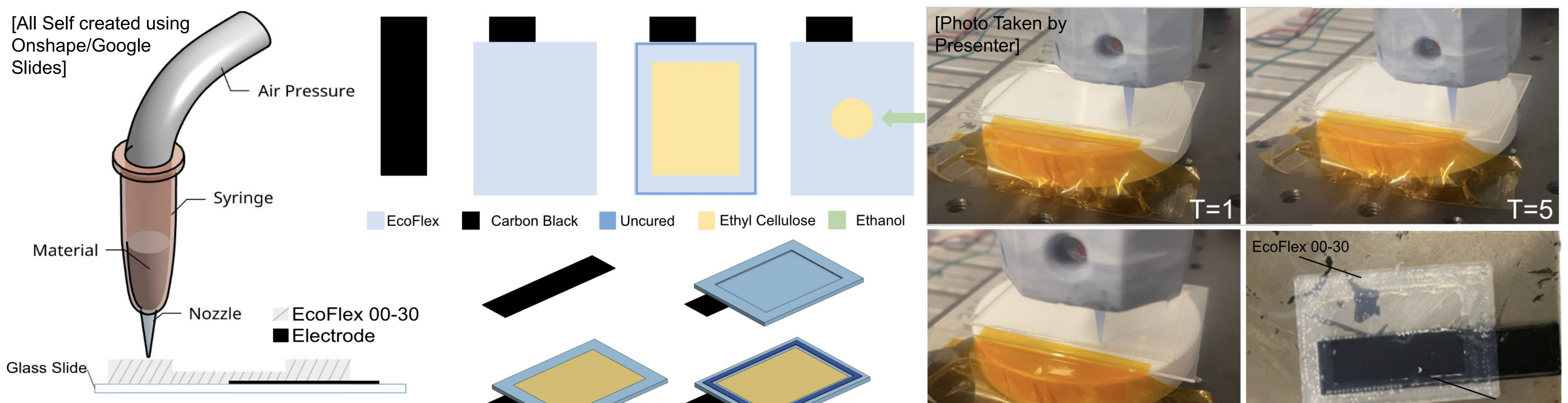
[By presenter in Google Slides]

Design Criteria & Constraints

Metric	Description of Metric	Value
Strain	Change in dimensions of the actuator.	>20%
Energy	Work generated during actuation	1 N•mm
Directionality	Possible directions of actuation	Unidirectional
Frequency	Frequency of Actuation	>=1 Hz
Accuracy	Accuracy of control of the actuator	>60%

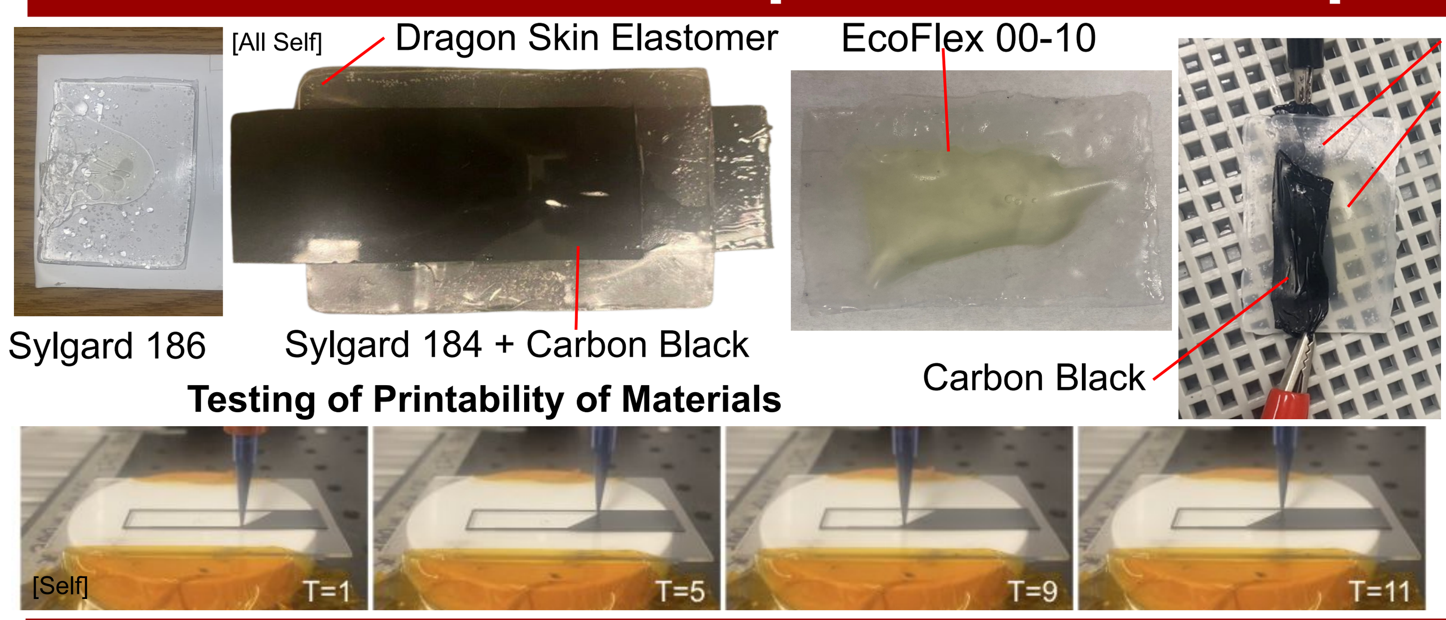
[By presenter in Google Slides]

DIW 3D Printing of Ventricular Assist Devices



DIW (Direct Ink Write) 3D Printing

Material Preparation and Experimentation



Selected Combination

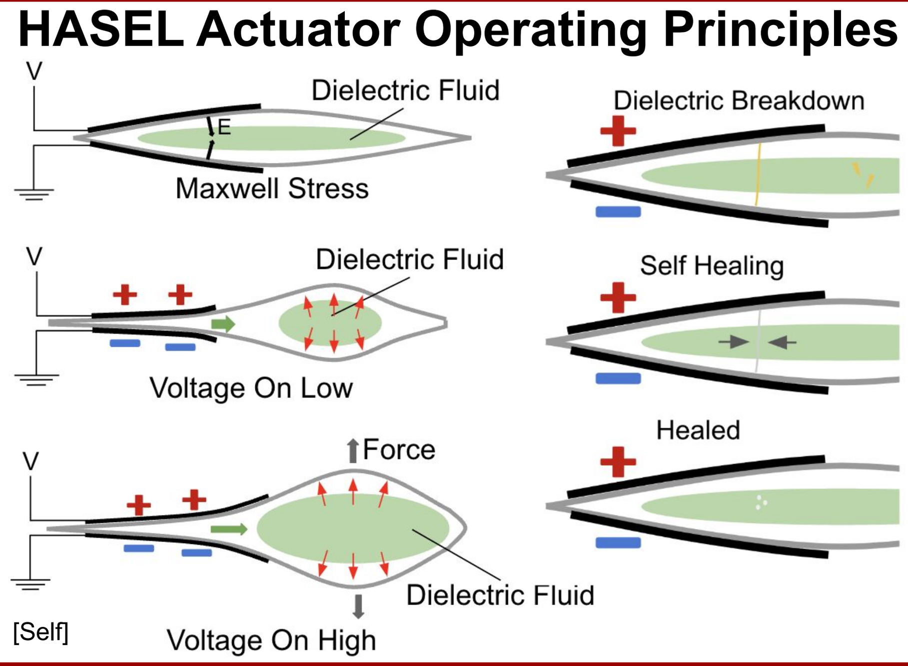
Testing of Printability of Materials

Material Suitability

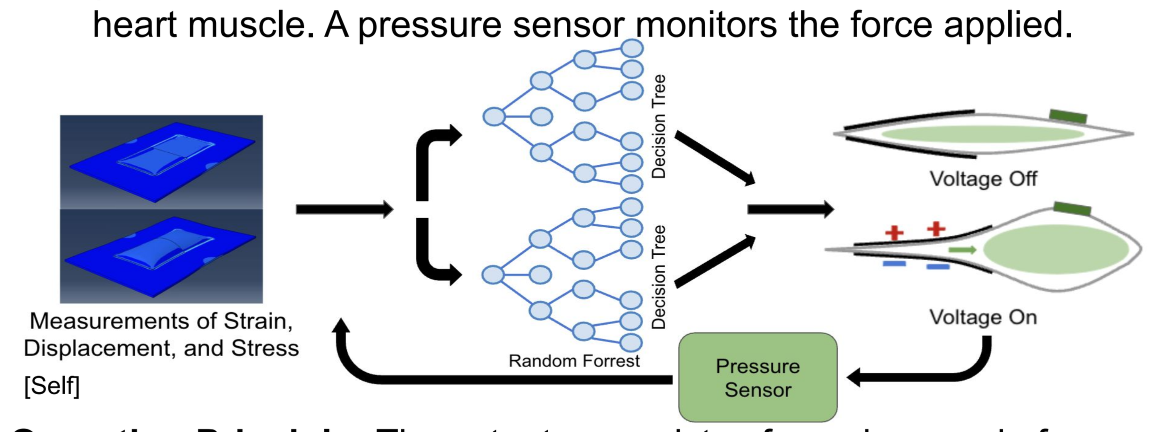
Material	Young's Modulus	Suitability
EcoFlex 00-10	50 kPA	⊗ (Durability)
EcoFlex 00-30	100 kPA	✓
Sylgard 184	1.84 MPa	⊗
Sylgard 186	2.4 MPa	⊗

System Design with HASEL Actuators and ML Control

HASEL Actuator Operating Principles

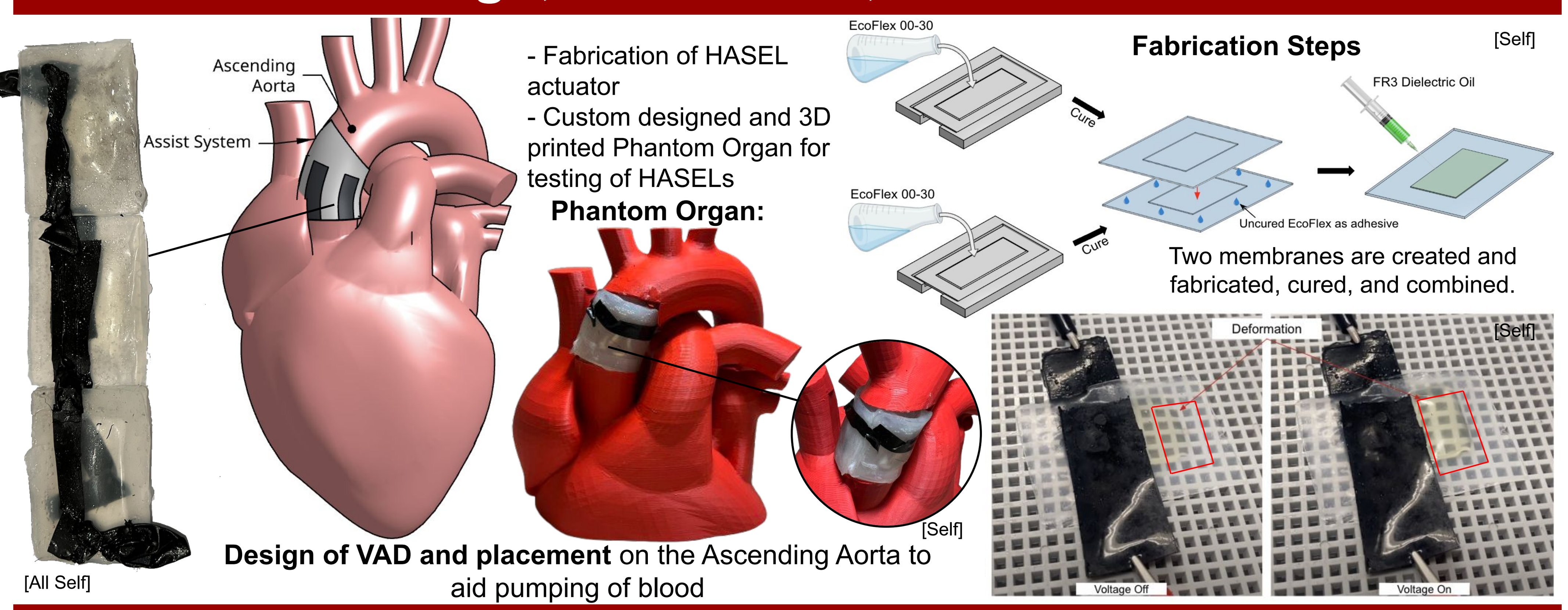


ML Model trained using the FEM data is used to determine the voltage to the HASEL. This determines the output force applied to the heart muscle. A pressure sensor monitors the force applied.



Operating Principle: The actuator consists of pouches made from a flexible and inextensible shell that is filled with a liquid dielectric and covered with electrodes. Electrostatic forces displace the liquid

VAD Design, Fabrication, and Performance



- Fabrication of HASEL actuator
- Custom designed and 3D printed Phantom Organ for testing of HASELs

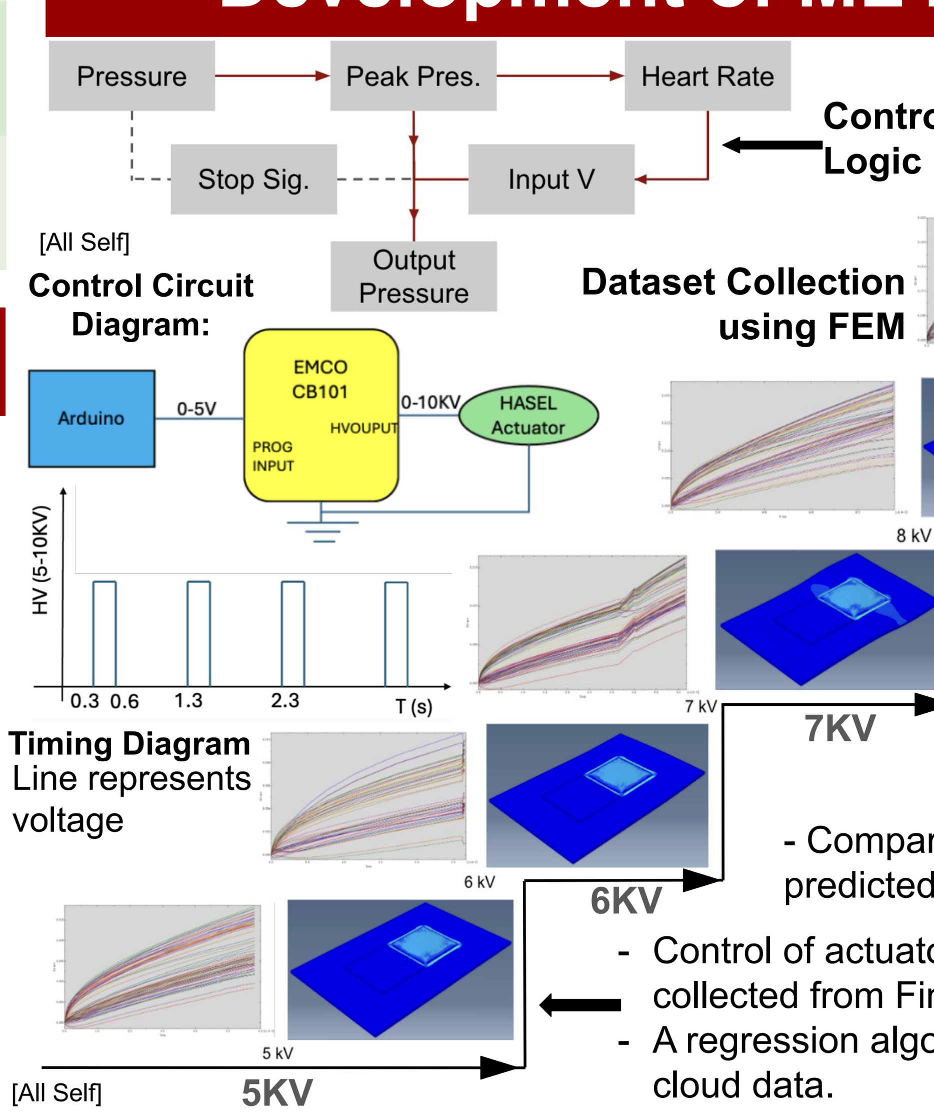
Phantom Organ:

Fabrication Steps [Self]

Two membranes are created and fabricated, cured, and combined.

Design of VAD and placement on the Ascending Aorta to aid pumping of blood

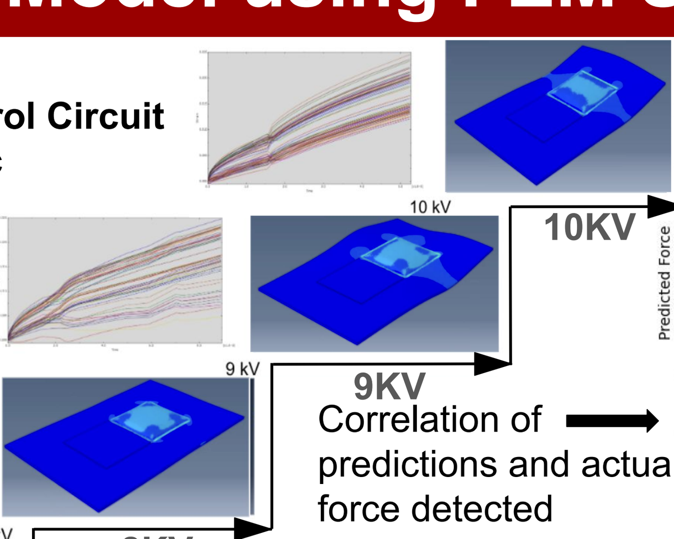
Development of ML Model using FEM Simulations



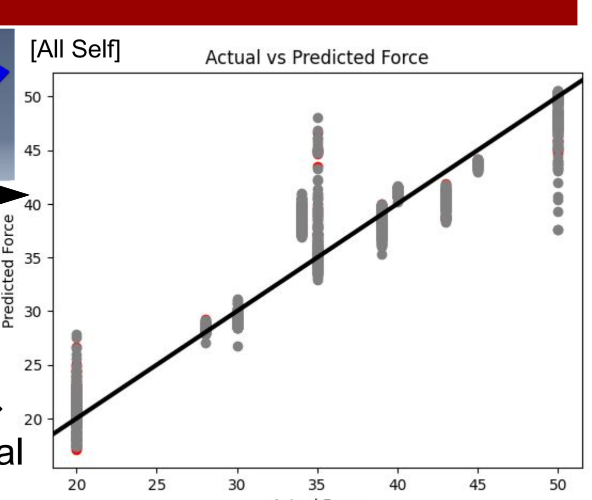
Control Circuit Logic

Control Circuit Diagram:

Timing Diagram Line represents voltage

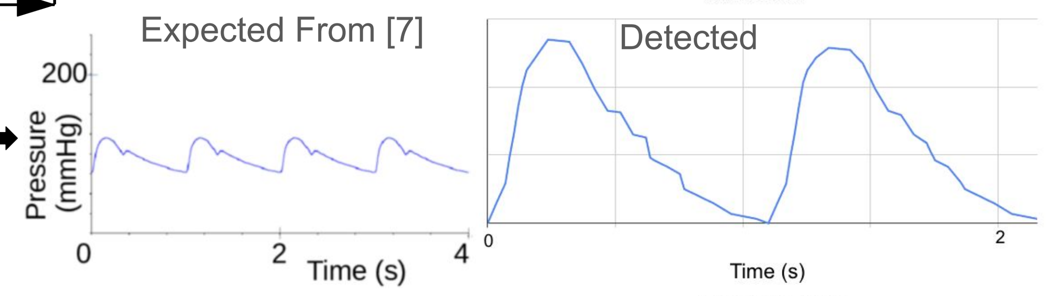


Dataset Collection using FEM



Correlation of predictions and actual force detected

Syncing with Cardiac Cycle:



- Comparison of reported pressure with predicted pressure operating at 8 KV

- Control of actuators is implemented using data collected from Finite Element Modeling simulations
- A regression algorithm is developed to analyze point cloud data.

Theoretical Model

$p = \varepsilon E^2$ where ε is the dielectric permittivity of the liquid, p is the electrostatic pressure

E is the electric field given by $E = \frac{V}{D}$ where V is applied voltage, D is thickness of dielectric

$\Sigma M = \varepsilon E^2$ Maxwell stress pulls the electrodes together and compresses the dielectric

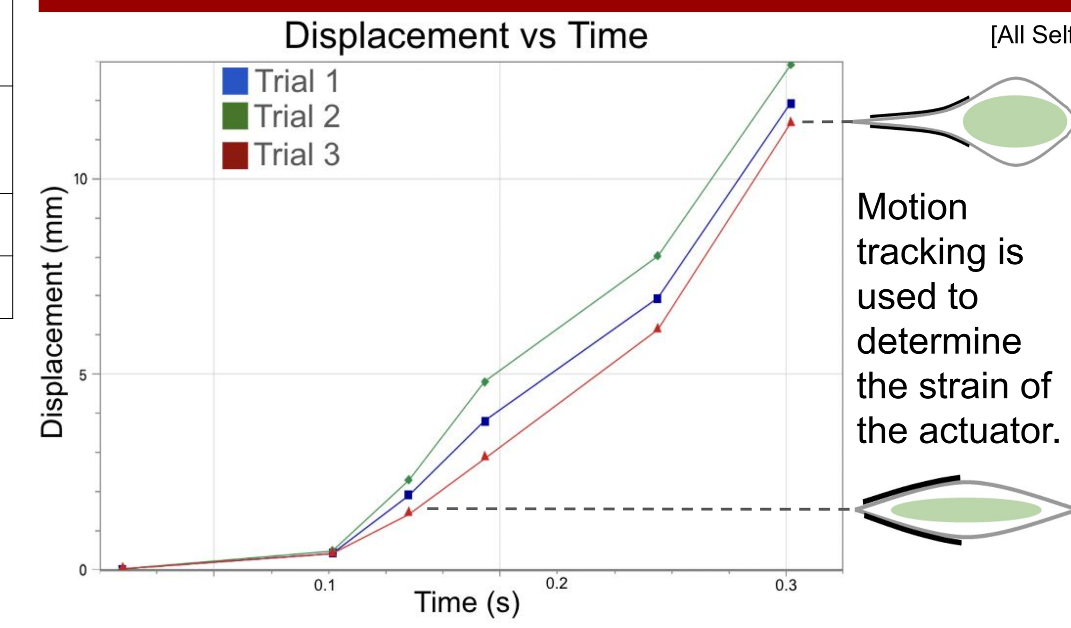
Substituting for electric field gives the pressure in terms of voltage as follows $p = \epsilon\left(\frac{V}{D}\right)^2$

which simplifies to the following: $p = \frac{\epsilon V^2}{D^2}$

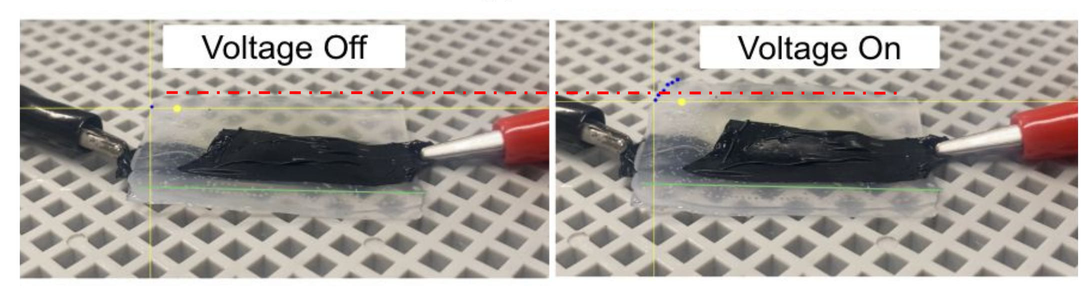
$V = \sqrt{\frac{pD^2}{\epsilon}}$

Is the relationship used to determine the relationship between the internal pressure of the VAD and the voltage applied for FEM simulations.

Deformation Characteristics



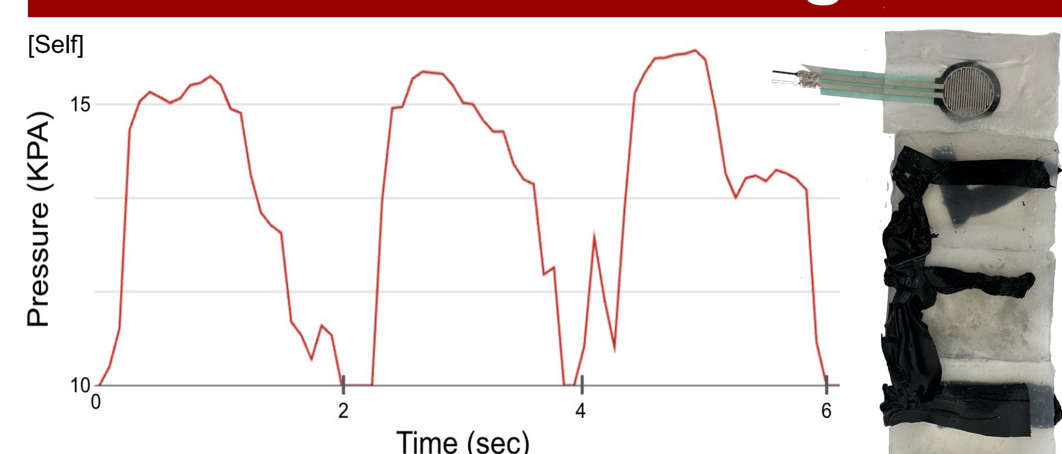
Motion tracking is used to determine the strain of the actuator.



Assessment of Design Criteria

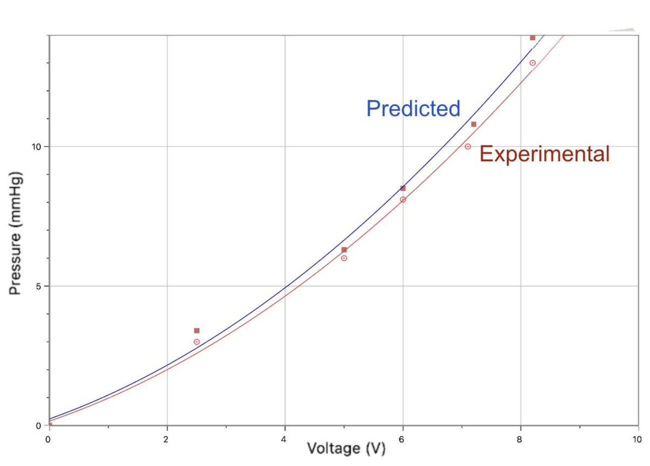
Strain	32.9%	Directionality	Unidirectional
Energy	5.49 N•mm	Frequency	3 Hz

Pressure Sensor Integration



The VAD exhibits consistent pressure output across various trials measured with the pressure sensor.

A force resistive sensor is implemented in the actuator through coating within an elastomer casing.



Conclusions

- **Hydraulically Amplified Self-Healing Electrostatic Actuators** are implemented for **biocompatible, soft ventricular assist devices**, reducing complications with rigid solutions and previous soft actuation methods.
- A **strain of 32.9%** and **energy of 5.49 N/mm** at an actuation frequency of 2 Hz is achieved for effective cardiac assist.
- An AI algorithm with an **accuracy of 91%** trained using point cloud data from **Finite Element Analysis** simulations is developed to provide **accurate control predictions** of HASEL actuators for use in ventricle assist.
- **DIW 3D printing** of silicone elastomers is developed for **rapid and accurate fabrication** of soft elastomer actuators.

Selected References

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