

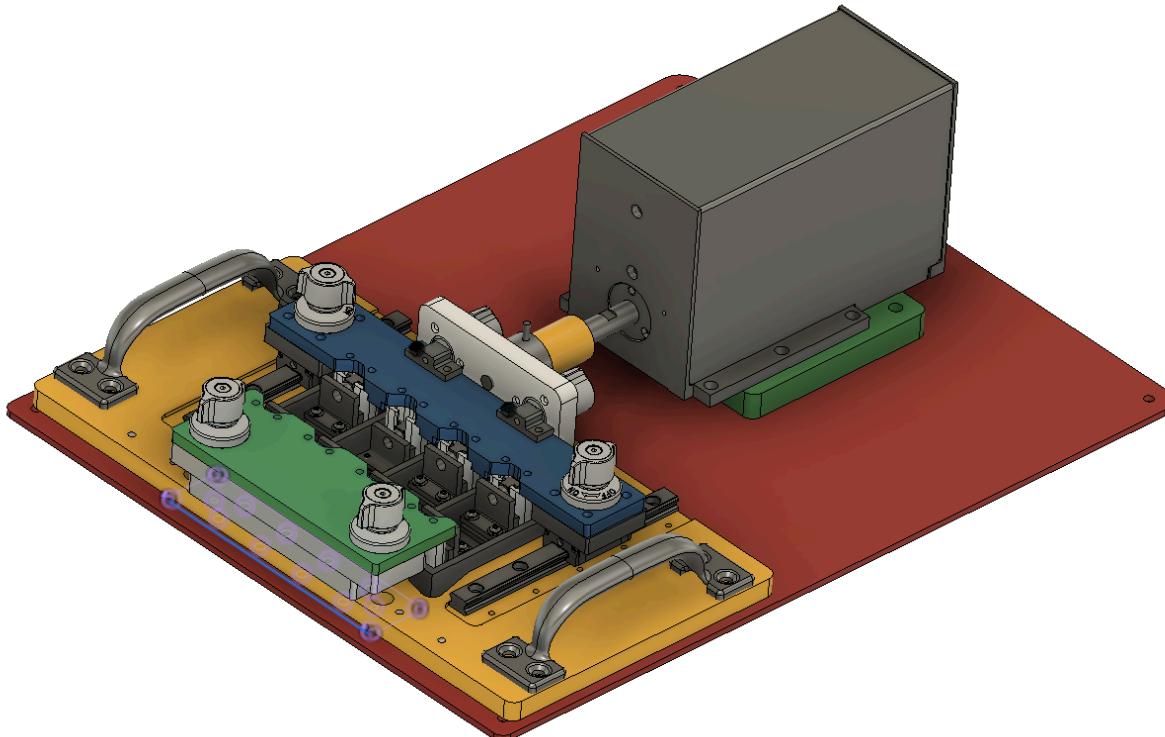


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Biomechanical Culture Reactor: Growing Synthetic Musculoskeletal Tissues

Shiley Center For Orthopedic Research and Education

Dr. Peter Chen and Erik Dorthe



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Abstract

Musculoskeletal tissue repair such as that of tendons and meniscus play a vital role in recovery from numerous sports-related injuries and in improving the quality of life amongst the elderly population. Orthopedic scientists are constantly researching novel techniques for growing artificial cells on tissues that can replace or supplement traditional methods for musculoskeletal tissue repair. Dr. Peter Chen and Erik Dorthé, scientists from the Shiley Center of Orthopedic Research and Education researching on orthopedic repair methods, would like to see a biomechanical culture reactor (also referred to as a “cell stretcher”) device that can provide tensile and compressive forces on tissues to artificially foster their growth. This device shall provide these types of forces, operate reliably within an incubator environment at approximately 37°C and 90% relative humidity, and feature an effective system for refilling the nutrient solution necessary for sustained tissue development. The current design approach integrates a precise pushing and pulling mechanism driven by a SMAC (Smart Motor Actuator Company) linear actuator capable of high accuracy motion control, a low-friction linear gantry constructed from stainless steel rails to minimize wobble and enhance stability, and modular clamps made from sterilizable stainless steel, ensuring a secure grip on the tissue samples. Final results of the cell stretcher system indicate low coulombic friction of 0.7 N and operating force of 18 N, closely achieving the required force output. The future implications of this device hold great potential for regenerative medicine and biofabrication with further refinements and tests.

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Chapter 1: Project Description

1.1 Background

The motivation behind developing a biomechanical culture reactor lies in addressing the clinical need for effective regeneration of musculoskeletal tissues, particularly tendon and meniscus tissues. These tissues are commonly damaged in sports-related injuries or age-related conditions such as knee osteoarthritis, often requiring surgical interventions like tendon repair or knee replacement. The culture reactor aids in tissue regeneration by applying controlled mechanical stimulation—stretching or compressing the tissues—in a laboratory setting, replicating natural conditions to promote healthy tissue growth.

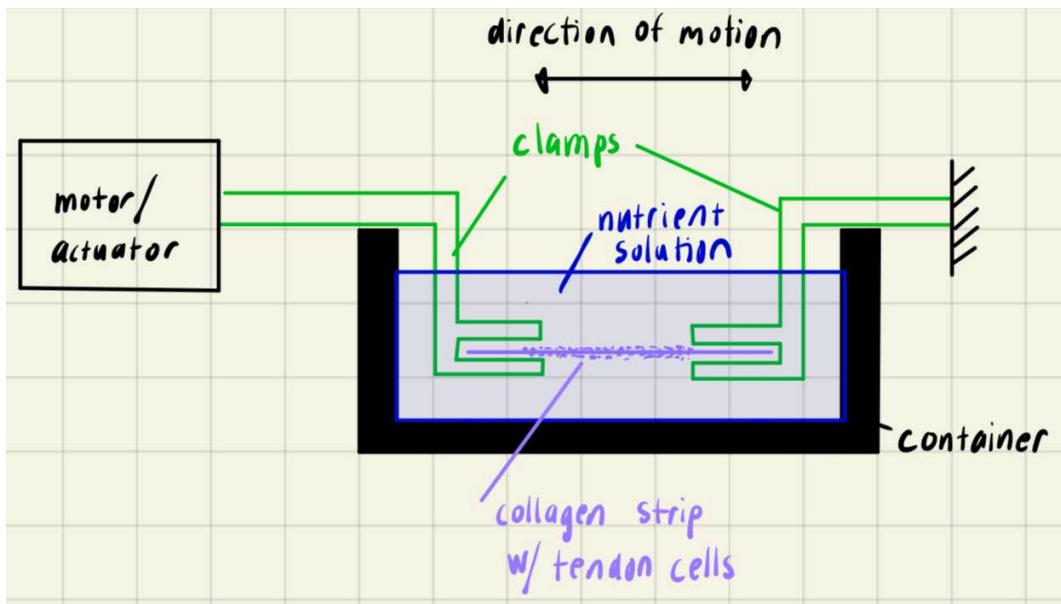


Figure 1.1.1 Drawings of Design Configurations

This project is sponsored by Dr. Peter Chen and Erik Dorthe from the Shiley Center for Orthopaedic Research and Education (SCORE; as seen in Figure 1.1.2), who are seeking a system capable of applying tensile loading (stretching) to tendon tissues and compressive loading (squeezing) to meniscus tissues. These mechanical forces are critical in promoting proper growth by mimicking the natural physiological conditions tissues experience in the human body. Specifically, these forces help cells create a proper extracellular matrix, a foundational structure necessary for healthy and functional tissue growth. Tissue samples will be immersed in a nutrient-rich solution for approximately two weeks to sustain cell activity during mechanical stimulation. Figure 1.1.1 presents a rudimentary sketch of the proposed system.



Figure 1.1.2 Shiley Center for Orthopedic Research and Education

Currently, SCORE employs a commercial cell stretcher limited to applying only tensile forces. Moreover, this device relies on proprietary silicone beds, each costing approximately \$50 per experiment, resulting in substantial ongoing costs given the frequent need for replacements. The biomechanical culture reactor designed in this project seeks to overcome these limitations by introducing a dual-function (tension and compression) capability and utilizing cost-effective, reusable components to significantly reduce operational expenses.

1.2 Review of Existing Solutions

The sponsors' facility currently employs a machine called the ShellPa Pr (as seen in Figure 1.2.1) that provides tensile forces up to 10 N on tissue samples to achieve a 10% strain. Tissue samples are loaded onto a proprietary silicone bed, which are then placed into the machine; in order to load them properly onto the silicone bed, the sponsors had designed a custom clamp to firmly hold the samples. The ShellPa Pro currently costs roughly \$10,000 and is limited to tensile forces. In addition, the silicone beds have to be replaced after every experiment, and the design also makes the manual changing of the nutrient solution difficult and cumbersome. Table 1.1 shows a comparison between the ShellPa Pro and the proposed biomechanical culture reactor system.



Figure 1.2.1 Image of a ShellPa Pro Model

Table 1.1 Comparison Between ShellPa Pro and Proposed Design

Shellpa Pro	Proposed Design
Tension loading only	Tension and compression loading
20 N max force	41.5 N max force
10% max strain	$\geq 10\%$ max strain
Disposable tubs, expensive to replace	Disposable collagen samples, inexpensive for the lab to produce, and sterilizable petri dishes.
Difficult manual re-feeding	Easier manual re-feeding
Clamps restricted by silicon bed design	Modular clamp design

1.3 Statement of Requirements

The sponsors have requested the development of a new biomechanical culture system capable of applying both tensile and compressive forces to soft tissue samples, specifically

tendons and meniscus tissues. Tensile and compressive applications will not be concurrent within one experiment, but rather respective to the experiment being run. This system must be fully functional within a standard cell incubator environment, operating at approximately 37°C with over 90 % relative humidity. To meet the experimental and biological needs, the system must satisfy the following requirements:

1. Deliver forces up to 20 N on tissue samples.
2. Operate reliably within the incubator conditions mentioned above.
3. Apply cyclic loading at frequencies up to 1 Hz or lower.
4. Achieve up to 10 percent strain on samples.
5. Include an automated or user-friendly nutrient feeding system to maintain cell viability over extended periods.
6. Be sterilizable, with components that are either autoclavable or compatible with chemical sterilization.
7. Feature modular, removable clamp designs that are compatible with various tissue geometries and can support both tensile and compressive loading.

A critical limitation in the existing setup with the ShellPa Pro is the clamp design, such as one seen in Figure 1.3.1, which often becomes the bottleneck in executing reliable experiments. More specifically, the clamps used in the experiments are custom built to work only on the machine with no room for improvements (such as making it taller or thinner). Moreover, the clamps can only undertake tensile testing. The new system must address this by incorporating a universal, easily interchangeable clamp mechanism that operates for tensile and compressive testing, ensures secure and reproducible loading, simplifies handling, and minimizes failure during testing.

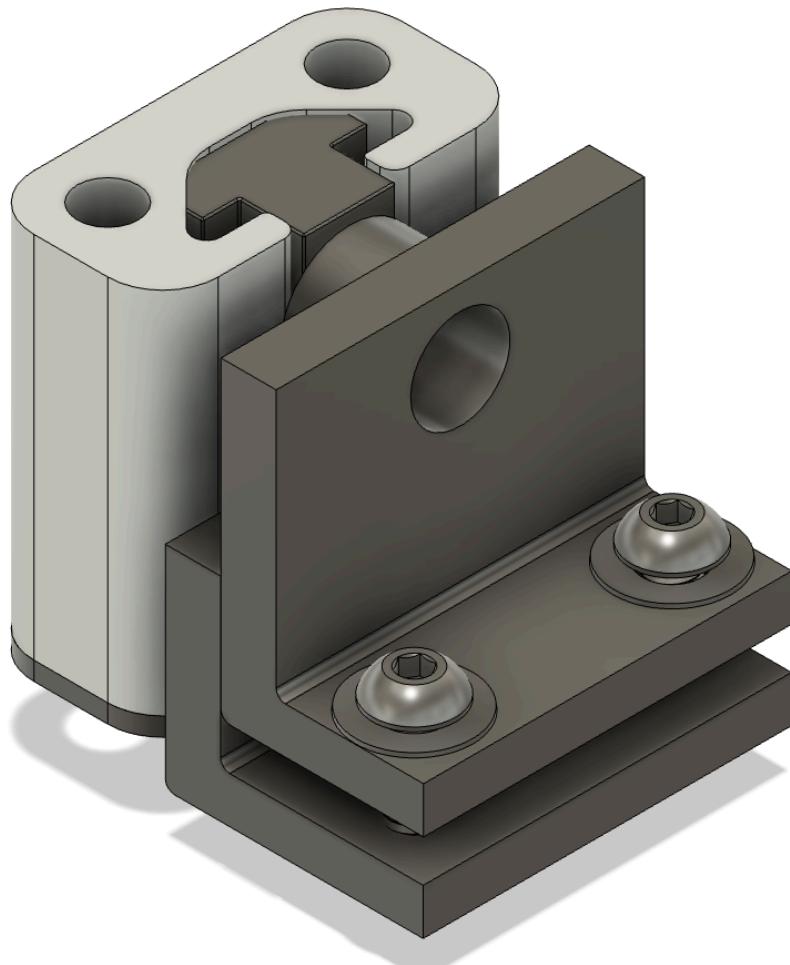


Figure 1.3.1 Tensile Clamp

1.4 Deliverables

The final goal of this project was to design a machine that could induce tensile and compressive forces meeting the requirements previously stated. This machine included a “stretching” mechanism, which translated into a pushing and pulling motion, to accomplish these mechanical stimulations. Additionally, an easier implementation for manual nutrient solution refeeding was implemented to simplify and expedite the nutrient solution replacement process compared to the existing ShellPa Pro system. The clamps were designed in a modular manner, enabling straightforward replacement and compatibility with various specimen geometries.

First Priority Deliverables:

1. This machine shall need to be able to stretch and compress, delivering 20N force at 1 Hz cycle to achieve 10% strain on samples.
2. This machine shall be able to utilize various clamp designs for various specimens.
3. This machine shall be able to operate under incubator conditions.
4. This machine and all parts shall be sterilizable.

Second Priority Deliverables:

1. There shall be a feeding mechanism that shall make it easier to replace the nutrient solution than the current machine.
2. The machine should be able to stretch multiple samples in parallel.

Chapter 2: Description of Final Design Solution

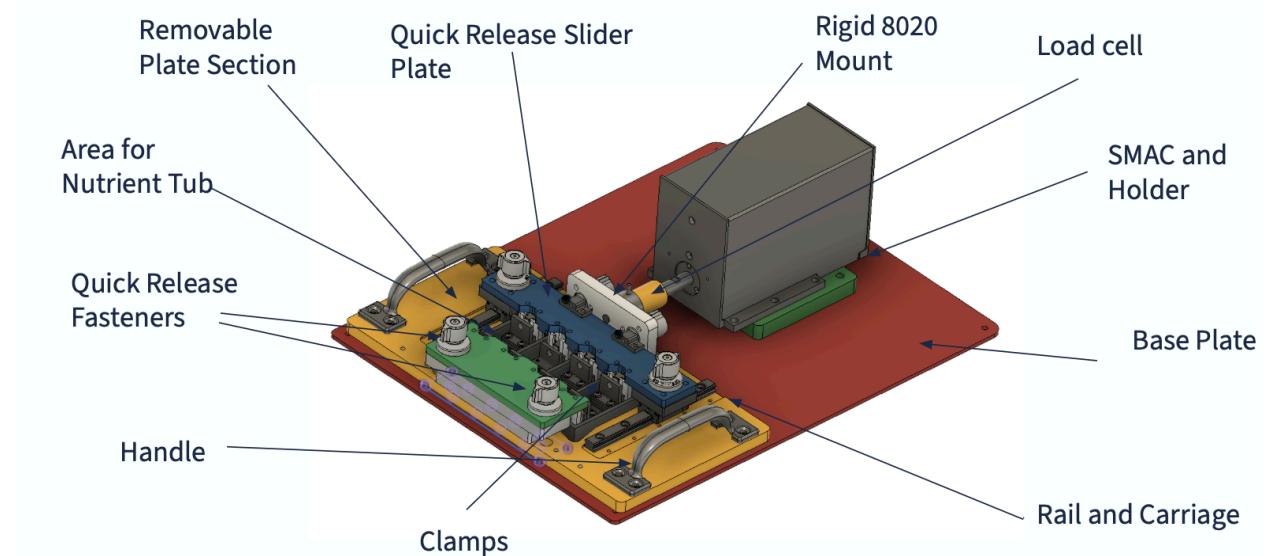


Figure 2.1.1: Ideal CAD Concept of Final Design Solution

The final design of the Biomechanical Culture Reactor, as seen in Figure 2.1.1, integrates six main subsystems: the SMAC actuator, custom lift plate, linear rail carriage, modular clamp interface, load cell assembly, and the petri-dish nutrient tray. All components are mounted on a precision-machined aluminum baseplate designed for high stiffness and compatibility with incubator environments. The SMAC actuator provides programmable tension and compression to the mounted tissue specimens, with cyclic strain control up to 10% at 1 Hz. This motion is transferred through a linear rail carriage system for smooth and low-friction actuation.

Specimens are held in place using modular clamps—interchangeable between compression and tension modes—mounted onto a removable lift plate that enables easy extraction of the culture system for media replacement. The quick-release fasteners ensure minimal disruption during removal. A 5kg ATO load cell provides real-time feedback, ensuring applied forces stay within the desired range. The final design prioritizes modularity, sterilization compatibility (via aluminum and stainless steel components), and scalability for future automation.

A challenge encountered was uncertainty in the overall system. There is inherent misalignment between the SMAC shaft and the rigid 8020 mount (as seen in Figure 2.1.2), and there is play (wobble) present in the quick release slider plate. These factors result in inconsistent force transmission and hinder accurate motion. The misalignment, in particular, disrupts smooth linear travel during experimental runs. To mitigate these issues, locating pins were added to the

quick-release slider plate (as seen in Figure 2.1.3), and an additional plate was manufactured (also highlighted in Figure 1.3.2) to better distribute the load across the SMAC shaft, thereby reducing misalignment. While this design significantly curtails the misalignment, a small degree of it remains. However, this residual misalignment is not visibly noticeable and has been minimized to a level that does not severely impact system performance.

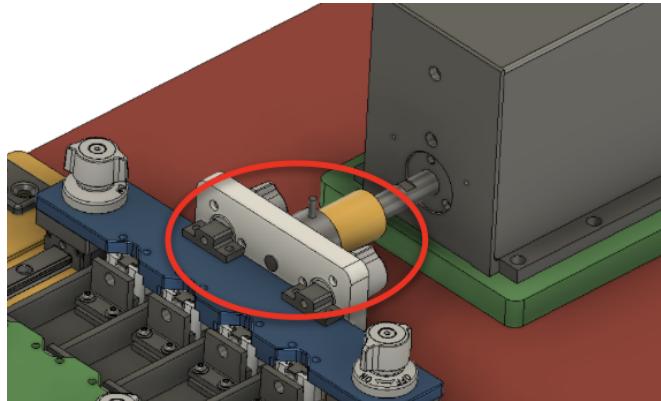


Figure 2.1.2: Location of Potential Misalignment

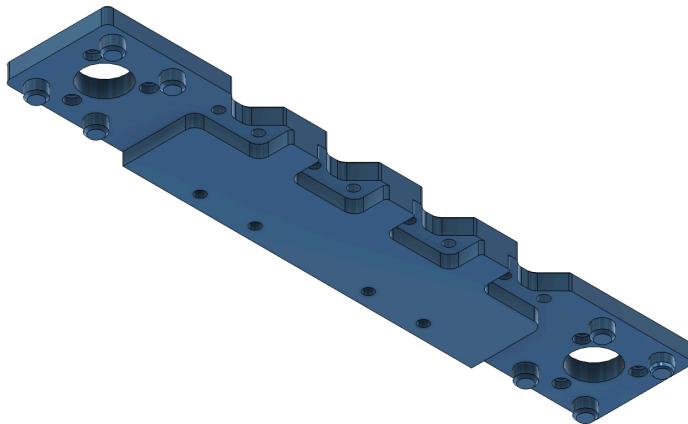


Figure 2.1.3: Locating Pins on Quick Release Slider Plate to Mitigate Play (Wobble)

Chapter 3: Design of Key Components

3.1 SMAC Actuator

Overview

The purpose of the actuator is to provide a mechanism to deliver tensile and compressive forces to the specimen samples. Some choices that were considered include piezoelectric motors, stepper motors, and linear actuators, however the SMAC actuator was chosen because of the ease of procurement and performance specifications.

Functional Requirements

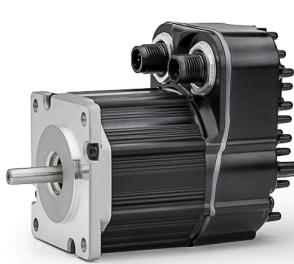
- The actuator shall provide up to 20 N of force.
- The actuator shall run in 1 Hz cycles.
- The actuator shall contain a resolution of 1 μ m.



Figure 3.1: Picture of SMAC Actuator used in the design

Comparison of Choices Considered

Table 3.1: Comparison of Choices

Designs	Pros & Cons
 ClearPath-SDHP: CPM-SDHP-2310H-EQN	<p>Pros:</p> <ul style="list-style-type: none">• Has precise increments (0.01 mm)• Able to achieve 10% strain <p>Cons:</p> <ul style="list-style-type: none">• Expensive• May not work well in 1 Hz cycle
 Stepper Motor and Lead Screw	<p>Pros:</p> <ul style="list-style-type: none">• Inexpensive• Has Precise increments (0.01 mm) <p>Cons:</p> <ul style="list-style-type: none">• Potential backlash



SMAC Actuator: LAL90-050-535DM

Pros:

- Has Precise increments (0.01 mm)
- Can run in 1 Hz cycles
- No backlash

Cons:

- Expensive (however SCORE Lab had a spare which was used, thus no actuator expense)

Final Design Choice and Justification

After thorough evaluation and comparison of various actuator types—including piezoelectric motors, stepper motors with lead screws, and SMAC linear actuators—the SMAC actuator LAL90-050-535DM was selected for the final system (as seen in Figure 3.1). This decision was influenced significantly by several key advantages the SMAC actuator demonstrated throughout the evaluation process.

Firstly, the actuator provided an exceptional positional resolution of $10 \mu\text{m}$, exceeding the precision required for reliably achieving the necessary strain increments in the biological samples. Its high-accuracy linear positioning ensured repeatability, crucial for maintaining consistent mechanical stimuli during extended experimental periods.

Secondly, the SMAC actuator delivered consistent, backlash-free performance due to its unique moving-coil design, which was particularly advantageous compared to the stepper motor and lead screw option, where potential backlash could negatively impact experimental accuracy. The absence of backlash in the actuator eliminated concerns about drift and unintended motion, which are critical for maintaining the integrity and repeatability of tests that last over multiple weeks.

Furthermore, the actuator effectively operated at the required cyclic frequency of 1 Hz without loss of accuracy or mechanical instability, unlike some of the alternatives considered, such as the ClearPath-SDHP servo motor, which might struggle to maintain the precise movement needed consistently at the specified frequency. The robustness of SMAC actuator's design offered reliable cyclic operation, crucial for mimicking the physiological conditions necessary for tissue growth and maturation.

3.2 Clamps: Tension

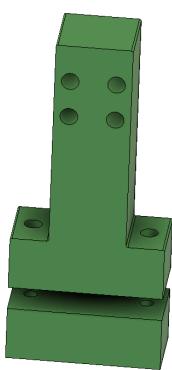
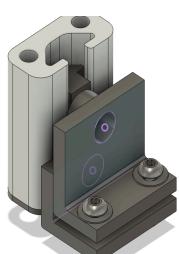
Overview

The clamps used in this design serve as a holder for the specimen during experiments. The clamps enable the specimen to stretch and compress, allowing them to grow during the course of the experiment. There are two types of clamp design: one for tension, the other for compression. The specimen size used for tensile experiments is roughly 20 mm by 5 mm.

Functional Requirements

- The clamps shall be easily sterilizable (thus made out of metal).
- The clamps shall be modular (can be replaced with other types of clamps easily).
- The clamps shall be able to hold the samples throughout the experiment without causing them to slip.

Table 3.2: Comparison of Tension Clamp Designs

Designs	Pros & Cons
 First iteration of tension clamps	<p>Pros</p> <ul style="list-style-type: none">• Easy to manufacture in either steel or aluminum• Provides a strong clamping grip on sample <p>Cons</p> <ul style="list-style-type: none">• Difficult to use in incubator and experimental settings
 Second iteration of tension clamps	<p>Pros:</p> <ul style="list-style-type: none">• Modular with T-slots and T-nuts• Provides a strong clamping grip on sample• Easy to use <p>Cons:</p> <ul style="list-style-type: none">• More challenging to manufacture in metal than the first iteration

Final Design Choice and Justification

After evaluating multiple iterations of clamp designs, the second iteration was selected for the final system due to its superior functionality, adaptability, and user-friendly features. This version incorporated modularity through the use of T-slots and T-nuts, enabling quick interchangeability between different clamp types. This feature was especially beneficial for the project since the system needed to accommodate both tensile and compressive samples with differing geometries and dimensions. The modular interface allowed for faster setup and teardown between experiments, reduced the risk of sample mishandling, and provided long-term flexibility for future experimental configurations.

In terms of mechanical performance, the second iteration also maintained a strong and secure grip on the specimen throughout the loading cycles. This was crucial, as slippage during stretching or compression could compromise experimental data and hinder proper tissue development. The design's ability to maintain a consistent clamping force under cyclic mechanical loading improved the reliability of results and ensured that strain measurements remained accurate throughout the testing period.

3.3 Linear Rail System

Overview

The design utilizes a gantry to translate the linear motion of the SMAC actuator to the array of clamps holding the specimens. This enables the specimen to receive tensile and compressive forces that aid in their growth and development

Functional Requirements

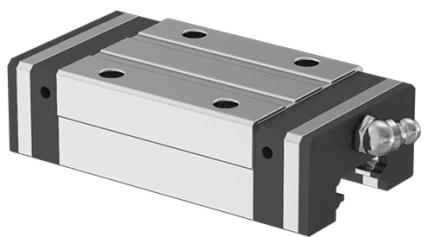
- The rails shall exhibit minimal friction and wobble when in operation.

Comparison of Designs Considered

Table 3.3: Comparison of Linear Rail Systems

Design Ideas	Pros & Cons
<p>Creality Ender 3 V3 SE Rails</p> 	<p>Pros:</p> <ul style="list-style-type: none"> • Inexpensive • Readily available • Small • Used in high-cycle applications <p>Cons:</p> <ul style="list-style-type: none"> • Not stainless steel • Very greasy • Non corrosive • High friction
	<p>Pros:</p> <ul style="list-style-type: none"> • Heavy-duty rails • Inexpensive <p>Cons:</p> <ul style="list-style-type: none"> • Extremely High Friction • More suited for CNC applications • Poor quality carriages • Lacks vital parts

HGR20 Linear Rail Guide



McMaster-Carr Linear Rail and Carriages

Pros:

- Low friction
- Premium quality materials and finish
- Anti Corrosive
- Stainless Steel rails

Cons:

- Expensive
- Smaller design compared to other options
- Uses M2.5 bolts for fastening - worries about fragility

Final Design Choice and Justification

The rail and carriage system from McMaster-Carr was chosen because it exhibited extremely low friction during inspection and seemed extremely durable.

3.4 Clamps: Compression

Overview

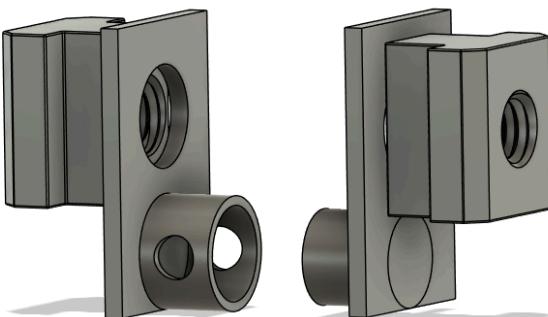
In addition to tensile loading, the final design was also developed to perform compression experiments. While the tension tests used collagen strip specimens approximately 30–50 mm long, 10 mm wide, and 1 mm thick, the compression tests involved a different sample geometry—specifically, cylindrical specimens measuring 5 mm in diameter and 3 mm in thickness. These clamps were responsible for securely holding the cylindrical samples in place within a nutrient medium while the gantry, actuated by the SMAC linear actuator, cycled back and forth to apply controlled compressive loading. Ensuring compatibility with both specimen types was essential for maintaining the versatility and modularity of the overall bioreactor system.

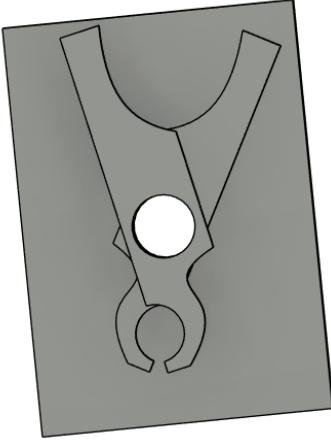
Functional Requirements

- Needs to hold a cylindrical specimen 5mm in diameter and 3mm thick.
- Needs to allow the pass-through of the specimen.
- Needs to hold the specimen tightly avoiding a slip.

Comparison of Designs Considered

Table 3.4: Comparison of Clamps

Designs	Pros & Cons
Peg and Hole 	<p>Pros:</p> <ul style="list-style-type: none">• Provides strong, stable constraint for the puck-shaped specimen• Minimizes slippage and misalignment during compression• Ideal for precise, repeatable loading cycles• Suitable for use in long-duration experiments <p>Cons:</p> <ul style="list-style-type: none">• More difficult to machine due to tight tolerances• Increased fabrication time and cost• May require manual alignment of peg and hole for each use

<p>Scissor Clamp</p> 	<p>Pros:</p> <ul style="list-style-type: none"> • Easier and faster to manufacture (laser cut) • Lightweight and cost-effective • Spring-based closure is intuitive and user-friendly • Suitable for early testing and prototyping <p>Cons:</p> <ul style="list-style-type: none"> • Less constrained—higher risk of specimen slipping • Performance depends heavily on spring tension • Spring degradation over time can reduce reliability • May not handle higher loads or long-term use as well as the peg-and-hole design

Final Design Choice and Justification

The peg and hole design was chosen for the selection of the compression clamps. This design provides a strong constraint for the pegs that will enable compressive forces to be delivered. Moreover, it reduces slippage and misalignment during compression testing. One major drawback of this design is manufacturability due to tight tolerances and increased fabrication time.

3.5 Quick Release Fasteners

Overview

The user needs to be able to quickly separate key parts of the assembly in order to perform manual refeeding of the nutrient medium. Parts to be quickly released include the plates holding the slots for clamps as well as load cell and linear actuator from the gantry. The quick release fasteners are an alternative to using traditional fasteners such as bolts and nuts which may create a large delay in nutrient refeeding and provide extra parts that may be easily misplaced.

Functional Requirements

- Secure Connection: Must firmly fasten aluminum plates and stainless steel blocks without unintended detachment during operation.
- Tool-Free Operation: Should allow engagement and release by hand (e.g., quarter-turn or button press), without requiring screwdrivers, wrenches, or Allen keys.
- Sterilization Compatibility: Must be constructed entirely from corrosion-resistant metals (stainless steel or anodized aluminum) to withstand alcohol wiping and incubator conditions (37°C, 90% humidity).
- Compact Form Factor: Must have a low-profile design to fit within spatial constraints inside the reactor's petri dish platform and avoid interfering with adjacent components.
- Repeatable Reliability: Should be durable for repeated fastening cycles (20+ uses) without significant wear or degradation of locking performance.

Table 3.5: Comparison of Different Quick Release Fasteners

Designs	Pros & Cons
IMAO Quarter Turn Fasteners 	Quarter turn to fasten and unfasten Pros: <ul style="list-style-type: none">• Full Stainless Steel Available• Small connecting pin• Interfaces between plate and block• Short profile• Easy quarter turn operation Cons: <ul style="list-style-type: none">• Expensive• Wide Body
	Button interface to fasten and unfasten Pros:

<p>IMAO QCBU Ball Locking Fastener</p> 	<ul style="list-style-type: none"> • Full Stainless steel • Quick Axial release through button push • Can interface between plate and block <p>Cons:</p> <ul style="list-style-type: none"> • Very tall, • Wide receptacle • Expensive
<p>Motorcycle 1/4 turn Quick Release Fasteners</p> 	<p>Screw mechanism for fastening</p> <p>Pros:</p> <ul style="list-style-type: none"> • Steel • Very small profile • Easy Quarter Turn release • Inexpensive <p>Cons</p> <ul style="list-style-type: none"> • Interfaces between 2 plates
<p>CAMVATE M5x19 Quick Release Locking Lever</p> 	<p>Pros</p> <ul style="list-style-type: none"> • Inexpensive <p>Cons</p> <ul style="list-style-type: none"> • Does not release axially • Timely unscrewing motion

Final Design Choice

After comparing multiple fastening mechanisms, fixtures from the IMAO company were selected. More specifically, the IMAO Quarter Turn Fasteners were chosen as the final solution due to their optimal balance of performance, reliability, and integration ease. These fasteners provided a secure mechanical connection between key components—specifically, the lift plate, clamp carriage, actuator mount, and load cell interface—while maintaining a compact profile suitable for the limited space within the incubator-compatible reactor base.

The tool-free quarter-turn locking mechanism allowed users to detach and reattach parts in under 10 seconds, a major improvement over traditional fasteners which often required several

minutes of careful disassembly. This quick-release functionality significantly reduced downtime during nutrient refeeding and helped maintain sterility by minimizing exposure time. In addition, their stainless steel construction ensured that they were compatible with frequent alcohol-based sterilization and resistant to corrosion from prolonged exposure to humidity.

Although other options—such as the IMAO QCBU ball-locking fasteners—offered similar strength and usability, they were ultimately excluded due to their taller design, which conflicted with the low-clearance setup of the petri dish platform. Similarly, while the motorcycle-style fasteners were attractive due to their small size and low cost, they lacked sufficient structural integrity for repeated axial loading between plate and block components.

Chapter 4: Prototype Performance

4.1 Theoretical Predictions

The SMAC actuator selected for this system is capable of producing up to 41.5 N during continuous-duty operation and up to 63 N for short bursts. For the purposes of this project, its usage was limited to 40 N to ensure safe, reliable performance under long-term conditions, as each experimental cycle is expected to run continuously, 24 hours a day, over a two-week period.

This limitation highlights the critical importance of minimizing friction throughout the mechanical system. Since force feedback is obtained using a load cell, any friction introduced by the linear guide slider or misalignments could distort the readings and compromise data accuracy.

The collagen specimens used in this system vary in size. For some configurations, the expected maximum force required may approach the upper threshold of the actuator's capacity. For example, if four large samples are loaded simultaneously, the total required force could exceed:

$$F_{Total} = 4 * 10N = 40N$$

This configuration would utilize nearly the full rated capacity of the actuator. On the other hand, for smaller specimens, each requiring approximately 3 N, the total force would be:

$$F_{Total} = 4 * 3N = 12N$$

This lower load would fall well within safe operational margins. Regardless, the design was required to accommodate both high-load and low-load scenarios, reinforcing the need for efficient load transmission and minimal friction.

The frictional force can be estimated using the Coulomb friction model:

$$F_f = \mu N$$

Where:

- F_f is the frictional force.
- μ is the coefficient of friction (assumed to be 0.001, within the range of 0.0006–0.0012 for precision linear guides).

- N is the total normal load on the bearing, including preload, gravitational load, and any bending moments.

Using data provided from the sponsors, a plot of average stress versus strain for five collagen samples were obtained, as seen in Figure 4.1.1. From this graph, the yield strength is approximately 2.9 MPa.

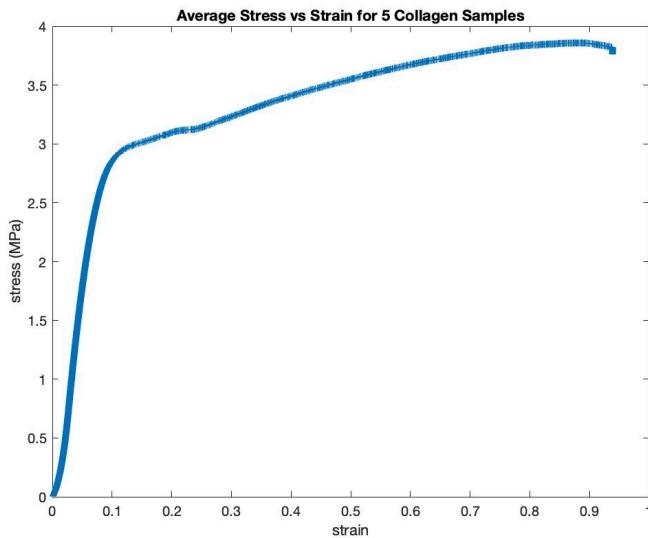


Figure 4.1.1: Plot of Average Stress vs Strain for 5 Collagen Samples

From Figure 4.1.2, potential friction forces and their locations are introduced. The vertical distance between the specimen and the linear rail is approximately 5 mm. Additionally, the SMAC actuator and quick-release fasteners introduce a vertical offset due to their placement above the height of the petri dish. This geometry results in a bending moment applied to the carriage system. The estimated moment due to this configuration is:

$$M = 1.8Nm = 0.9Nm \text{ per bearing}$$

Given that the linear bearings have a spacing of approximately 30 mm, this moment translates to a couple force of:

$$F_{couple} = \frac{0.9Nm}{0.015Nm} = 60N$$

Applying the Coulomb model to calculate the additional friction introduced by this couple force:

$$F_f = \mu F_{couple} = 0.001 * 60N = 0.06N \text{ (per side)}$$

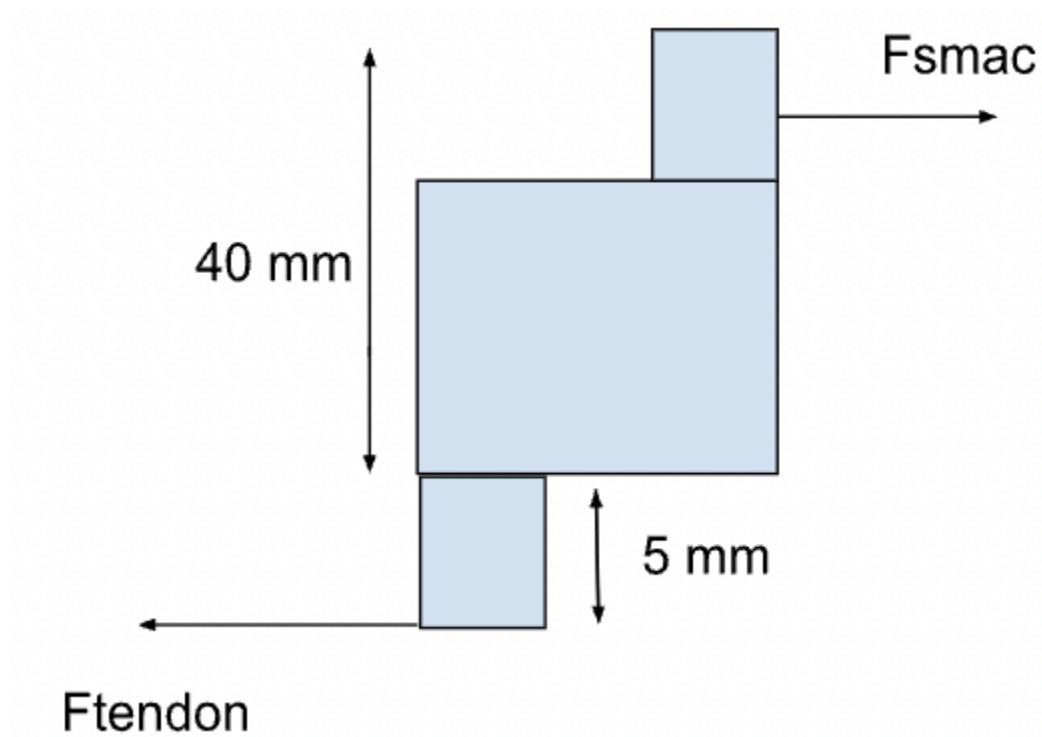


Figure 4.1.2: Schematic of Potential Forces for Friction Calculations

Thus, the estimated friction introduced by the moment load remains well below 1 N, ensuring that the force readings obtained from the load cell are not significantly affected. The linear rail used is rated for a maximum moment load of 9.08 Nm (per the manufacturer's specifications), confirming that the current configuration operates safely within the bearing's design limits.

4.2 Test Conditions

To evaluate the performance of the preliminary system, two initial validation tests were conducted under different operating conditions. These tests were designed to verify the functionality of the SMAC actuator under load and to assess the level of internal system friction

in the absence of a specimen. These tests were conducted on an earlier iteration of the design, and their results will be compared to the final iteration in the subsequent sections.

The first test involved dynamic loading of a sample to simulate physiological strain conditions. A string with a length of 20 mm was inserted into the fixture and secured using the modular clamps. The test parameters were configured to apply a cyclic strain of 25% at a frequency of 0.2 Hz. This corresponds to a 5 mm displacement amplitude, oscillating in both directions from the neutral position. These parameters were inputted into the LabVIEW software that interfaces with the actuator's controller. The objective of this test was to validate whether the actuator could maintain consistent force output across multiple loading cycles, as well as to confirm that no sample slippage or system instability occurred. The load cell output during this test is shown in Figure 4.2.1.

$$\text{Strain} = \frac{\Delta L}{L_0} = \frac{5\text{mm}}{20\text{mm}} = 25\%$$

As illustrated in the graph, the system successfully completed three full loading cycles, each achieving a peak load of approximately -17.5 N. This confirmed that the actuator was capable of approaching the upper threshold of the 20 N force requirement. Moreover, the repeatability and sharp transitions in force magnitude indicated proper alignment of the actuator and minimal backlash or mechanical play in the linear rail system.

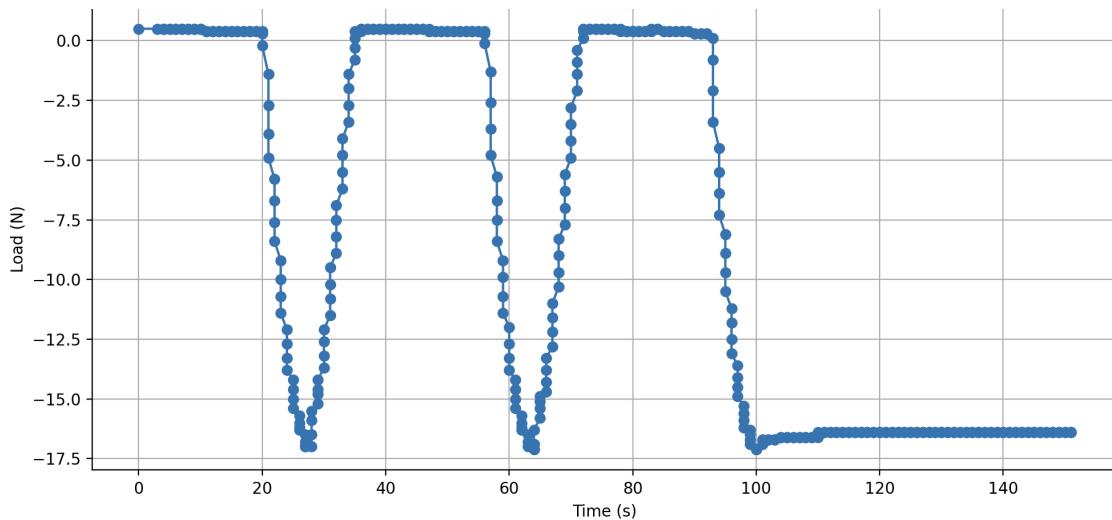


Figure 4.2.1: Test involving a 20 mm sample, with a strain of 25% at 0.2 Hz cycles on the Previous Iteration

The second test focused on quantifying internal system friction. In this case, the system was operated without any specimen inserted. The clamps remained empty, and the actuator was programmed to run at 0.2 Hz. The goal of this test was to isolate and measure the resistance generated by the linear carriage and mechanical components such as bearings, guide rails, and joints. This form of testing was critical to ensure that frictional forces were not significantly influencing the load cell readings, especially during low-load conditions.

The output from this test is presented in Figure 4.2.2. The measured force amplitude fluctuated around ± 1 N, indicating the presence of low but non-negligible internal friction. Given that some hysteresis is expected at higher speeds due to dynamic effects such as inertial drag and guide misalignment, the results were within acceptable limits for continued testing and refinement. Furthermore, the test verified that the linear rail and gantry assembly offered sufficiently smooth translation to support both high-frequency testing and extended continuous operation.

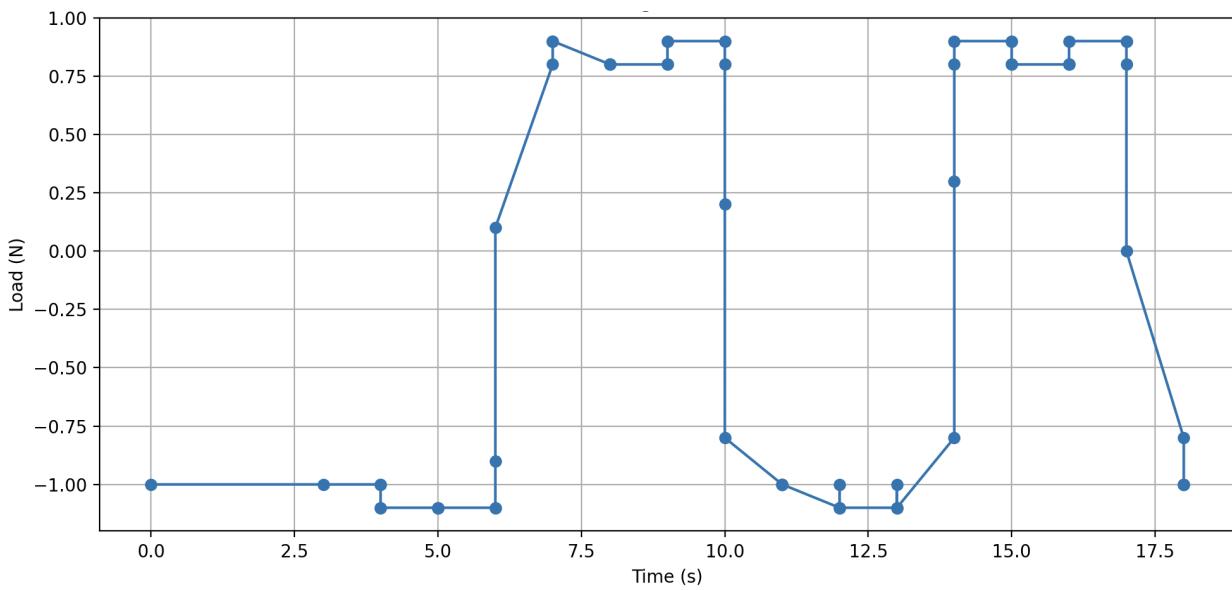


Figure 4.2.2: Test involving no load at 0.2 Hz cycles on the Previous Iteration

For the final design iteration, the same tests were conducted. The first test, similar to the tests conducted in the preliminary system, consisted of dynamic loading of a 20 mm sample at 0.2 Hz cycles. The load cell output during this test is shown in Figure 4.2.3.

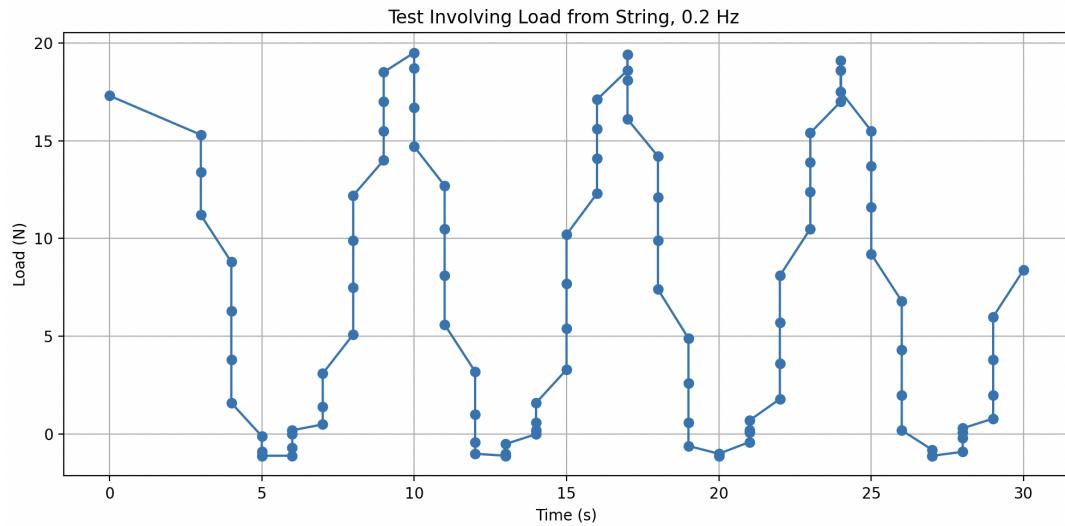


Figure 4.2.3: Test involving 20 mm sample at 0.2 Hz Cycles for the Final Design Iteration

As seen in Figure 4.2.3, the maximum force obtained was 18 N, thus closely matching the required force output of 20 N from the actuator.

For the second test, similar to the second test conducted on the preliminary system, inertial system friction was measured. With improved designs, the overall system should have had lower friction compared to the preliminary system. The result of this test can be seen in Figure 4.2.4.

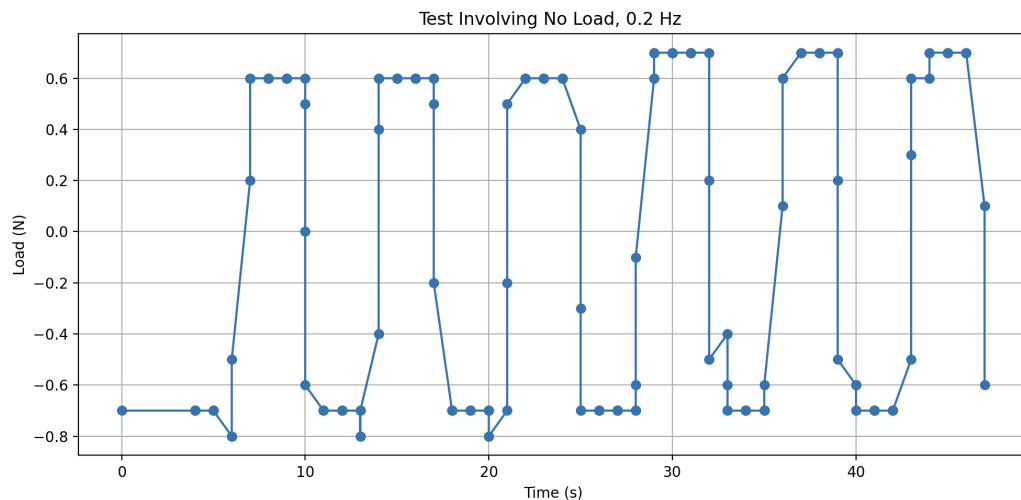


Figure 4.2.4: Test involving No Load at 0.2 Hz Cycles for the Final Design Iteration

As seen in Figure 4.2.4, the maximum friction measured was roughly 0.65 N.

4.3 Results

The results of the initial performance tests confirmed that the mechanical design was capable of meeting the majority of the functional force and frequency requirements.

For the first test involving a 20 mm string specimen and 25% strain at 2 Hz, the system achieved a maximum measured force of approximately 17.5 N, which is close to the 20 N target outlined in the functional specifications. The load cell data showed consistent waveform patterns across two full actuation cycles. In both cycles, the peak force remained steady, and the return to baseline after unloading was rapid and smooth. The consistent force profile suggests that there was no sample slippage, deformation of the clamp assembly, or mechanical lag during actuation. This validates the structural integrity of the clamps and the repeatability of the actuator's motion under load. Furthermore, the system demonstrated the ability to maintain a fixed frequency of operation, with no signs of actuator oscillation damping or energy loss over the test duration.

In the second test, which assessed the internal friction of the system at 10 Hz without a sample, the load cell recorded a frictional force amplitude fluctuating around ± 1 N. This friction level is relatively low and suggests that the updated rail and carriage system—including proper alignment, bearing selection, and smooth surface finishing—has significantly reduced parasitic resistance. The ability to operate smoothly at a constant frequency without erratic force readings supports the robustness of the mechanical guidance system and confirms the success of friction mitigation efforts in the design.

Overall, both preliminary tests offered strong evidence that the mechanical subsystems are functioning as intended and that actuator force output, system stiffness, and motion fidelity meet the demands of the intended application environment.

The results of the final design performance tests also confirmed that the mechanical design was capable of meeting the majority of the functional force and frequency requirements. With applied forces meeting the requirements of 20 N and measuring an extremely low frictional force, the final system indicates that it can meet and exceed the requirements set forth at the beginning of the project while being as efficient as possible.

4.4 Comparison of Results

A direct comparison of the two test results illustrates the distinct operating conditions and validates key design improvements.

In the loaded test of the preliminary design (test 1), the actuator successfully produced peak forces nearing 17.5 N, which falls within 12.5% of the desired 20 N requirement. The force curves were highly repeatable, and the waveform maintained sharp transitions, demonstrating

that the actuator and control software were properly tuned for cyclical loading. In the loaded test of the final design iteration, peak forces were measured to be roughly 18 N, which slightly exceeds the peak force seen in the preliminary design. This indicates that the design changes initiated were successful in optimizing the system. The lack of force decay or phase lag across cycles in both design iteration tests further indicates that the clamps held the specimen firmly without slipping, even under high-cycle loading. This suggests that the mechanical interfaces between actuator, load cell, and specimen were securely integrated.

In contrast, the friction-only test (test 2) for both design iterations provided insight into the intrinsic resistance of the mechanical system. With no specimen inserted, the actuator's back-and-forth motion produced minimal reactive force, with the load cell detecting a maximum friction force of approximately 1 N for the preliminary design. This figure, though nonzero, confirms that frictional losses were contained to just 5% of the actuator's continuous load capacity. For the final design, the load cell measured about 0.65 N, thus indicating a further decrease in frictional force compared to the preliminary design. It highlighted a significant improvement in performance for the final design iteration, which can be attributed to design improvements undertaken.

The performance difference between the two tests can be interpreted in terms of system efficiency. Under load, most of the actuator's output was effectively transferred to the specimen, whereas under no-load conditions, internal mechanical friction became the dominant force captured by the load cell. This difference validates the team's approach to minimizing friction through component selection and alignment strategies.

Furthermore, the results imply that any small load measurements recorded in actual tissue tests—especially in the sub-2 N range—must be interpreted carefully, as they may include minor contributions from system friction. However, given the low friction baseline, the load cell readings for most biological samples (which are expected to fall in the 5–15 N range) will remain reliable.

In summary, the results of both tests for both the preliminary and final design iterations confirm that:

- The system meets force output and motion repeatability targets under realistic loading scenarios.
- Friction has been successfully minimized through mechanical design improvements.
- Load cell accuracy is reliable for both high-load and low-load applications, validating the mechanical performance of the prototype.

Chapter 5: Design Recommendations and Conclusions

5.1 Design Recommendations

Based on the testing outcomes and system performance analysis, several design improvements are recommended for future iterations of the biomechanical culture reactor. First, while the current gantry and linear rail system effectively minimized friction, further enhancements in alignment accuracy and rail stiffness could yield even more precise load cell readings, particularly during low-force experiments. Improved machining tolerances and the addition of anti-backlash features may help reduce unwanted mechanical resistance.

The modularity of the system should also be enhanced. The implementation of more intuitive quick-release mechanisms and clamp-swapping features would streamline the process of specimen replacement and nutrient refeeding. Incorporating alignment pins or integrated connection guides would further reduce assembly error and setup time.

On the software side, although LabVIEW provided a workable interface for basic control, future development of a more user-friendly graphical user interface (GUI) could benefit operators, particularly for real-time monitoring and feedback adjustments. A closed-loop control system incorporating force or displacement sensors would also improve experimental consistency by allowing automatic compensation for mechanical drift or sample variability.

Material selection should continue to prioritize sterilization compatibility. Components that contact the culture environment, such as clamps and fasteners, must withstand repeated autoclaving or chemical sterilization cycles without degradation. Future parts may benefit from being designed explicitly for ISO 17665 sterilization compliance.

Finally, as the platform evolves toward clinical research applications, integration of redundant sensing and self-check protocols would enhance reliability. This includes features like fail-safe locking mechanisms or force-limit alerts to prevent accidental overload or sample damage during long-duration testing.

5.2 Safety Considerations

The nature of this project involves limited direct interaction with human operators during active experimentation, thereby posing minimal immediate safety risks. However, the biological context of the device introduces strict biosafety considerations. The most critical safety-related factor is contamination control. Since the tissue samples are cultured in a nutrient-rich environment over extended periods, any compromise in sterilization can invalidate the entire experiment.

Clamps, which are immersed in the culture medium and are in prolonged contact with the biological specimens, represent the most sensitive component in terms of sterility. These clamps were fabricated from stainless steel specifically to endure autoclaving and repeated exposure to high-humidity, high-temperature conditions. The petri dish used for holding the specimens is disposable and replaced after each test, reducing the risk of microbial cross-contamination.

Although the system does not pose physical danger to users under current laboratory operation, if the design is scaled toward semi-automated or clinical use, considerations regarding pinch points, fastener failure, and system shutdown protocols will become more important. As such, future revisions should include a formal hazard analysis process and possibly incorporate mechanical safety features such as enclosures or interlock systems.

5.3 Applicable Standards

The components of the device were selected and fabricated to conform to relevant engineering and environmental standards. The linear rails meet ISO 12090-1:2011, which governs the geometry and performance of rolling bearing systems. Their stainless steel construction ensures long-term corrosion resistance and environmental durability, and they are fully recyclable at the end of life.

The linear carriages used in conjunction with these rails meet RoHS 3 (Directive 2015/863/EU) and REACH (EC 1907/2006) regulations. These certifications confirm that no restricted hazardous substances are used in their production, and that the materials are safe for handling in a laboratory environment. While the carriage bodies are recyclable, the internal ball bearings may contain lubricants that require degreasing prior to disposal or reuse.

The load cell employed in the system carries an IP67 ingress protection rating, confirming that it is dust-tight and resistant to temporary submersion in water, which is ideal for high-humidity incubator conditions.

Should the system be advanced toward clinical testing or therapeutic development, it would be subject to additional regulatory requirements. If applied to tendon repair or rehabilitation, the device would likely be classified by the FDA as a Class II or Class III medical device. This classification would require preclinical and clinical validation, as well as biocompatibility testing under ISO 10993. The cultured tissue produced by the system would be expected to conform to ASTM F2255, which defines acceptable mechanical performance standards for engineered tissue. Sterilization validation would also be required under ISO 17665, particularly if autoclaving is the intended cleaning method for reusable components.

5.4 Impact on Society

The biomechanical culture reactor developed through this project has the potential to contribute significantly to biomedical research and therapeutic innovation. Musculoskeletal conditions, including tendon injuries and meniscal degeneration, affect millions of people worldwide each year. Current treatment strategies often rely on donor grafts or invasive surgeries, both of which present complications such as limited availability and lengthy recovery times. This project presents a step toward developing bioengineered tissue constructs that could serve as a future alternative.

The reactor enables researchers to apply highly controlled mechanical stimuli to cultured samples, allowing for the investigation of how tensile and compressive forces influence cell differentiation and tissue formation. This function supports a growing body of research into regenerative medicine and biofabrication. By allowing tissue to be grown under physiologically relevant mechanical conditions, the reactor serves not only as an experimental platform but also as a potential prototype for future therapeutic systems.

Furthermore, the design prioritizes cost-effective components and modularity, making it a candidate for adoption in smaller or underfunded laboratories that lack access to more expensive commercial bioreactors. With future refinement, this system could become an accessible, scalable platform for orthopedic tissue engineering research worldwide.

5.5 Professional Ethics

In undertaking this project, all team members upheld the ethical principles defined by the National Society of Professional Engineers (NSPE), including commitments to honesty, safety, and professional integrity. Parts and materials were sourced responsibly from certified vendors, and all components were evaluated to ensure compliance with relevant safety and environmental standards.

The team remained committed to academic transparency, maintaining detailed documentation of design decisions, test results, and failures. Furthermore, great care was taken to ensure that the device would be used solely for its intended purpose: to support preclinical research and education in biomedical engineering. In the context of laboratory research, ethical conduct also includes strict adherence to biosafety protocols, particularly given the project's proximity to biological specimens and potential use in BSL-2 environments.

The team also recognized that design reliability is inherently tied to research integrity. A malfunctioning device could compromise experimental data or lead to misleading conclusions,

which would ultimately undermine scientific progress. As a result, emphasis was placed on robustness, validation, and repeatability throughout the development cycle.

5.6 Lessons Learned

Over the course of this project, the team developed not only a functional prototype but also a deeper understanding of the interdisciplinary challenges involved in biomedical device development. One of the most important lessons was the necessity of iterative prototyping. Initial clamp designs, although theoretically sound, failed under real-world incubator conditions due to inadequate material selection. This prompted a redesign using stainless steel and anodized aluminum to ensure durability, chemical resistance, and sterilizability.

Another major insight was the significant impact of friction on mechanical performance. Even minor frictional forces introduced during carriage movement were found to skew load cell readings, affecting measurement accuracy. This led to a focus on sourcing precision linear components and refining the gantry alignment.

Sterilization requirements also influenced system architecture more than initially anticipated. While 3D-printed plastics offered quick iteration early on, they proved unsuitable for repeated sterilization, resulting in delays and the need for mid-project reengineering of several subsystems. The importance of defining sterilization compatibility early in the design phase became evident.

Additionally, team dynamics evolved significantly. Early-stage ambiguity in task division led to inefficiencies, but clear communication and defined roles ultimately improved productivity. Project management tools and weekly check-ins helped maintain alignment during the later stages. Supply chain delays and material availability also presented challenges, reinforcing the importance of contingency planning and proactive vendor communication.

These experiences shaped not only the final prototype but also the team's mindset going forward, preparing each member for future projects in academic, clinical, or industry settings.

5.7 Conclusions

This project successfully developed a functional and modular biomechanical culture reactor capable of applying controlled tensile and compressive forces to biological specimens. Through iterative design, testing, and refinement, the team produced a system that satisfies key requirements for force output, modularity, sterilizability, and low-friction operation. The device

demonstrated reliable performance across test conditions and offered a platform for future biological research focused on orthopedic repair and tissue engineering.

Beyond the technical accomplishments, the project highlighted the importance of multidisciplinary collaboration, rigorous standards adherence, and iterative learning in engineering practice. The system represents a promising step toward scalable, cost-effective platforms for soft tissue research and holds the potential to inform future innovations in regenerative medicine and biofabrication.

Continued development, including expanded testing with living cells and integration of closed-loop control systems, will be necessary to transition the reactor from a proof-of-concept to a research-grade or clinical tool. Nonetheless, the current results provide a strong foundation for both academic exploration and potential translational application.

Acknowledgements

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Department of Mechanical and Aerospace Engineering, UC San Diego

Professor Nathan Delson

Jackie Chen

Thomas Chalfant

Stephen Mercsak

UCSD Makerspace

David Lesser

Mark Liu

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Appendix A: Project Management

A.1 Task Distribution

- Sponsor: Dr. Peter Chen, Erik Dorthe— SCORE Lab
- Alexander Haken: CAD design/assembly, CNC machining, CAM toolpaths, labview programming for SMAC/load cell interface
- Kaustubh Kanagalekar: Load cell readings and SMAC interfacing, data collection, rapid prototyping (3D printing, water jet)
- Jason Liu: CNC machining, logistics
- Sheen Shaji: IMAO quick release fasteners implementation, overall system design
- Justin Dang: CNC machining, R&D, analysis

A.2 Project and Intermediate Milestones

- The project was taken on and roles were assigned to the team members.
- The team met with the sponsors to establish deliverables and goals.
- The SMAC linear actuator was chosen for the device.
- The team successfully interacted and established control of the SMAC linear actuator through serial communication.
- A load cell was chosen.
- The first design utilizing rods and linear motion bearings was prototyped and used for risk reduction.
- The design was revised to include lessons learned from risk reduction.
- The load cell was calibrated and further tested.
- A revised design utilizing a large linear rail system was prototyped.
- The load cell was physically integrated into the system and used to analyze friction in the system.
- The system was revised with higher quality linear rails and the lift plate was integrated. This system was then prototyped using 3D-Printing.
- The final assembly was manufactured and assembled.

A.3 Risk Reduction Efforts

For risk reduction efforts, an early version of the gantry was prototyped to study the interaction between it and the SMAC actuator that was chosen. The geometry is shown in the figure below. The geometry still included a linear sliding gantry. However, instead of utilizing a parallel linear rail system like in the final design, this earlier iteration utilized parallel rods. Each side of the gantry was press fitted with a linear motion bearing. During testing, the SMAC actuator was able to successfully push and pull the linear gantry. Problems with the rod and linear bearing approach were also discovered. Due to overconstraint, misalignments were not very forgiving leading to jamming in the mechanism. This was taken into account in future iterations, as greater measures were taken into consideration to reduce misalignment and constraints.

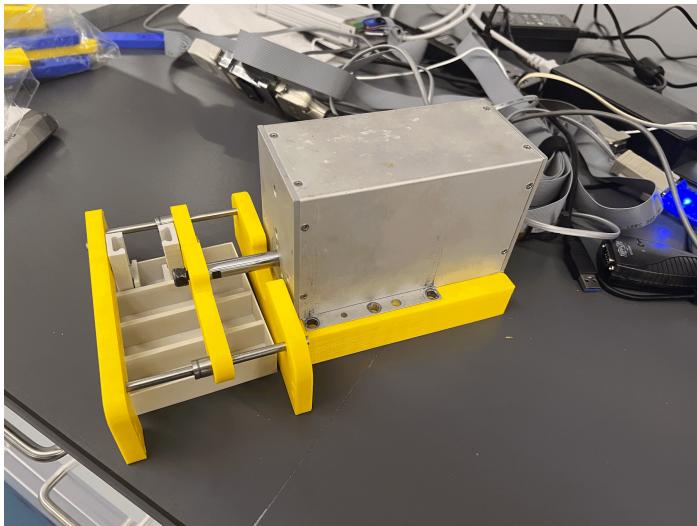


Figure AA. SMAC set up for risk reduction.

A.4 Lessons Learned

One of the major design challenges that was solved was the issue of uncertainty of misalignment and play. These uncertainties arose in part due to overconstraining the system during the design stage. These issues were mitigated by adding locating pins to further rigid the system and to create a rigid mount that would absorb and distribute forces better. However, there are still imperfections regarding this in the system that are hoped to be addressed in the future.

In addition, better machining techniques were learned during fabrication and assembly of the system. Better clamping techniques for metal stock, changing parts to ensure design for manufacturability, and optimized drilling techniques were used throughout the manufacturing process.

Appendix B: Executive Summary

The healing of musculoskeletal tissues such as tendons and meniscus is a critical area of orthopedic research, with tissue culture playing a central role in developing regenerative treatments. The Shiley Center for Orthopedic Research and Education (SCORE) Lab sponsored the development of a biomechanical stretcher machine capable of applying cyclical tensile and compressive strains to engineered tissues *in vitro*. This system was designed to simulate physiological loading environments, fostering the growth of functional cell matrices in tendon and meniscus samples. The reactor is designed to be fully operable within a standard laboratory incubator, using off-the-shelf containers and prioritizing sterilizability, modularity, and ease of use. The system delivers controlled 1 Hz cyclic loading at 10% strain and up to 20 N of force, satisfying the primary biological requirements for tissue stimulation over a two-week experiment. The device integrates key parts including an aluminum base plate, a lift plate that is easy to remove, a SMAC linear actuator for precise actuation, and interchangeable clamping systems for both tensile and compressive loading. The tension clamp system, iteratively prototyped and manufactured, reliably secures collagen specimens, while compression is delivered via a scissor-style or peg-and-hole clamp configuration. A load cell integrated with LabVIEW provides real-time force feedback, while quick-release IMAO clamps allow for easy disassembly of the lift plate and other components and sterilization. Handles enable easy transportation of the lift plate for changing solution media. Compared to commercial systems like ShellPa Pro, the team's design improves stability, ease of use, and scalability, while reducing cost by using rigid, disposable trays and improved mechanical alignment via machined rails and fasteners. Furthermore, a simple lid design is placed on top of the area where tissues and specimens are undergoing experimentation to prevent any dust or particles from falling. Preliminary testing showed consistent actuation and forces of 18 N with minimal system friction, validating the system's capability to maintain desired loading parameters. Future directions include implementing more advanced control software, improving nutrient feeding robustness, and refining compression clamp design for enhanced biological relevance. This system stands to significantly aid researchers in developing synthetic cell therapies by providing a controlled and customizable mechanical environment for cell culture, accelerating the translation of orthopedic

tissue engineering from bench to bedside. A CAD diagram of the system can be seen in Figure AB.

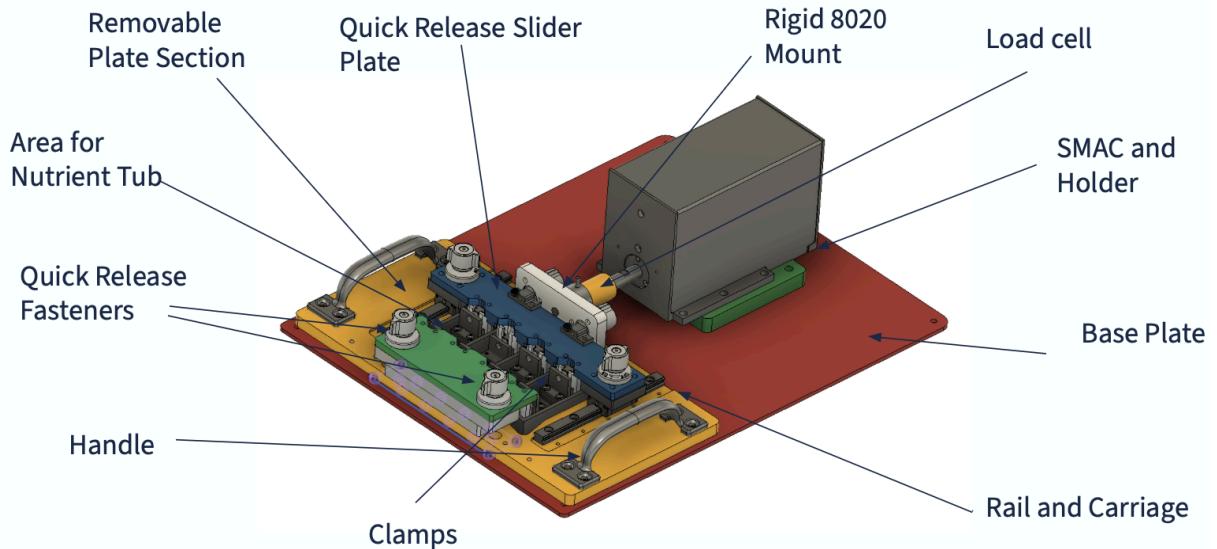


Figure AB. CAD of the Designed Solution highlighting key features.

This machine can serve as a valuable tool and with further development may have potential for FDA approval for clinical research.

Appendix C: Individual Component Analysis

Alexander: Actuator precision+force+heat outputs, load cell analysis

Jason: Linear encoders for strain feedback

Justin: Clamps (compression, manufacturability, modular)

Kaustubh: Serial communication interface with SMAC driver

Sheen: Pumps and valves for auto feeding

Yulin (Jason) Liu

MAE 156A

Team 2

Individual Component Analysis – Linear Encoder

1. Brief Project Description

The Biomechanical Culture Reactor is a bioreactor designed to apply cyclic mechanical stimulation to tendon and meniscus cell cultures within a laboratory incubator. Tendon cells require cyclic tensile strain to develop properly, while meniscus cells need cyclic compression. To address this, the reactor operates in two configurations: one for applying tension to collagen strips seeded with tendon cells, and another for compressing cylindrical meniscus cell samples. Both configurations must maintain precise control over strain (10% elongation/compression) and force (20N) while operating in a humid, 37°C incubator environment. A critical challenge lies in ensuring sterility and compatibility with nutrient perfusion systems. The device incorporates alcohol-sterilizable components and a closed-loop control system using linear encoders for real-time strain feedback.[3]

2. The Functional Requirements

Accurate strain measurement is critical for validating mechanical stimulation protocols in the bioreactor. The sensors must track displacement of cell cultures in Petri dishes or collagen gels with high precision while operating in the incubator's high-humidity environment [8]. Key functional requirements include:

- I) The device must deliver 10% strain ($\pm 0.1\%$ precision) at a frequency of 1Hz to simulate physiological loading conditions. For a typical 20mm sample, this requires a displacement resolution of 0.02mm. Additionally, the actuator must generate up to 20N of force in both tension and compression modes to ensure proper cell development.[3]

- II) All components must operate reliably in an incubator environment maintained at 37°C and 90% relative humidity. Materials must withstand repeated alcohol sterilization (e.g., isopropyl/ethanol wiping) without corrosion or degradation.[2]

III) The reactor must accommodate modular clamps for two types of samples: Tendon cells cultured on woven collagen strips (30–50mm length, 10mm width, 1mm thickness) and meniscus cells housed in cylindrical biopsy punches (6–8mm diameter). Clamps must secure samples without inducing bending stress or slippage.

IV) A perfusion system must continuously supply nutrient-rich media to cell cultures while maintaining low shear stress (<1 Pa) to avoid damaging cells. Fluid flow rates should be adjustable, and the system must allow periodic media replacement without disrupting experiments.[1]

3. A short description of at least 3 different components options

I) SMAC LAL90-050-535DM Linear Actuator

A laboratory-grade actuator with a built-in linear encoder (5 μ m precision) and corrosion-resistant aluminum housing. Validated for continuous operation in 37°C, 80% RH incubators. Its closed-loop control system eliminates backlash, making it ideal for long-term cell culture experiments.[4]

II) Celera Motion Mercury 1500HS Optical Encoder

A high-speed, ultra-precision optical linear encoder designed for applications requiring nanometer-level accuracy. Its compact design and robust sealing make it suitable for laboratory environments like bioreactors, though optical components may require protection from condensation in high-humidity incubators.[6]

III) Aikron AUMS Magnetic Linear Encoder

A humidity-resistant sensor with 5 μ m resolution and quadrature output. Its magnetic sensing technology avoids contamination risks in humid environments, making it suitable for incubator conditions.[5]

4. A summary table

Component	Specifications	Cost & Shipping	Pros	Cons
SMAC LAL90-050-535DM	*5 μm precision *Corrosion-resistant aluminum *Closed-loop control system	Available in lab	Free and been used for previous experiments	Advanced controller (PID and LabVIEW) for precision. Complex integration with high-cost actuator.
Celera Motion Mercury ,1500HS	*1 nm optical precision *Lab-grade sealing *High-speed feedback	1200; 4 weeks	Precision	Condensation damage and requires sealed enclosure.
Aikron AUMS	*5 μm resolution *IP67 humidity resistance *Magnetic sensing	295; 3 weeks	Less expensive and rapid prototyping	Simple integration with controllers. Limited precision for strict strain requirements.

5. Describe how the decisions made based on your ICA will affect other aspects of the overall team's design

The selection of the SMAC LAL90-050-535DM Linear Actuator was driven by its specifications, existing lab availability, and alignment with project constraints:

I) Precision, Force, and Environment Requirements [8]

- A. The actuator's peak force of 65.5 N and continuous force of 41.5 N [7] exceeded our required 20N for both tension and compression modes, ensuring robust performance.
- B. Its encoder resolution of 5 μm [7] met the ±0.1% strain accuracy needed for 10% elongation/compression of collagen strips and meniscus samples.
- C. The SMAC's operating temperature range (0°C–65°C) [7] and corrosion-resistant aluminum housing [7] ensured reliability in the incubator's 37°C, 90% RH environment, even after repeated alcohol sterilization.

I) Dimension and Cost [8]

- A. Its total mass is 2,850 g [7] and moving mass 340 g [7] simplified mechanical integration with the reactor's modular clamps.
- B. By reusing lab-owned SMAC actuators, the team saved \$495/unit, allowing prioritization of subsystems like the perfusion system or sterilization.

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Kaustubh Kanagalekar

Individual Component Analysis

Brief Project Description: This project is led by Dr. Peter Chen from the SCORE (Shiley Centre for Orthopedic Research and Education) lab, which is affiliated with UC San Diego. The SCORE lab focuses on researching novel innovations to repair musculoskeletal damage. A great focus of this project is the development and rebuilding tissue samples for meniscus repair. The project's primary objective is to design a biomechanical culture reactor that will provide tensile and compressive forces to tissue samples in a controlled environment that will facilitate the growth of these tissue samples for future use in humans. A robust environment with loading is desired in order to fully mature the tissue samples. Key design considerations include modularity for different experimental setups for current and future experiments and sterilization for preserving tissue environment. A secondary objective of this project is to design a nutrient feeder that would provide a liquid solution to the tissue samples. This liquid solution is essential for the growth and viability of tissue samples.

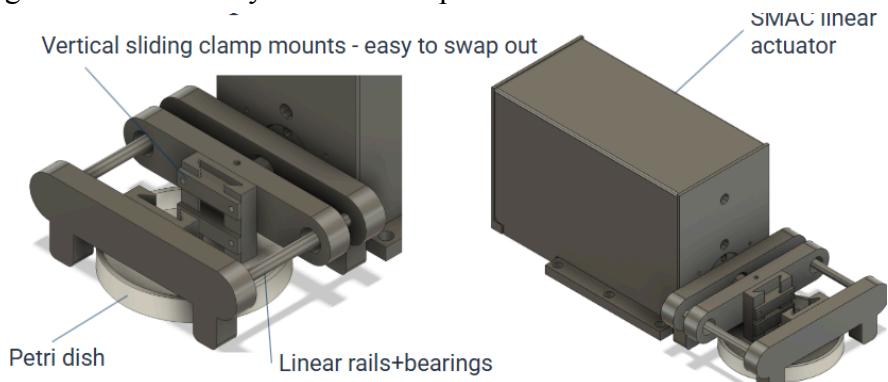


Figure 1: CAD of preliminary project idea

Functional Requirements of ICA:

Some of the major requirements for the project are

- 1) The biomechanical culture reactor shall provide 20 N of force in tension and/or compression to the tissue samples
- 2) The biomechanical culture reactor shall achieve 10% strain at a continuous duty cycle of 1Hz with 0.01mm precision
- 3) The biomechanical culture reactor shall be able to operate within a 37°C environment (within a standard incubator environment)

All these points shall be achieved using the actuator selected for the project. For the project, the SMAC Linear Actuator LAL90-050-535DM is the preferred choice of actuator, because the SCORE lab has a spare actuator that is available for use, along with the actuator exceeding all the functional requirements.

For the individual component analysis, a serial communication interface with the SMAC driver will be explored. More specifically, researching different types of serial communication protocols and harvesting data from the actuator will be investigated.

The LAC 1 Manual, the technical reference manual for the SMAC Linear Actuator LAL90-050-535DM, has a lot of valuable information pertaining to establishing serial communication between the actuator and a host device [1]. The LAC 1 Manual specifies the following information-

- 1) RS-232 serial communication interface.
- 2) baud rate of 9600 (although it is adjustable)
- 3) 8 Data Bits
- 4) 1 Stop Bits
- 5) No Parity
- 6) XON/XOFF Handshake flow control

Which is extremely vital in selecting the correct modes for proper interfacing

Background:

RS-232 [2]

RS-232 is a type of asynchronous serial communication protocol commonly found in older electronic devices. In order to send data, RS-232 uses negative and positive voltages to encode bits into messages. However, the mechanism of using the logic is different from most modern communication protocols as RS-232 uses 0 (+3 -> +15 V) for positive voltage and 1 (-15 -> -3 V) for negative voltage, which can add confusion when working with such devices. As RS-232 is asynchronous, it doesn't have a dedicated clock signal to facilitate data exchanges. Instead, it works by having start and stop bits that separate data packets to transmit information. Data cannot be simultaneously transmitted and received with a RS-232 protocol, thus each device can

either send data or receive data at a particular time. In a standard RS-232 connector, the most likely signals used are TX, RX, GND. TX stands for transmission (signal getting transmitted from one device to another). RX stands for receiving (signal getting received from one device to another). GND stands for the ground signal. TX for device 1 will be connected to RX of device 2, and vice versa, to facilitate communication between devices; meanwhile GND is connected to GND for grounding the signals.

Baud Rate [3]

Baud rate is a type of measurement for the number of times a signal can be changed in a second. Some of these changes can be a voltage shift or a pulse being induced. Baud rate is necessary for communication systems because it aids in the method of communication efficiency, allows for optimal bandwidth utilisation, and ensures robustness in communication.

Data Bits [4]

Bits are the smallest unit of data, which can be represented by 0 or 1. Bits often represent information that's being transmitted by the device

Stop Bits [5]

Stop bits are signals at the end of each transmitted character that indicate completion and provide timing for the receiver before the next character is sent is complete.

Parity Bits [6]

Parity bits are used in communication to validate if the transmitted data is correctly received by the receiver.

Handshake Flow Control [7]

A handshake flow control ensures that data is transmitted only when both the sender and receiver are ready and able to do so. The Xon\Xoff flow control enables a receiver from not receiving additional data from the transmitter in case it has enough data received in the queue to process.

Some ways to achieve serial communication between the actuator and host device are the following:

- 1) NI VISA
- 2) pySerial
- 3) MATLAB serial port
- 4) SMAC GUI

NI VISA [8]

VISA stands for Virtual Instrument Software Architecture, an application programmable interface that is helpful in connecting serial, GPIB, ethernet, and many other communication methods using LabVIEW. NI VISA uses common operations across instruments, adjusting for different interface types, which makes it easier to switch between them. It is also easy to use as it is graphically programmed and is modular in platform portability.

pySerial [9]

pySerial is a python library that allows serial communication using python scripting. Data can be easily sent and received using pySerial. pySerial is also easy to use, is modular (can work with Windows, MacOS, and Linux systems), and can be connected to other python modules for seamless connectivity.

MATLAB serial port [10]

MATLAB has a serial port connection that can allow serial communication using the MATLAB interface. While this is extremely powerful, the issue with MATLAB is that of accessibility, as a licence is often required to run MATLAB scripts and applications.

SMAC GUI [11]

SMAC graphical user interface enables users to tune multiple parameters for a SMAC actuator. It is menu driven, provides real time analysis, and is extremely user friendly.

Table Summary of achieving serial communication

Interface	Pros	Cons	Cost
NI VISA	<ul style="list-style-type: none"> - Existing code is provided in LabView - Graphically programmed (better visualisations) - Proven 	<ul style="list-style-type: none"> - Learning curve (in using the software) - Issues with downloading on newer MacOS versions 	Free if using community version Paid versions available but not necessary for project's

	functionality (easier to debug in case something is amiss)		purpose (\$528/yr for LabView Base)
pySerial	<ul style="list-style-type: none"> - Extensive documentation present - Faster run time than NI VISA due to scripting - Modular (can work with any OS) 	<ul style="list-style-type: none"> - Learning curve (in both coding in python and then pySerial) - Unknown functionality (never tried this before) 	Free
MATLAB Serial Port	<ul style="list-style-type: none"> - Extensive documentation present - More experience with using MATLAB for general coding - Modular (can work with any OS) 	<ul style="list-style-type: none"> - Unknown functionality (never tried this before) - Cost and licensing issues to run externally 	Free for students Paid for outside use (\$860/yr for MATLAB standard)
SMAC GUI	<ul style="list-style-type: none"> - Little programming required (very beginner friendly) - User friendly GUI - Provides data and graphical feedback tools 	<ul style="list-style-type: none"> - Only Windows based (no support for MacOS or Linux) - Limited functionality(a lot of tools are pre-programmed) 	Free with Actuator or Controller purchase (~\$2500 for actuator)

Future Impacts to Project

The SMAC interface choice will have an impact on the load cell selection, user interface/convenience, and data logging. For the load cell selection, if the LabView NI VISA interface is chosen, which seems the most likely candidate, then a load cell that can easily

communicate using serial will be selected, in order to better connect the SMAC interface and the load cell for a seamless connection. Regarding user interface/convenience, the NI VISA interface is a bit old fashioned and not modern looking, thus it may look plain to the user. However, as long as the interface achieves everything (i.e. can let the user input the desired strain, cycle level, etc), this is not a concern. In terms of data logging, it will all be recorded in the native LabView data collection method, which is often a DAQ (data acquisition model). Converting this DAQ to a CSV or text file may be necessary in order to perform data verification and validation or perform any kind of mathematical analysis on the data, which may bring additional challenges and complexities to the overall project.

References

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- [2] Maker.io Staff, "Understanding the RS-232 standard," *Digi-Key*, Oct. 25, 2023. [Online]. Available: <https://www.digikey.com/en/maker/blogs/2023/understanding-the-rs-232-standard>
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- [9] C. Liechti, "PySerial documentation," *PySerial*, 2001-2020. [Online]. Available: <https://pyserial.readthedocs.io/en/latest/pyserial.html>. [Accessed: Feb. 26, 2025].
- [10] MathWorks, "Serial port devices," *MathWorks*, [Online]. Available: <https://www.mathworks.com/help/matlab/serial-port-devices.html>. [Accessed: Feb. 26, 2025].
- [11] SMAC, "Graphical user interfaces," *SMAC*, [Online]. Available: <https://www.smac-mca.com/technical-resources/graphical-user-interfaces>. [Accessed: Feb. 26, 2025].

Individual Component Analysis: Clamps and Clamp Interface

Team 2: Biomechanical Culture Reactor

Justin Dang

Background

The Bioculture reactor is a device which can provide the mechanical and biological requirements demanded by cells in order to grow. In which case there will be two types of cells that will be cultivated : tendon and meniscus cells. Tendon cells require tension and meniscus cells require compression. The tendon cells will be populated on a collagen strip whereas the meniscus cells are presented as a small short cylinder. This means each of them has a different clamping method which will need to be easily swappable. They will be put in 1hz cycles of 10% strain for 2 weeks. Tensile and compressive experiments will not occur simultaneously, however both types of cells will need to be supplied with a nutrient solution in order to survive. They also need to be submerged in this solution hence the petri dish. Ideally we can further develop an auto feeding feature with a pump which can supply a slow flow of the solution to the cells where the flow out equals the flow in.

After the experiment, samples will be load tested and analyzed. The long term goal is to be able to promote meniscus and tendon recovery at a very high rate and even full replacements.

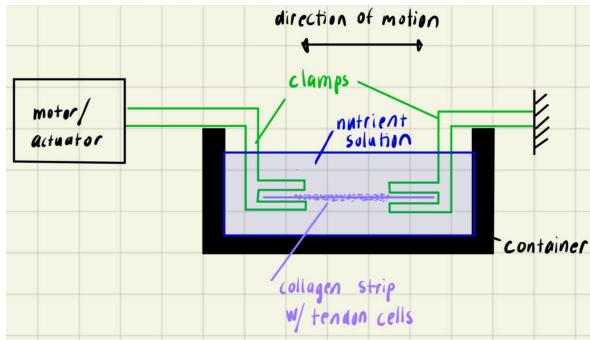


Figure 1: 2D Sketch of Concept

Functional Requirements

We will likely be manufacturing our own clamps. However off the shelf mechanisms will be explored before being ruled out if so.

1. Material

- a. Needs to be Sterilizable
 - i. Autoclave or Alcohol Bath
- b. Be in incubator environment; 37C and high Relative Humidity
- c. Not react or interfere with nutrient solution or cells

2. Fabrication

- a. Be able to be manufactured without too much hassle
 - i. 3DOF machine max

3. Geometry

- a. Fits within the petri dish or 4 rectangular well plate
 - i. Specimen submerged
- b. Does not cause overflows of the nutrient solution
- c. Not quite as restricted in height or depth only width

4. Accessibility

- a. Types of clamps are interchangeable in the machine
- b. Can be clamped easily
 - i. One handed operation
 - ii. So if using bolts then either threaded backplate or nylock with nut holder
- c. Will not come loose over course of 2 weeks

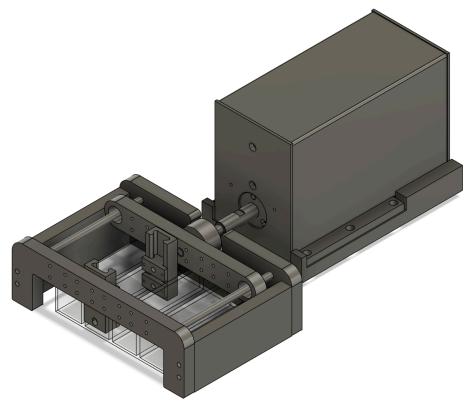


Figure 2: CAD of Current Design

- d. Sample will not slip over course of 2 weeks
 - i. Additional: how can we see this?

Description of Findings

Options

1. Current Clamps used The current clamps are designed by Eric who helps our Sponsor Dr. Chen oversees the project. It consists of two pieces which slide onto the rods of the Shellpa. They have two parts which have two additional pins for alignment. They clamp together with some screws that go through the top plate and into the bottom plate which is threaded. The top and bottom interfaces are knurled and Eric says that this is sufficient so that the tendon cells on the collagen strip do not slip under load.



Figure 3: ShellPa Chamber holder with pins

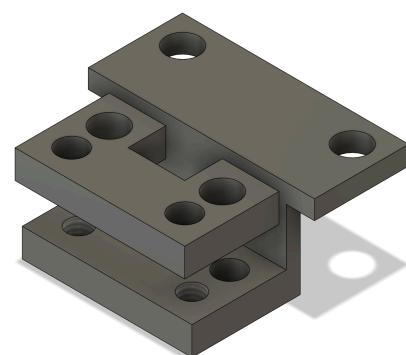
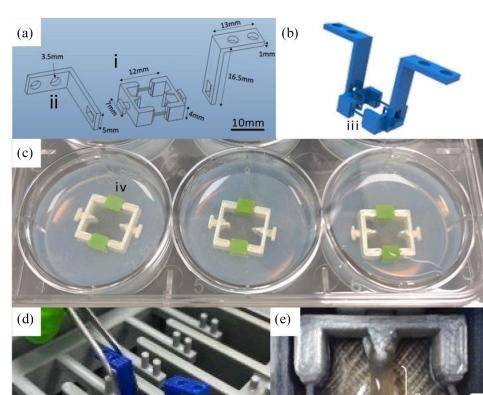


Figure 4: Current Clamps which replace Stretch Chamber

2. 3d Printed Bio Reactor Chamber

This lab is conducting research along the lines of what our sponsor is doing. They are using machines similar to the Shellpa Pro: EBERS-TC3 and CellScale MCT6. They conduct a wide range of tests on a wide range of cells from 1-15% strain and 1-21 days. The table detailing these loads and durations can be found in the appendix. They also operate in an incubator environment pretty much identical to our sponsor from what I can tell. 37C and 5% CO₂.

The most important takeaway is that they have been able to make 3d printed parts, specifically PLA,



sterilizable using XTC-3D which is a commercially available resin coating. They also mentioned that they coated their tubs in polydimethylsiloxane (PDMS) to make the well surface have lower adhesion which should not be a problem in our current design which has samples suspended above the well surface, but good to note.

Figure 5: 3d Printed Clamps (PLA)

3. Quick Change tool post Dovetail

These can be used to secure a tool in place with the turn of a lever. It is quick and elegant. However, they are probably too large for our application and would interfere with the rest of the build.



Figure 6: Quick change tool post

4. Our Current Idea

We are currently using a design which is essentially a wedge shape which has a slot which clamps can be lowered into. We rounded the edges to the radius of an endmill we could use to make manufacturing easier/ possible.

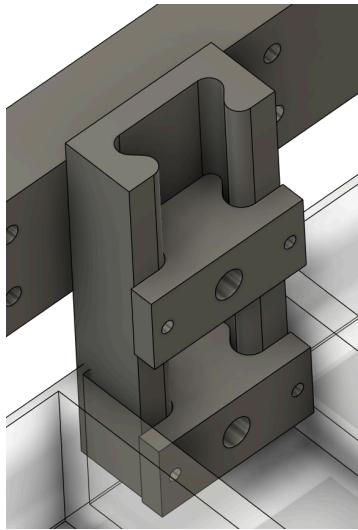


Figure 7: Rounded Wedge Slider

Material

1. Stainless steel
2. Aluminum
3. Delrin
4. Resin
5. PLA

Comparisons

Component	Pros	Cons
Current Clamps	We know that the interface works	Wouldn't interface well with new machine. Not great to manufacture
3d Printed Clamps	Sky is the limit. Easy manufacturing. Complex geometry and designs ok.	Might have low accuracy and not as strong. Creep resistance low.
Quick Change tool post	Very easy to attach clamp to	Heavy, large, might need to modify it to fit anyways defeating the purpose of off the shelf

Wedge Slider	Easy to operate	Moderate manufacturing process. Might have to get an endmill which is longer than usual -> more expensive.
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Material	Strength	Creep Resistance	Manufacture	Cost	Sterilizable	TOTAL
Stainless Steel	5	5	1	1	5	17
Aluminum	4	4	2	2	3	15
Delrin	3	3	2	3	3	14
Resin (Print)	2	2	3	4	2	13
PLA (Print)	2	1	5	5	2	14

Impact on Overall Design

The impact on the overall design and other components of the project are very low. Considering there are many different well sizes and shapes to choose from, we could change the shape of our well if needed. Currently the long rectangular shape would be the most efficient. The gantry could need to be remade, however since it will be waterjetted, it will not be a super big hit. The auto feeding system will not be affected since it will be implemented later on if possible. Thus, it would be designed around the already made clamps and selected wells.

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- <https://journals.sagepub.com/doi/10.1177/2041731420942462>
- <https://www.mcmaster.com/products/quick-change-tool-posths/>

Appendix

Janvier AJ, Canty-Laird E, Henstock JR.

A range of bioreactors use linear actuators to apply tensile forces *in vitro*, but differences in their culture environments can limit a direct comparison between studies. The widespread availability of 3D printing now provides an opportunity to develop a ‘universal’ bioreactor chamber that, with minimal exterior editing can be coupled to a wide range of commonly used linear actuator platforms, for example, the EBERS-TC3 and CellScale MCT6, resulting in a greater comparability between results and consistent testing of potential therapeutics. We designed a bioreactor chamber with six independent wells that was 3D printed in polylactic acid using an Ultimaker 2+ and waterproofed using a commercially available coating (XTC-3D), an oxirane resin. The cell culture wells were further coated with Sylgard-184 polydimethylsiloxane (PDMS) to produce a low-adhesion well surface. With appropriate coating and washing steps, all materials were shown to be non-cytotoxic by lactate dehydrogenase assay, and the bioreactor was waterproof, sterilisable and reusable. Tissue-engineered tendons were generated from human mesenchymal stem cells in a fibrin hydrogel and responded to 5% cyclic strain (0.5 Hz, 5 h/day, 21 days) in the bioreactor by increased production of collagen-I α 1 and decreased production of collagen-III α 1. Calcification of the extracellular matrix was observed in unstretched tendon controls indicating abnormal differentiation, while tendons cultured under cyclic strain did not calcify and exhibited a tenogenic phenotype. The ease of manufacturing this bioreactor chamber enables researchers to quickly and cheaply reproduce this culture environment for use with many existing bioreactor actuator platforms by downloading the editable CAD files from a public database and following the manufacturing steps we describe.

Individual Component Analysis: Alexander Haken

Alexander Haken

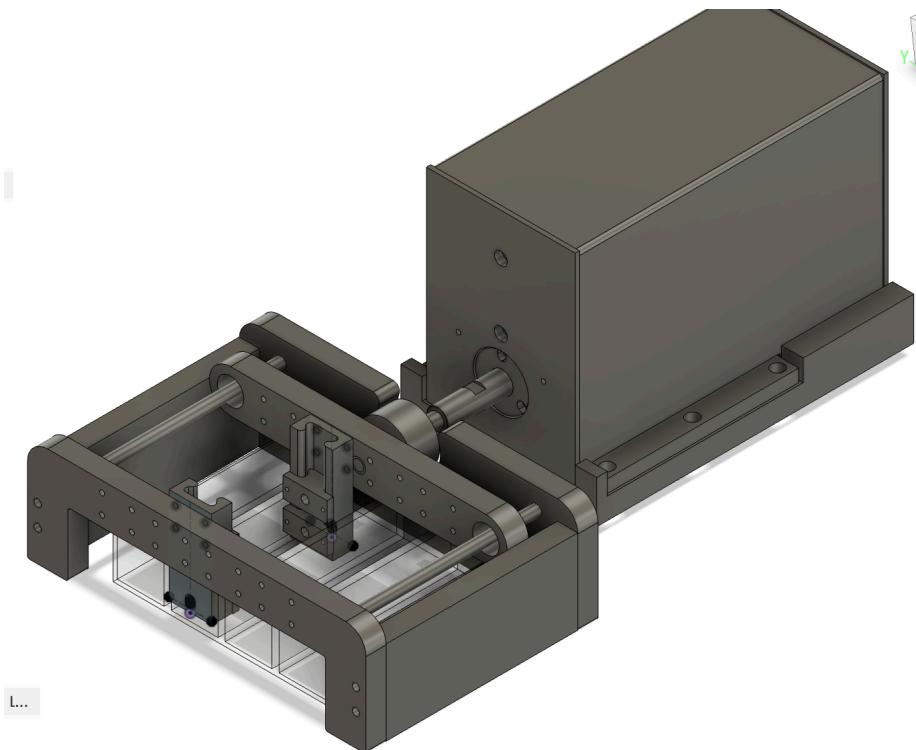
Dr. Nathan Delson

MAE 156a

Individual Component Analysis: Actuators and Load Cells

Project Background:

Dr. Peter Chen and Erik Dorthe, our project sponsors from the Shiley Center for Orthopedic Research and Education are researching growing tendon and meniscus cells in the lab with the goal of eventually having synthetic replacements for human tendons in the future. Right now, the objective is to facilitate cell culturing in human trials. Our project objective is to create a device which can apply tensile loads or compressive loads to cells while they are submerged in a nutritional solution. Below is a CAD rendering of one of the concepts for the device:



The device has two interchangeable clamps, one fixed to the frame and the other attached to a sliding gantry. This report is divided into two sections. The first will focus on the actuator selection which moves the clamps back and forth. The second will focus on a load cell for measuring the forces on the samples.

This actuator has several important functional requirements. It must be able to move precisely enough for robust control over the experiments. We define “precise enough,” as having 0.1% strain control increments on a 1cm sample (which would be in the smaller end of samples that we work with). This translates to 10 micrometers of precision. The actuator also should be able to exert 20 newtons of force on the stretched/compressed object. The actuator will be operating in an incubator environment with high humidity and a 37 degree Celsius ambient temperature, and must both withstand this heat and not output so much heat as to cause

disruption to the incubator operation. The actuator must be sterilizable, potentially by immersion in an isopropyl alcohol bath between experiments.

Three actuator options which were considered were stepper motors attached to lead screws, continuous-rotation servo motors attached to lead screws, and SMAC moving coil actuators.

One specific stepper motor we considered was the NEMA 8 stepper motor+lead screw combo sold by oyostepper.com. This stepper motor had a precision of 0.005 mm translation per step assuming a lead screw with 1mm of translation per rotation was attached, while being relatively affordable at \$45. While these motors are rated to work in environments up to 50 Celsius, due to the small thermal mass heat dissipation may be more of a challenge. Furthermore, backlash considerations with the lead screw may limit the actual precision.

Another option we considered was a clearpath continuous rotation moving servo motor. These motors offer extremely fine-grained rotational control, of only 0.057 degrees achievable resolution. This translates to a tiny 0.16 micron theoretical resolution when attached to a 1mm/rotation pitched lead screw, however backlash considerations would limit the true power of the actuator to be lower. They are unfortunately quite expensive, at \$570 per unit, but they do meet all of our requirements.

The 3rd actuator option considered was a SMAC-MCA LAL90-050-535DM linear actuator which the lab has for us. This is a 27 year old actuator for which the data sheets are not publicly available, but after reaching out to SMAC motors sales engineer Mike Ferris replied back that the datasheet for the newer LAL95-050-7x-1 would be an accurate substitution. The SMAC motor has 5 microns of precision, and due to the nature of how it operates, backlash is not a concern. It also has a built-in encoder, and is rated for 41.5 N of continuous force. While

similar actuators retail for about \$2,500 new, and have a \$1,500 controller, the lab has one we can use. As it exceeds all our specifications and is free for our use, this is what we are using in the initial prototypes of our device.

The SMAC actuator does have built-in load sensing, but our sponsors gave us the feedback that it is unreliable, so we should use a load cell to directly measure force. For our load cell choice, we considered a DYMH-103 profile tensile+compressive load cell and a s-type load cell design (both from multiple manufacturers). The amazon clones had identical specs, but due to concerns about reliability we are opting to go with a load cell from ATO which is a reputable manufacturer. Below is a table comparing the specifications of the two load cell types we considered.

	S-type load cell	DYMH load cell
Tensile+Compressive Load Measurement	Yes	Yes
Accuracy	0.05% F.S.	0.3% F.S.
Capacity	100 N	100 N
Driving voltage	0-10V	5-15V
Sensitivity	2+-0.2 mV/V	1.25+-0.05 mV/V
Cost	\$177.78	\$137.78

All the load cells selected output a signal of only about 0-20mV when driven by a 5V supply, which is too small for most devices to read without an amplifier. We considered two specific load cell amplifiers: The sparkfun HX711 and the ATO LCTR-OA amplifier. The

sparkfun HX711 contains both an amplifier and a 24 bit digital to analog converter.

Size	Sparkfun HX711	ATO-LCTR-OA
Output	Serial data containing load cell information	Either 4-20mA current, 0-5V, or 0-10V
Driving voltage	2.6-5.5v	5V
Sensitivity	(1/(2^24))V resolution, after analog to digital converter	0.05% F.S.
Power supply	2.6-5.5v	18-30V
Cost	\$10.95	\$81.27

Based on the fact that the sparkfun HX711 produces a serial output (whereas we would need to read the ATO-LCTR with an arduino) and the greater affordability of the HX711 chip, we are trying out the sparkfun load cell amplifier first. Both load cell types considered are precise enough for our needs, as they give us +-0.2 Newtons and +- 0.05 N respectively. We are choosing the cheaper DYMH profile load cell due to its easier packaging with the extremely compact cell stretcher design. We believe that this load cell+amplifier combination can provide accurate data on the forces involved with this design.

References:

Mike Ferris, SMAC Moving Coil Actuators, mferris@smac-mca.com, February 24, 2025

Stepper motor:

<https://www.oyostepper.com/goods-1083-NEMA-8-External-Acme-Hybrid-Stepper-Linear-Actuator-05A-282mm-Stack-Screw-Lead-1mm-003937-Lead-Length-100mm.html>

Teknic Servo Motor:

https://teknic.com/model-info/CPM-SDHP-2310H-EQN/?model_voltage=75#downloads-section

ATO DYMH 103 Load Cell:

<https://www.ato.com/tension-and-compression-load-cell-1kg-to-200kg?srsltid=AfmBOorgMi0m5Q53wEpIESNFV-A4NIO5ErftbsBPhfkdlqb2Ytk-xo93>

Amazon DYMH Load Cell:

<https://www.amazon.com/DYMH-103-Tension-Compression-Sensor-Applicable/dp/B07H58ZH8C/>

ATO S-type micro load cell:

<https://www.ato.com/micro-load-cell-s-type-0kg-to-200kg>

ATO Load Cell Amplifier:

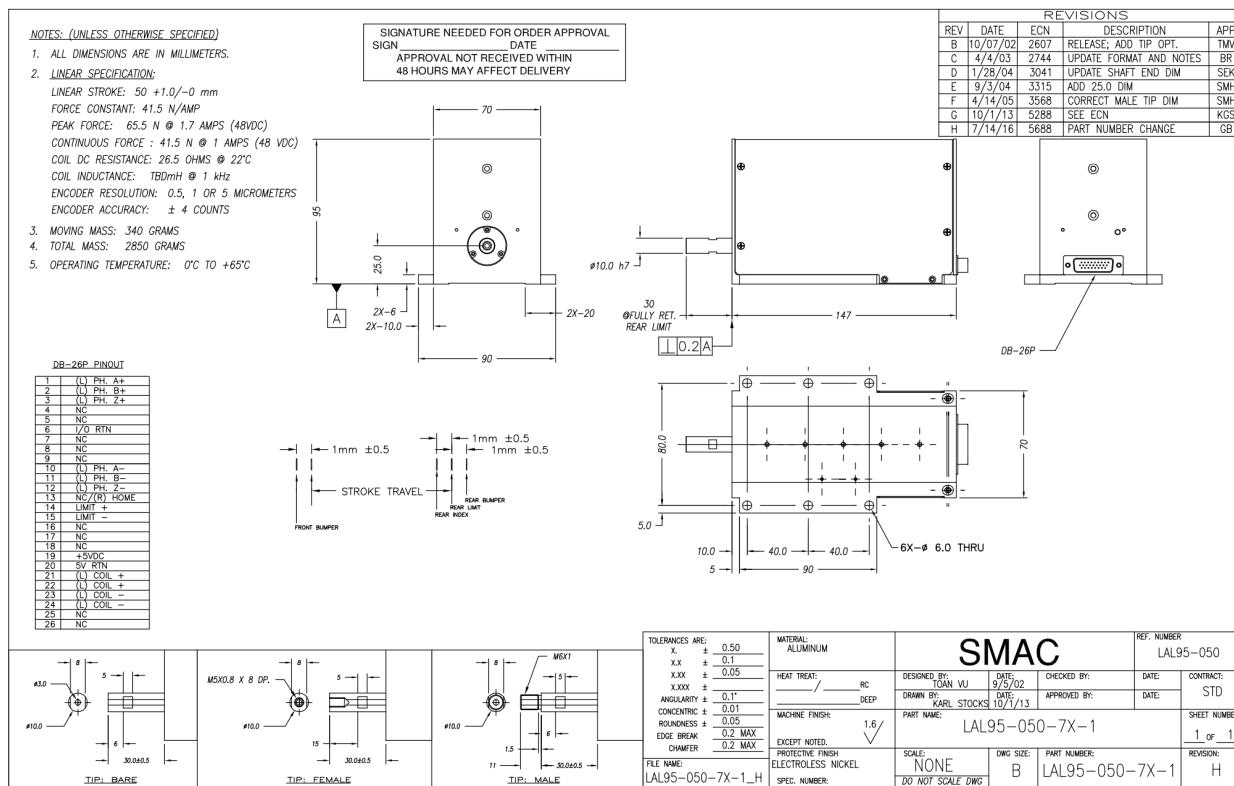
<https://www.ato.com/load-cell-transmitter-output-0-5v-4-20ma>

Sparkfun Load Cell Amplifier:

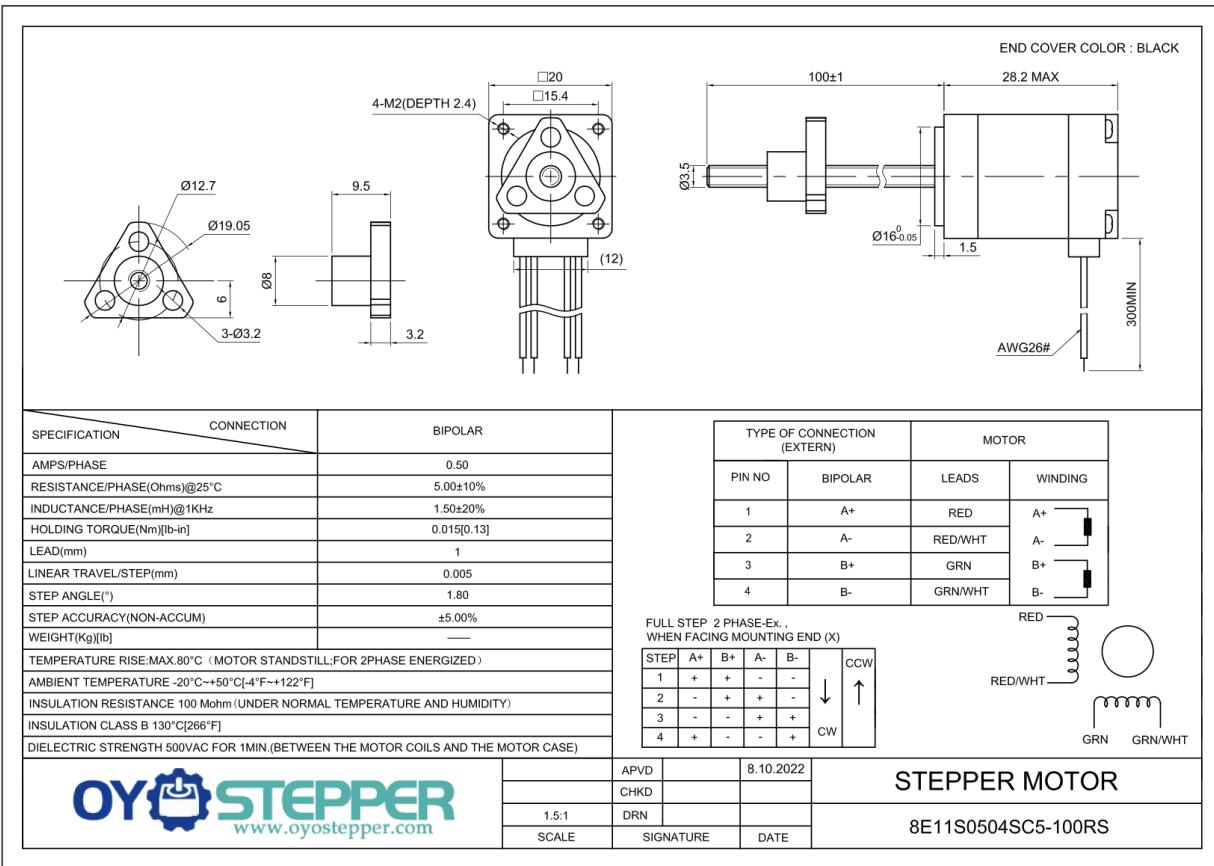
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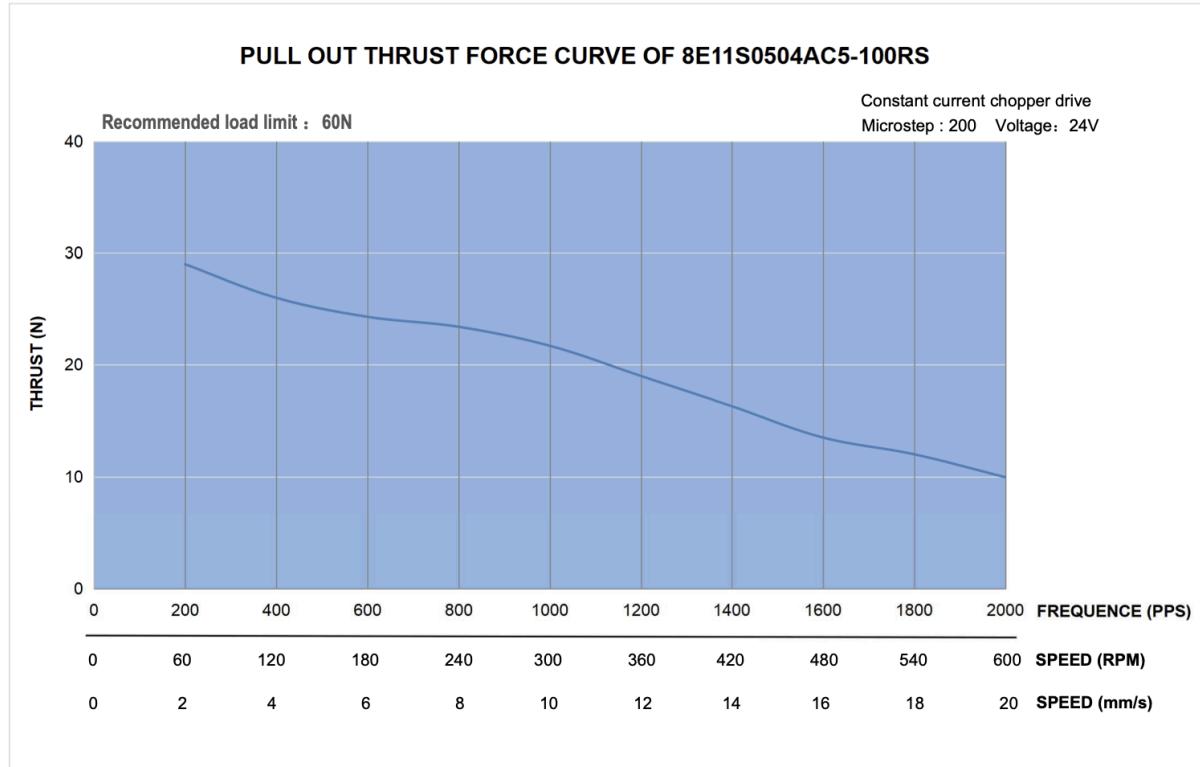
Appendix:

Specification Sheet for SMAC-MCA 95:



Specification sheet for Oyostepper NEMA-8 Stepper motor+ lead screw combo:





Specification Sheet Clearpath Servo Motor

Motor Frame Size	NEMA 23 - 2.33 in (59.18 mm) sq.
Length	3.59 in (91.19 mm)
Input (bus) Voltage Range	24-75 VDC (90 VDC max)
Peak Torque (@75 VDC)	223 oz-in (1.6 N-m)
Cont. (RMS) Torque (@75 VDC)	45 oz-in (0.3 N-m)
Max Speed (@75 VDC)	4000 RPM
Achievable Resolution	0.057 degrees
Repeatability	0.03 degrees
Shaft Diameter	0.250 in (6.35 mm)
Weight	1.5 lb (0.7 kg)
Rotor Inertia	0.4 oz-in ² (0.1 kg-cm ²)
Controller Signal I/O Voltage Range	4.0 to 28 VDC
Maximum Radial Load	25 lbf (111.2 N)
Maximum Thrust Load	5.0 lbf (22.2 N)
Ambient Temperature¹	-40° to +70° C
Ambient Humidity	0-100%
Environmental Protection (IP Rating) ?	IP67 & IP66K
Regulatory Certifications³	UL (pending); cUL (pending); CE; RoHS
Safety²	Supports STO (IEC 60204-1) Safety Requirements
Country of Origin	USA
Warranty	3 Years

Specification data for ATO DYMH load cell:

Model	ATO-LCC-DYMH-103
Weight	0.1kg
Capacity Range *	0kg~500kg
Matched Display Controller	ATO-DDC5-CHB (Click it to the controller page)
Matched Transmitter	ATO-LCTR-OA (Click it to the transmitter page)
Accuracy	0.3%F.S (linearity + hysteresis + repeatability)
Sensitivity	1.0~1.5mV/V (Low range variations may differ)
Creep	±0.05%F.S/30min
Zero Output	±1%F.S
Temperature Effect on Zero	±0.05%F.S/10°C
Temperature Effect on Output	±0.05%F.S/10°C
Operating Temperature	-30°C~+70°C
Input Impedance	400±10Ω
Output Impedance	350±10Ω

Insulation Resistance	$\geq 5000\text{M}\Omega$
Safety Overload	150%F.S
Overload Limit	200%F.S
Bridge Voltage (excitation voltage)	DC 5-15V, suggest DC 10V
Material	Stainless steel
Protection Class	IP67
Cable Length	2m
Wiring	EXC+: Red, EXC-: Black, SIG+: Green, SIG-: White

Specification Data for ATO S-type load cell:

Model	ATO-LCS-DYLY-108
Weight	0.1kg
Capacity Range *	0kg~200kg (0~2000N)
Matched Display Controller	ATO-DDC5-CHB (Click it to the controller page)

Matched Transmitter	ATO-LCTR-OA (Click it to the transmitter page)
Accuracy	0.05%F.S (linearity + hysteresis + repeatability)
Sensitivity	2.0±0.2mV/V (Low range variations may differ)
Creep	±0.05%F.S/30min
Zero Output	±2%F.S
Temperature Effect on Zero	±0.05%F.S/10°C
Temperature Effect on Output	±0.05%F.S/10°C
Operating Temperature	-20°C~+80°C
Input Impedance	350±30Ω
Output Impedance	350±5Ω
Insulation Resistance	≥5000MΩ/DC 100V
Safety Overload	150%F.S
Ultimate Overload	300%F.S
Bridge Voltage (excitation voltage)	DC 5V
Maximum Bridge Voltage	DC 15V

Material	17-4PH stainless steel
Protection Class	IP66
Cable Length	1.5m
Wiring	EXC+: Red, EXC-: Black, SIG+: Green, SIG-: White

Sheen Shaji

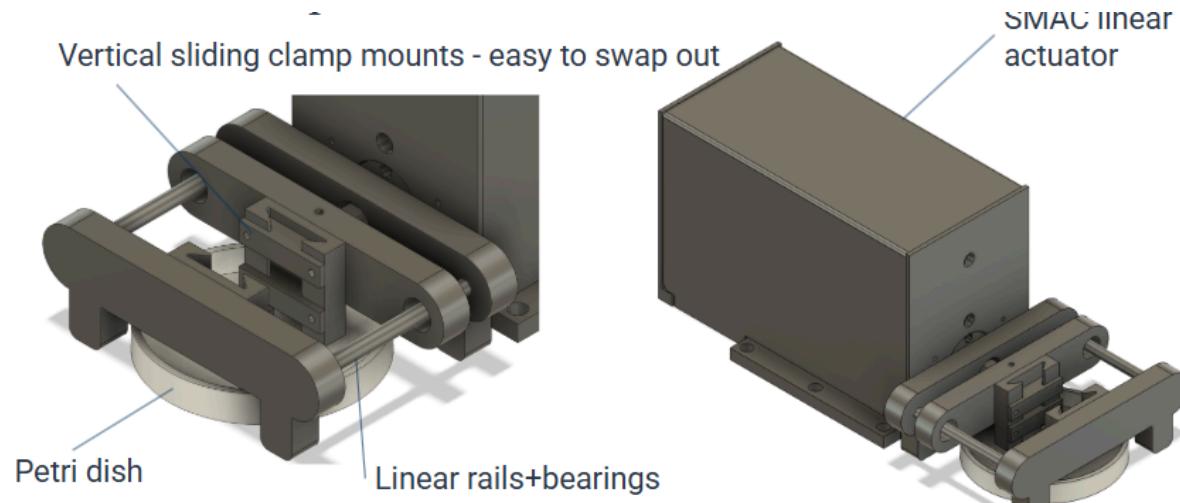
MAE 156A

14 March, 2025

Individual Component Analysis: Mechanism for Auto Feeding

Project Description

We want to develop a new device to put tendon cells in tension and meniscus cells in compression to achieve 10% strain . The forces need to be exerted in cycles of 1hz The cells are placed on 20cm long strips of collagen protein, which are then clamped and stretched. THe mechanism is depicted below. In addition, the cells need to be immersed in a nutrient solution, which is why they are placed in a petri dish.Although a secondary goal, we hope to implement a method to automate the cycling of the nutrient solution.



Functional Requirements of Auto Feeding

To minimize intervention during the experiment it would be optimal if the mechanism can be controlled from outside. We are choosing to use pumps for our purposes. The flow rate needs to be controlled well so as to not exert too much force on cells while pumping in the nutrients. The flow should be extremely slow on the microliter scale, as this flow will be administered directly onto the specimen or injected into the filament. The lab has needles for administration to the sample. It would be good if the flow could be monitored externally to ensure a similar amount of filament is pumped in as is pumped out. Additionally, we need to ensure that the petri dish is not overflowed or that the specimen is dried out.

Three Potential Options

Biotechs Micro-Perfusion Pump: This is a peristaltic pump that is able to achieve very low flow, down to 0.8 microliters per second. Instead of a stepper motor, it utilizes a dc motor regulated by a tachometer, for high precision and smoothness during operation. The dc motor eliminates typical issues with imprecision typically exhibited by peristaltic pumps. The pump is also dual channel, so it can pump in and out at the same time and has some failsafes to prevent overflow of the petri dish. This device can be operated plugged in or on an internal battery. It costs \$1,895.25.



NE-1000 One Channel Programmable Syringe Pump: This pump utilizes one syringe and can pump at rates as low as 0.73 $\mu\text{L}/\text{hr}$. By combining with a second pump, they can be operated together as one pump with dual channel configuration. This can utilize syringes between 1 and 60 mL. It can be programmed around dispensing volume or flow rate. This device costs \$815. Syringe pumps are often preferred as they are known for being more precise than peristaltic pumps.



Pump 33 DDS (Dual Drive System) Syringe Pump: This system is also dual channel. It fits a wide array of syringes, from 0.5 μ l to 60 ml. Both pumps can be ran independently, with separate flow rates, syringes, directions, etc. The device has an accuracy of 0.25%. The device can achieve a flow as low as 1.02 pl/min. This device has really good usability since it has a large color touch screen for programming. However, it can also be programmed through a computer.



Comparison Table:

Pump	Pro	Cons
------	-----	------

Biotechs Micro-Perfusion Pump	-tachymeter regulation -dual channel -programmable -can be battery powered -external speed control	-very expensive -analog interface -will need to design external interface
NE-1000	-cheapest - 0.73 $\mu\text{L}/\text{hr}$ -both volume and flow rate can be programmed	- single channel -syringes need to be replaced
Pump 33 DDS	-1.02 pl/min flow -dual channel -programmable	-syringes need to be refilled or replaced

Other Considerations:

Other Considerations to make mainly revolve around how the rest of the design needs to be adjusted for pipe routing. The sample needs to be covered, whether it is by covering just the container, or the entire mechanism including the actuator. This is to prevent contamination from dust and other cells in the incubator. However since the specimen does not need to be sealed- the cells need CO₂, we are able to create openings to allow the tubes to enter the structure. It needs to be considered where the pump will be placed. If the pump is placed inside, it needs to be able to withstand incubator conditions of heat and humidity. If placed outside, the tubes extending from the pump need to be quite long to reach the specimen inside the incubator. Additionally, the tubes need to be properly routed, ensuring no sharp bends, etc to mitigate interruptions in the flow. Additionally when planning routing, it needs to be ensured that the tubes do not interfere with the main tension and compression mechanism. Another consideration is to make sure that the pump has a user friendly interface for lab personnel to utilize without much difficulty.

References

<https://bioptechs.com/product/perfusion-pumps/>

<https://www.syringepump.com/Micro.php>

<https://www.harvardapparatus.com/pumps-liquid-handling/syringe-pumps/microfluidics/pump-3-3-dds-dual-drive-system-syringe-pump.html>

Phone Call:

Morgan (Sales with background in microbiology research in lab)

Bioptechs

Discussed the first pump option, as well as different considerations for choosing a pump such as viscosity of media.

Appendix D: Drawings

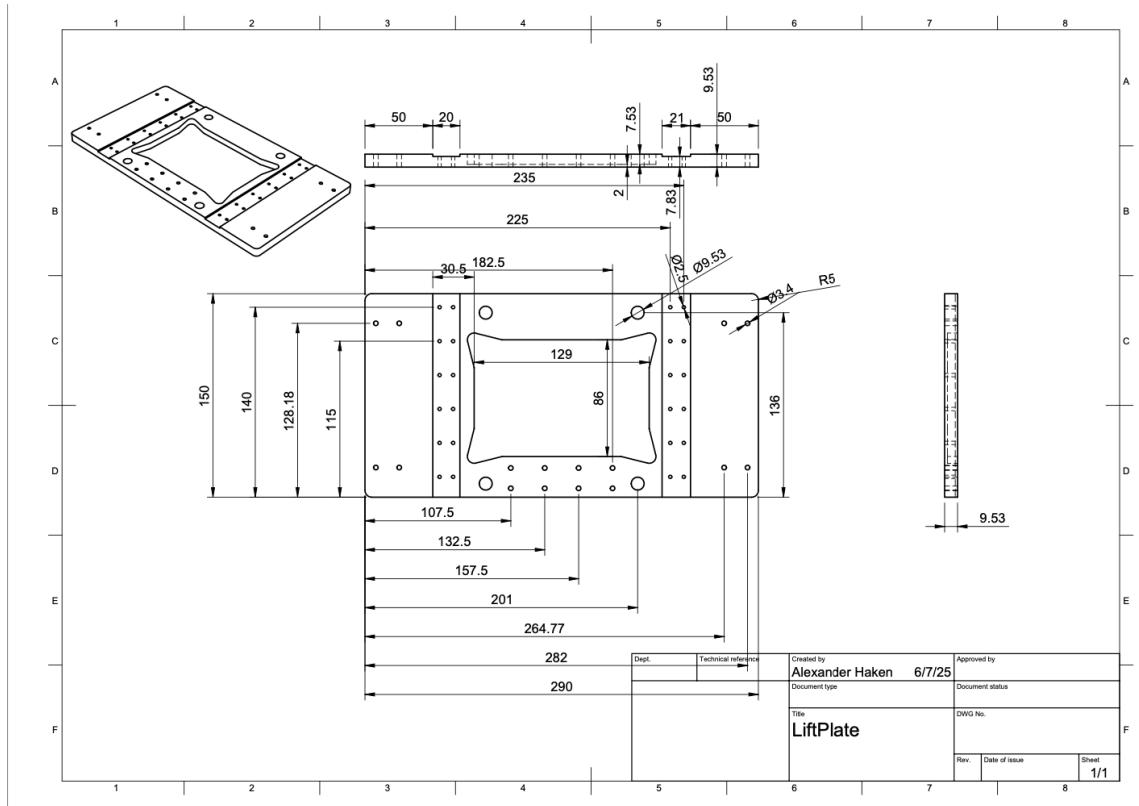


Figure AD1: Drawing of Lift Plate

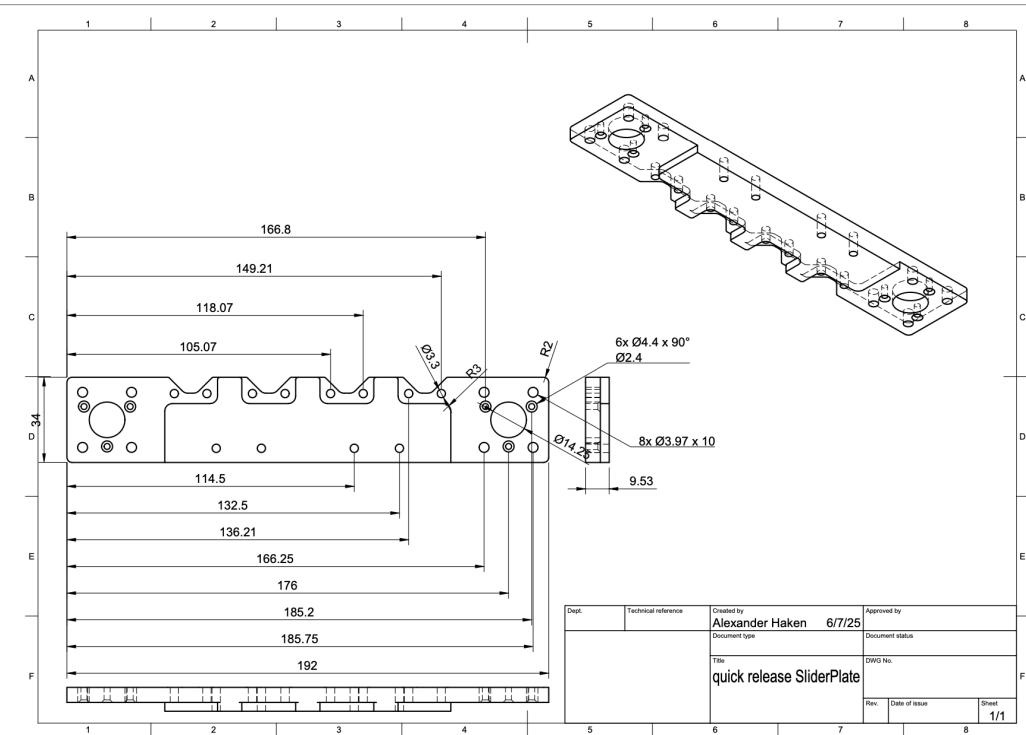


Figure AD2: Drawing of Quick Release Slider Plate

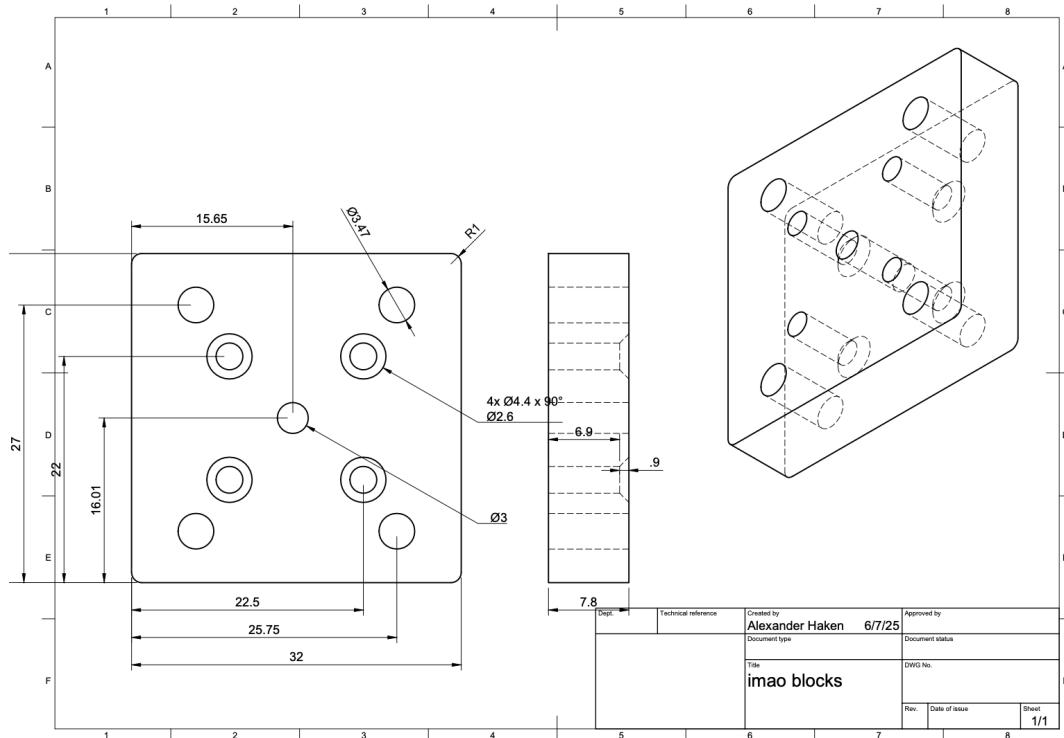


Figure AD3: Drawing of imao Blocks

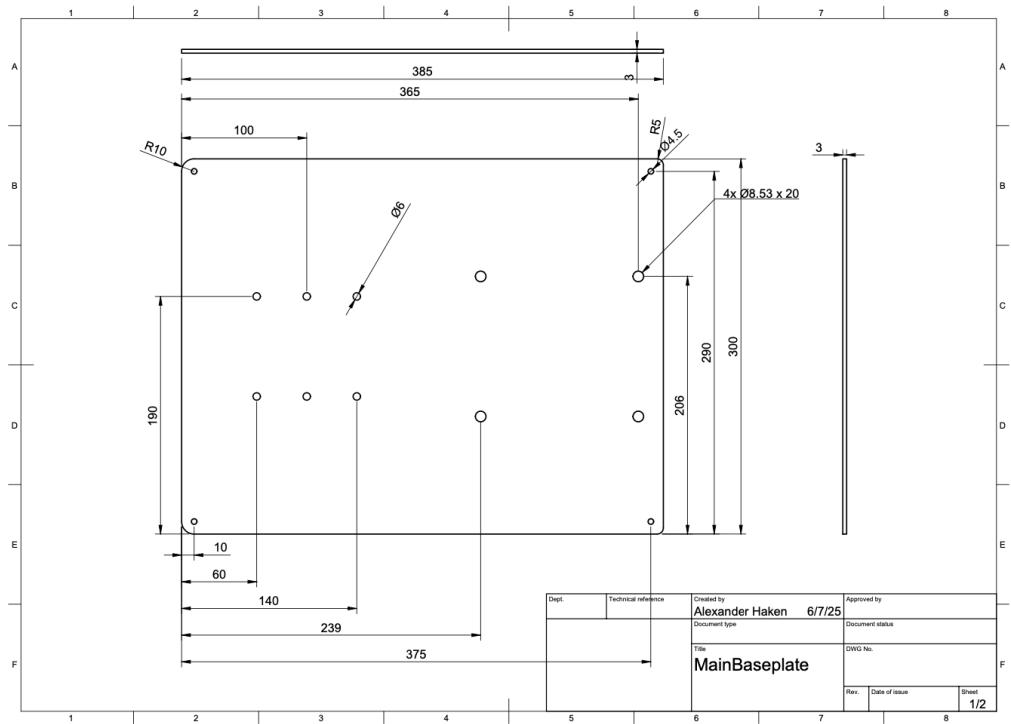


Figure AD4: Drawing of Main Base Plate

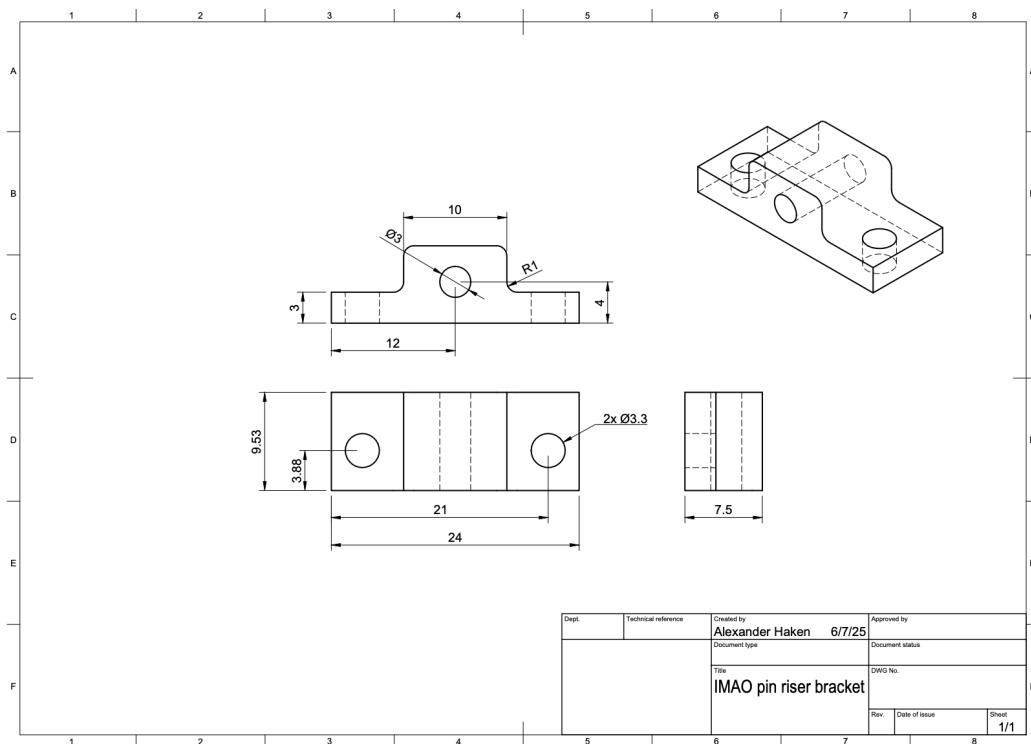


Figure AD5: Drawing for IMAO Pin Riser Bracket

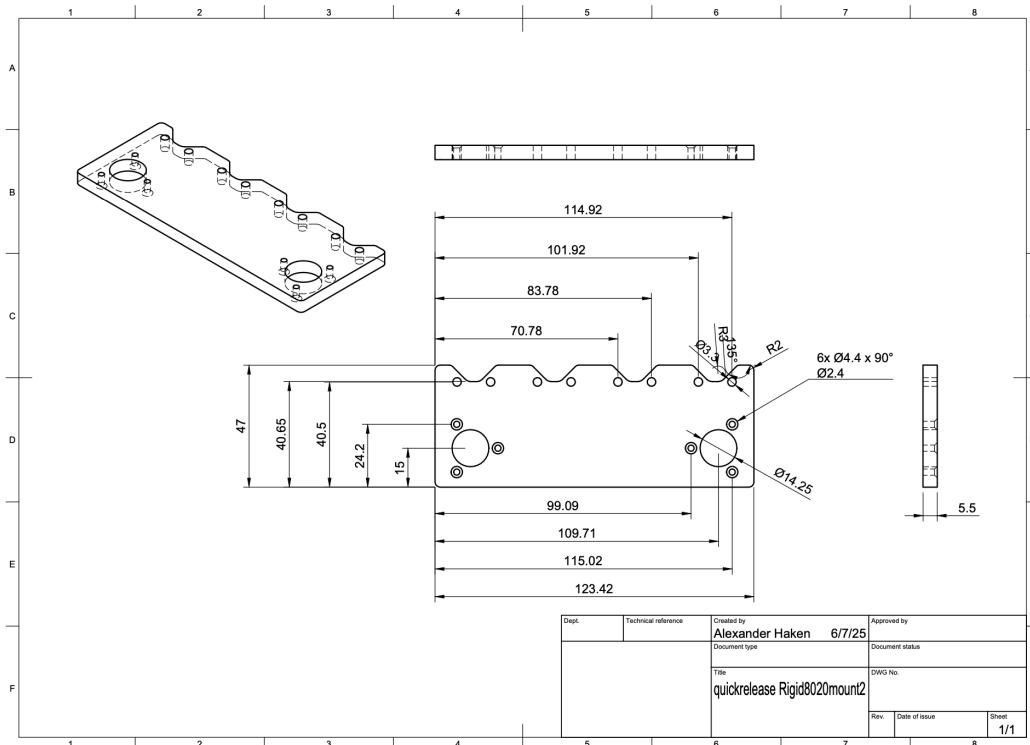


Figure AD6: Drawing for Rigid 8020 Mount

Appendix E: List of Suppliers / Purchased Part Information

ITEM DESCRIPTION: (Include Hyperlink to Webpage)	PART #:	QUANTITY:	PRICE EA:	PRICE EXTENDED
		1		\$ -
		1		\$ -
		1		\$ -
https://www.amazon.com/SparkFun-Load-Cell-Amplifier-HX711/dp/B079LVMC6X		1	\$ 10.95	\$ 10.95
		1		\$ -
		1		\$ -
ATO Load Cell 10kg https://www.ato.com/tension-and-compression-load-cell-1kg-to-200kg		1	\$ 137.98	\$ 137.98
		1		\$ -
		1		\$ -
		1		\$ -
1ft x 1ft x 0.375 https://www.onlinemetals.com/en/buy/aluminum/0-375-aluminum-plate-6061-t651/pid/1249		1	\$ 58.77	\$ 58.77
automationwerks t-slot 145 in https://www.automationwerks.com/Aluminum%20Framing/10mm-x-20mm-5mm-t-slot-extrusion-profiles		1	\$ 27.12	\$ 27.12
corrosion resistant carriage https://www.mcmaster.com/6709K275-6709K243/	6709K275	2	\$ 87.76	\$ 175.52
stainless steel rail https://www.mcmaster.com/6709K212/	6709K212	2	\$ 135.47	\$ 270.94
		0	\$ -	\$ -
		0	\$ -	\$ -
		0	\$ -	\$ -
		0	\$ -	\$ -
		0	\$ -	\$ -
		0	\$ -	\$ -
		0	\$ -	\$ -
		0	\$ -	\$ -

		0	\$ -	\$ -
		0	\$ -	\$ -
		0	\$ -	\$ -
		0	\$ -	\$ -
		0	\$ -	\$ -
		0	\$ -	\$ -
		0	\$ -	\$ -
		0	\$ -	\$ -
			Shipping	
			Sub Total	\$ 681.28
			Tax	\$ 59.61
			Total	\$ 740.89

Appendix F: Designs Considered

Prototype Performance For the risk reduction, a linear slider and actuator were prototyped, as seen in Figure AF1.

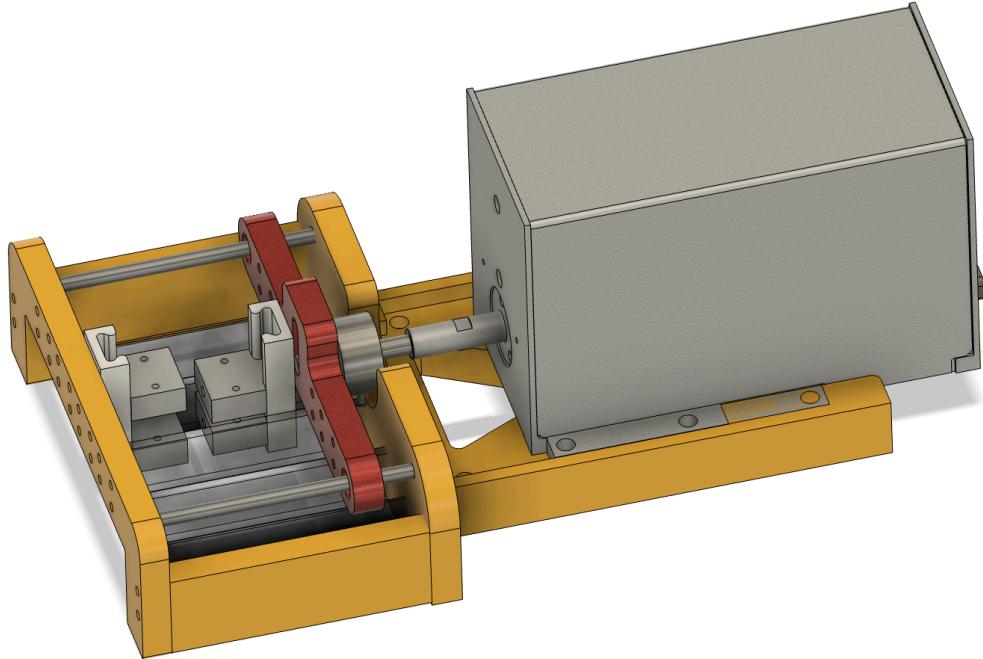


Figure AF1: Preliminary Prototype CAD model

As seen in Figure AF1, the SMAC moving coil actuator is present on the right. This is hooked up to a load cell, which is then threaded into a sliding gantry which has two press-fit linear motion bearings. The clamps (on the left) can slide up and down as is convenient.

The actuator was controlled with a LabView VI (code available at <https://github.com/arobotdinosaur/cellstretcher>), which output commands over serial to the actuator. The user could select a sample length, desired % strain, and a number of cycles, and the actuator would perform that specification. Maximum actuator velocity was scaled based off of the desired frequency for the oscillations.

Unfortunately, the slider was extremely prone to wobbling from side-to-side, likely due to the fact that there was an extremely narrow area in contact with the shaft, which combined with the substantial play in the bearings to allow for considerable wobble. Several more iterations of

the linear slider were designed. The 2nd fully assembled prototype is photographed in Figure AF2:

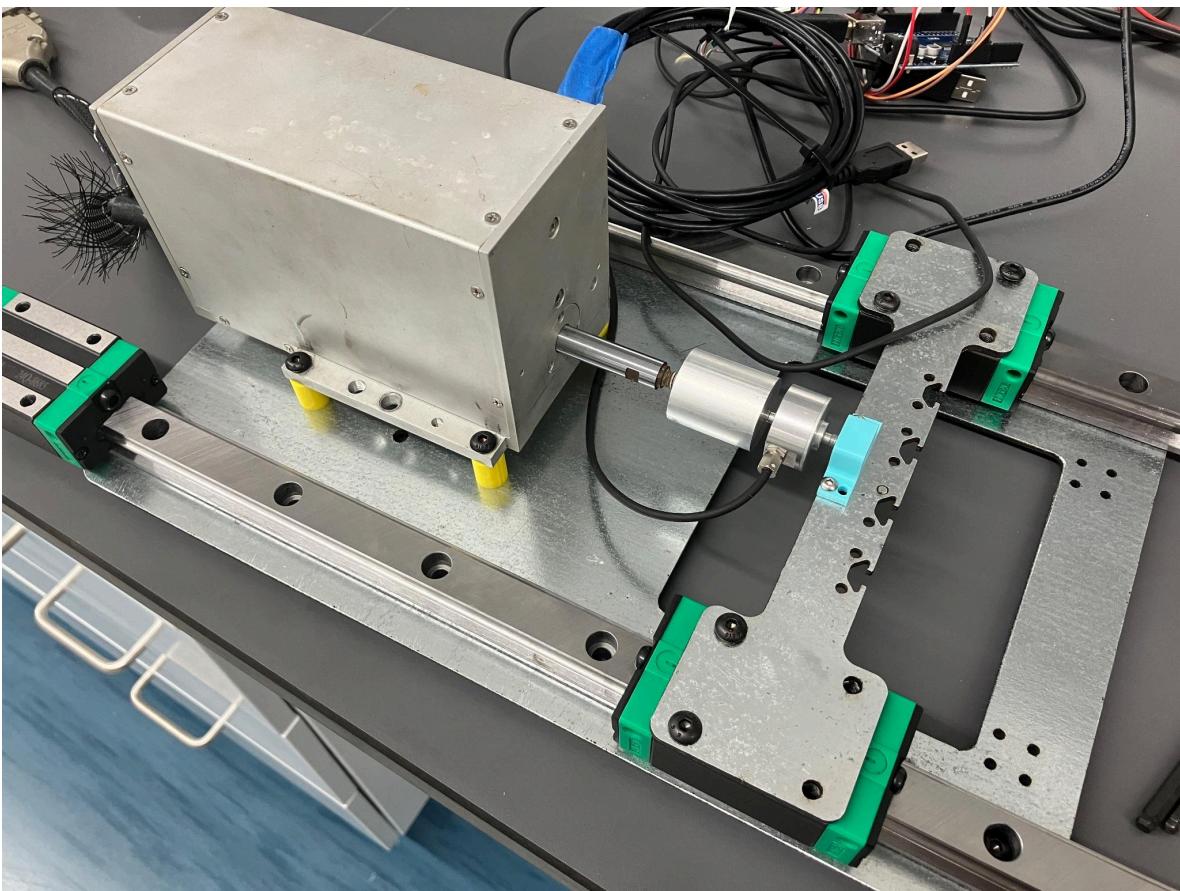


Figure AF2: Preliminary Prototype System Model

The linear guide rails on this iteration were intended for use on a small CNC machine, and had a relatively high sliding friction. They were also affordable but of questionable quality, with the recirculating balls falling out when one of them was taken on and off of the rail. An experiment with the load cell revealed values of up to 11 newtons of sliding friction. Considering forces were desired in the range of 10-40 newtons, this is a massive inaccuracy which resulted in the abandonment of the design in favor of smaller rails which would have a lower sliding friction.

Appendix G: Equations and Formulas Used

$$F_f = \mu F_{couple} \quad (G1)$$

$$\text{Strain} = \frac{\Delta L}{L_0} \quad (G2)$$

Appendix H: Budget

ITEM DESCRIPTION: (Include Hyperlink to Webpage)	PART #:	QUANTITY:	PRICE EA:	PRICE EXTENDED
		1		\$ -
		1		\$ -
		1		\$ -
https://www.amazon.com/SparkFun-Load-Cell-Amplifier-HX711/dp/B079LVMC6X		1	\$ 10.95	\$ 10.95
		1		\$ -
		1		\$ -
ATO Load Cell 10kg https://www.ato.com/tension-and-compression-load-cell-1kg-to-200kg		1	\$ 137.98	\$ 137.98
		1		\$ -
		1		\$ -
		1		\$ -
1ft x 1ft x 0.375 https://www.onlinemetals.com/en/buy/aluminum/0-375-aluminum-plate-6061-t651/pid/1249		1	\$ 58.77	\$ 58.77
automationwerks t-slot 145 in https://www.automationwerks.com/Aluminum%20Framing/10mm-x-20mm-5mm-t-slot-extrusion-profiles		1	\$ 27.12	\$ 27.12
corrosion resistant carriage https://www.mcmaster.com/6709K275-6709K243/	6709K275	2	\$ 87.76	\$ 175.52
stainless steel rail https://www.mcmaster.com/6709K212/	6709K212	2	\$ 135.47	\$ 270.94
		0	\$ -	\$ -
		0	\$ -	\$ -
		0	\$ -	\$ -
		0	\$ -	\$ -
		0	\$ -	\$ -
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		0	\$ -	\$ -
		0	\$ -	\$ -
		0	\$ -	\$ -
		0	\$ -	\$ -
			Shipping	
			Sub Total	\$ 681.28
			Tax	\$ 59.61
			Total	\$ 740.89

Appendix I: Proper Procedures

System Overview

It is imperative that the system is connected to a host PC/laptop using a RS232 connector. In order to run the system, one should download the LabVIEW interface and perform the following tasks

- Download and open the custom VI LabVIEW code (found in the code section of the website)
- Write the number of samples to be tested,
- Setting the “zero”
- Programming a desired strain, frequency, and number of cycles
- Run the program

A csv file with the load data and timestamps is saved after each run which can be downloaded for data collection and plotting purposes.

Future Purchases/Upgrades

A future upgrade to the existing system is to implement autofeeding. An autofeeding system can enable automatic feeding of the nutrient solution without any or very minimal human intervention. This could be achieved using a pump feeding solution to each channel using an automated, motorized mechanism designed to deliver a solution depending on the needs of the experiment.