# Chapter 2
# The Design of a Multi-Axial Testing Apparatus to Mimic Physiological Conditions for In-Vitro Testing of Porcine Descending Thoracic Aortas

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**Abstract** Understanding the mechanical behavior of aortic tissue under physiologically accurate loading is essential for modeling arterial tissue. Although uniaxial and biaxial tests provide valuable information, they do not fully simulate the loading of the aorta in vivo. The aorta is subjected to axial and torsional displacements, as well as internal pressure that result in extension, torsion, and inflation. We designed and constructed a testing apparatus capable of applying controlled displacements and pressurization while measuring the resulting shear and normal stresses in porcine aorta samples. The system integrates a lead screw mechanism for precise axial control, a stepper motor-driven shaft for torsional displacement, and a syringe-based saline inflation system for internal pressurization. The specimen is mounted horizontally and fully submerged in a saline bath, with water heaters keeping the fluid at a constant 37°C to mimic physiological conditions and preserve tissue hydration. A load cell measures the total axial load, a torque sensor measures the torque, and a pressure sensor monitors the internal pressure generated by the saline pump. Calibration has been completed to demonstrate the apparatus' ability to capture the mechanical behavior of aortic tissue. The completed system is intended to be a versatile, highly programmable, and low-cost platform for multiaxial biomechanical testing, with applications in disease research and biomaterial evaluation.

**Keywords** Aorta · extension · inflation · torsion

## Introduction

Accurate characterization of aortic mechanics under physiological loading is essential for advancing understanding of cardiovascular disease. Converting this clinical need to reliable models requires experimental data that captures the mechanical response of aortic tissue under multiaxial loading. Multiple experimental approaches have been developed, including uniaxial, biaxial, and inflation tests of arterial samples. However, because arterial tissue has nonlinear mechanical behavior, these setups do not replicate the combined axial and torsional displacements and pressurization the aorta experiences in vivo, which limits their ability to inform these models.

Uniaxial tensile tests have been used to characterize the basic stress-strain response of aortic samples [8]. Anisotropic behavior has been demonstrated by comparing longitudinal and circumferential stress-strain curves under uniaxial loading [5].

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Planar biaxial tensile experiments have examined how cardiovascular disease alters the mechanical behavior of aortic tissue under more physiologically relevant loading [3]. Aortic wall shear and circumferential stresses are linked to cardiovascular disease, and cyclic torsional shear tests have revealed a nonlinear shear stress response in porcine thoracic aorta samples [9]. The stress relaxation of aortic tissue has been investigated using combined constant normal force with torsional shearing conditions [7]. Similarly, the shear stress response has been studied under cyclic rotational shear and constant compressive strain [6]. Finally, tension-inflation testing has been employed to approximate the in-vivo circumferential stress environment of the aorta [4].

Despite these developments, most testing configurations do not simultaneously apply extension and torsional displacements and pulsatile inflation, which are all present in vivo [2] [1]. In this work, we developed a new multiaxial testing apparatus to apply prescribed axial and torsional displacements and inflation while measuring the resulting forces, torques, and pressures. The apparatus incorporates loading axes and measurement systems with the goal of enabling extension-inflation-torsion experiments suitable for model calibration.

## Experimental Methods

The apparatus (Figure 1) was designed to test tubular sections of porcine descending aorta by combining axial extension driven by a lead screw, torsion driven by a motor, and internal pressurization driven by a syringe. The apparatus simultaneously applies these displacements and pressurization, while measuring the resulting forces.

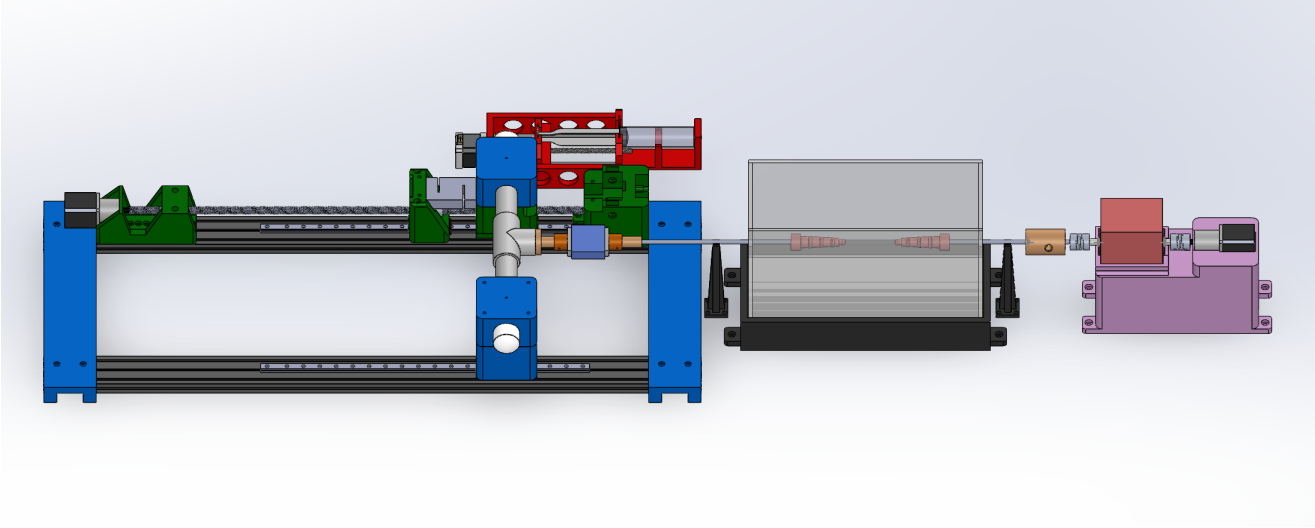

**Fig. 1** Multiaxial testing apparatus CAD for porcine aorta samples showing axial, torsional, and inflation components and saline tank.

The samples are clamped to custom 3D-printed PLA grips and secured using hose clamps to provide a leak-tight attachment while minimizing sample damage at the clamping sites. Each grip is rigidly coupled to a hollow stainless steel rod, and both the grip and rod feature a central bore that allows saline to flow through the sample for internal pressurization. The grips and rods are contained within an acrylic tank filled with saline. The rods transmit axial and rotational displacements and pass through sealed bearings integrated within the tank walls (Figure 2). These bearings ensure low-friction motion between the moving elements and the stationary walls.

On the left side of the apparatus, axial motion is applied through a screw-driven mechanism. The left side is adapted from a single-axis tensile testing machine. The hollow rod exits the tank wall and is connected to a calibrated S-type load cell. The load cell measures the axial force resulting from the applied displacement, and a custom PLA support ensures that the shaft and load cell are horizontally aligned. The opposite side of the load cell is fixed to a PVC adapter bar, which connects to the main axial tensile testing device. This device uses a lead screw driven by a stepper motor to move a carriage along a linear rail. The motor rotates the lead screw based on a prescribed distance and the lead screw pitch. The reaction force from the sample is captured by the load cell and can be processed into a stress-strain response.

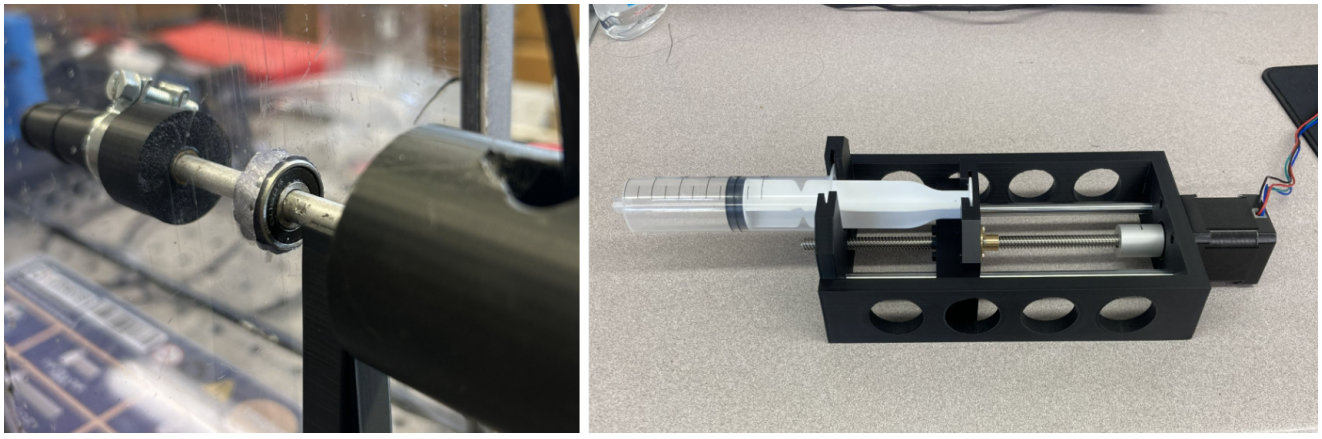

**Fig. 2** Detail of the 3D-printed grip and stainless steel rod supported by bearing integrated in the tank wall (left). Syringe-drive inflation system, with the syringe plunger connected to a lead screw drive (right).

The right side of the apparatus controls rotational motion and measures torque response transmitted through the hollow shaft. A second PLA stand supports the shaft and maintains horizontal alignment between the sample and other rotational elements. The shaft is coupled to a calibrated torque sensor to measure the torque resulting from rotational displacement. The torque sensor is coupled to a second shaft, which transmits rotational motion from a stepper motor. Both the torque sensor and stepper motor are supported by a custom PLA riser to ensure shaft alignment.

Internal inflation is controlled by a syringe-driven saline delivery circuit (Figure 3). A syringe is mounted on a custom 3D-printed stand. The syringe barrel is rigidly fixed to the frame, while the plunger is coupled to a lead screw mechanism driven by a stepper motor (Figure 2). Syringe-driven actuation is integrated into a closed saline circuit that directs flow between a reservoir and the specimen through check valves and tee fittings. The syringe connects to the hollow rod via a three-way tee fitting that also links to the reservoir, allowing saline to be drawn from the reservoir or delivered to the sample for inflation. A check valve between the tee and artery prevents withdrawal of fluid from the sample, and a second check

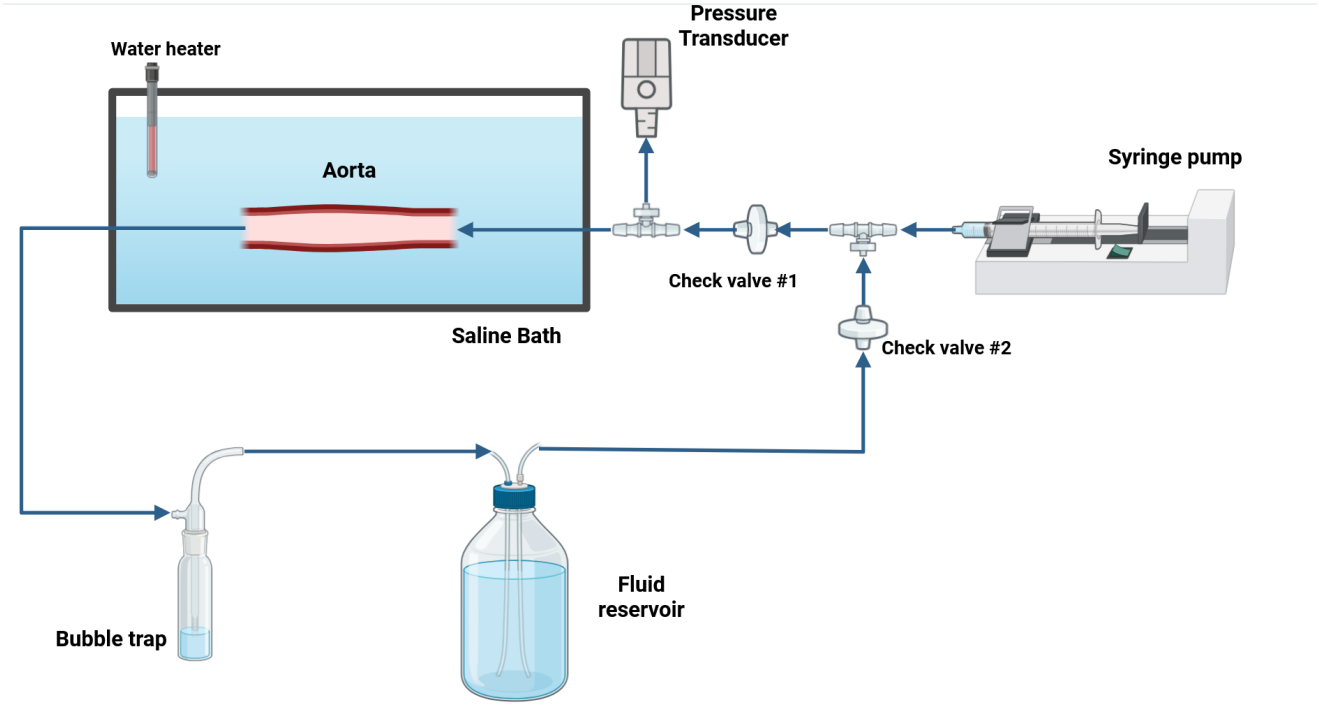


**Fig. 3** Schematic of the saline flow circuit including reservoir, check valves, and connections to sample.

valve between the reservoir and tee enforces the desired filling direction. A pressure transducer is mounted before the sample to monitor lumen pressure.

## Design Challenges and Troubleshooting

The original single-axis tensile testing machine was modified through several iterations to develop the multiaxial apparatus. The need for a tissue bath interfered with the lead screw, so we moved the extension axis laterally using 3D printed attachments and the PVC bar. The second rail was added to mitigate bending moments within the system and constrain extension parallel to the rails. To ensure correct tensile readings, we added a new load cell in line with the axis of the aorta. This load cell has a finer resolution compatible with the range of axial loads planned for experiments on aortic vessels ($< 25$N).

One major challenge emerged when developing the inflation system. We sought to implement a true through-loop, in which saline enters the proximal end of the aorta and exits distally, while still allowing the tissue to be gripped and driven in extension and torsion. The grips underwent several iterations of redesign to securely hold the tissue, seal the saline circuit from air, and reliably deliver saline to the sample. We then completed the circuit by implementing 3D-printed attachments that route the fluid hoses into the hollow rods.

## Conclusions

The multiaxial testing apparatus presented here enables controlled extension-torsion-inflation loading on porcine aorta samples. The system integrates subsystems for sample mounting, axial and torsion actuation, and syringe-driven inflation within a temperature-controlled saline tank, allowing physiologically relevant loading conditions. This apparatus forms a platform for more accurate characterization of aortic wall mechanics and future development and calibration of cardiovascular tissue models. Calibration of the load cell, torque sensor, and pressure sensor has been completed, but construction of the whole apparatus is ongoing. Ongoing and future work will focus on finalizing the control schemes, evaluation of experimental uncertainty, and conducting preliminary testing. Full implementation details for the control software, CAD models, and assembly are still being carefully evaluated. We aim to provide information regarding all of these fabrication details in the future.

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