MONTANA STATE UNIVERSITY

Department of Mechanical and Industrial Engineering

ETME 489R CAPSTONE: MECHANCAL ENGINEERING TECHNOLOGY DESIGN I

and

EMEC 489R CAPSTONE: MECHANICAL ENGINEERING DESIGN I

TIBIAL COMPRESSIVE OVERLOAD TESTING APPARATUS

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Prepared to Partially Fulfill the Requirements for EMEC 489/ETME489

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ABSTRACT / EXECUTIVE SUMMARY

This project originates from Dr. Blaine Christiansen's lab at UC Davis in Sacramento, California. His lab aims to study Osteoarthritis in the hopes of finding a cure for the disease. Osteoarthritis is a disease that breaks down cartilage in the joints causing painful movement. Currently, the lab at UC Davis uses mice as animal models to study Osteoarthritis. In order to have Osteoarthritis, it must be induced by ACL Rupture in the animal models and this is currently being done at UC Davis with an expensive and non-standard apparatus. The goal of this project is to replicate the Tibial Compressive Overload Testing Apparatus in a less expensive manner. Also, the design must be easy to obtain, assemble and operate so that other labs besides UC Davis can use this device if they desire.

To duplicate this device, it must meet a series of requirements provided to us by Dr. Christiansen including sterilization, force, velocity, stopping ability, data acquisition, and cost. The apparatus must at least be sterilizable with ethanol and prevent collateral injuries in the mouse by preventing the force applicator from exerting more than 14N of force or going farther than 2.25mm. Also, the apparatus must achieve a velocity of 200 mm/s to cause an ACL rupture instead of an avulsion. Then, the apparatus must very quickly stop the compression to ensure that nothing else in the leg is damaged besides the ACL. The data collected during the tests must be saved and the injury force must be displayed. Finally, the apparatus must cost less than $5,000. With the specifications in mind, a design for the apparatus that replicates the one already in Dr. Christiansen's lab was set out to be made but at a much lower cost.

TABLE OF CONTENTS

Chapter I. Introduction

The sponsor, Dr. Christiansen, requested a less expensive and easily assembled tibial compressive overload testing apparatus to replace what is currently being used at UC Davis. As learned from Dr. Christiansen, the device must be sterilizable, move quickly enough to cause ACL rupture (rather than ACL avulsion where the ACL disconnects from the bone rather than rupturing itself), be portable and user friendly, and be relatively inexpensive. In order to create a design that meets all these requirements a plan was formed to reach a design by the end of one semester. The actual device will be built and tested in a second semester.

Tasks
1. Create Problem Statement
1. Create Project Management Plan
2. Determine Specifications
3. Brainstorm Alternatives
4. Draft Project Schedule
5. Present Preliminary Design Review
6. Analyze & Revise Design
7. Present Critical Design Review
8. Order and Assemble Parts

Chapter II. Problem Statement

Statement of Need

This project aims to design and build a portable, repeatable device that will induce secondary osteoarthritis in mice through ACL rupture via tibial compressive overload.

Problem Definition

Osteoarthritis affects millions of Americans and is one of the most common reasons for a knee replacement. The implications of this disease are far reaching and impact recreation, work, and overall quality of life. Animal models are currently used to study this disease in several labs, but methodology used is highly varied and expensive. If executed successfully, this device could standardize the process for ACL rupture in animal model preparation in research labs across the country. An ideal prototype would be practical to manufacture, assemble and operate.

Level One Requirements

- Deliver a working prototype within the budget
- Prototype must:
    - Humanely produce injury
    - Accurately control the loading or displacement rate
    - Clearly record and display failure force (force at injury)
    - Terminate motion upon ACL rupture based on force time data
    - Follow sterilization protocol
    - Fit a mouse
    - Be usable by someone without engineering training
    - Be durable to reflect expected lifetime

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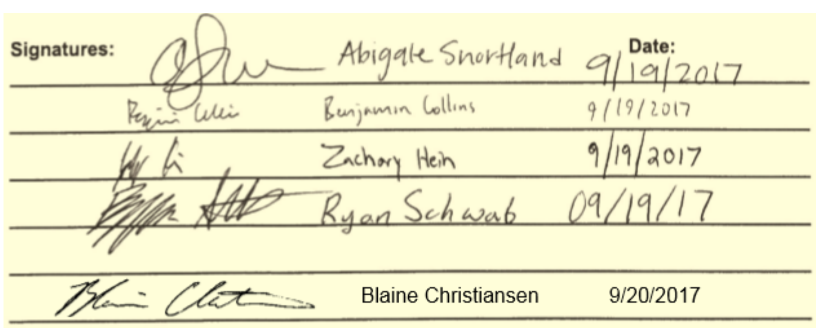

Chapter III. Background

In order to meet Dr. Christiansen's expectations, and surpass the performance of current testing apparatus, a thorough understanding of relevant background material is necessary. Subjects of concern include understanding the impact of osteoarthritis, current testing procedures, and potential safety hazards. Additionally, relevant regulations and practices, current apparatus design, and potential design elements should be addressed.

Osteoarthritis and Mice

Osteoarthritis (OA) is the degeneration of joint tissue. This condition, currently effecting 8-9% of the population in the United States,[1] leads to pain and disability and is costing the US health system over $80 billion.[2] Post-Traumatic Osteoarthritis (PTOA) is osteoarthritis induced by a traumatic injury. PTOA comprises approximately 25% of all OA in susceptible joints.[3,4] Currently, no FDA approved treatments for OA exist, yet "By 2020 OA is forecast to become the 4th leading cause of global disability."[5] Additional research is still necessary to facilitate the development of a disease-modifying OA drug as "factors contributing to the risk of PTOA … remain incompletely understood."[6]

The intensity of injury to a joint can lead to Type I, Type II, or Type III PTOA. Force exceeding the ultimate strength of a stabilizing structure (like the ACL) can lead to Type I PTOA. In this case, the structure that resists the force of the injury will tear or break, and PTOA develops likely due to the instability of the healing joint. Type I PTOA preclinical models will be produced with mice in this project.[6]

Type II and Type III PTOA are results of low level to major injury to the structural tissue in a joint. In these cases, the tissue may be heavily strained, but this does not result in a tear or failure. As seen in figure 1 (below), Type II and Type III PTOA inducing injuries can be harder to distinguish, but are both a result of overuse of the joint from either load magnitude or fatigue.

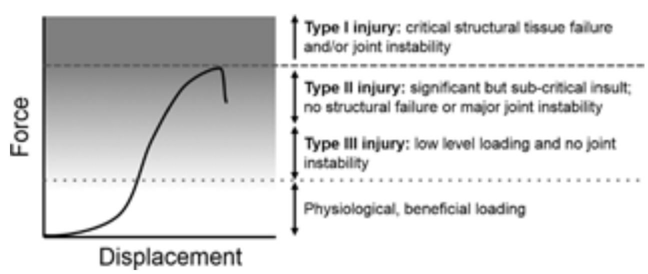

Figure 1: *"Idealized force-displacement graph of loading joint tissues to critical failure, which illustrates our proposed classification system for preclinical PTOA models. Type I models induce critical failure to a major supporting structure of the joint and/or joint instability; Type II models induce a significant but sub-critical joint injury and no joint instability; Type III models involve low-level loading and no joint instability; and Physiological loading induces an anabolic protective effect. The demarcation between Type I and other injuries is clear, being at the point of structural failure, but the boundaries between Type II and II injuries and Type III and physiological loading are less well defined and may change depending on other factors such as age, sex, injury repetition, etc."*[6]

Current understanding of OA and PTOA has come primarily from preclinical models using genetically modified mice. Additionally, no data suggests significant benefit of larger animals for preclinical models over mice.[6] Using mice for preclinical models is advantageous as there are already well tolerated and described methods for administrating anesthesia, and their small size allows for simpler controlled mechanical loading.[7] Measurements for pain and disability have become available in mice, allowing for a reliable comparison to human biopsychosocial models.[8] Finally, genetically modified mice experience rapid PTOA progression, making them ideal for PTOA research.[6]

Current Testing Procedures

Current testing procedures seek to model different mechanisms of injury, to include slow and fast injury.

Slow. Before running experiments on mice, it is important to ensure that mice are treated with National Institutes of Health guidelines. The current process involves anesthetizing mice with isoflurane and preloading tibia with a 1-2 N compressive force while the ankle is at an angle of 30 degrees. Then the tibia is compressed at a 1 (mm/s) loading rate with a Bose ElectroForce 3200 (Eden Prairie, MN, USA) until a target load of 12 N is reached. The injury is indicated by a decrease in compressive load. The average load for injury among these experiments was 10.19 N and the displacement did not exceed 2 mm. Total experiment time was about 5 minutes.

These parameters will be closely followed with capstone design to replicate injury as it has been made in the current lab. Compressive load may be applied by another means, electrical or mechanical, however. Compression rate and preloads and injury loads will also be designed to be the same within an accuracy of +/- 20%.

Fast. In an effort to induce ACL injuries closer to those that occur in humans, the Department of Orthopedic Surgery at the University of California-Davis Medical Center conducted a second study on murine mouse models[9]. This study focuses on comparing loading rate-dependent injuries in the mouse models. Previous work showed that at low speed loading rates (1 mm/s) caused ACL injury via Avulsion fracture versus high speed (500 mm/s) which induced mid-substance tears. Avulsion fractures, in this case, occur when a piece of the tibia or femur attached to the ACL breaks away[10]. However, when the injury occurs in the middle of the tendon, it is classified as a mid-substance tear. Midsubstance tears are a much more common failure mode because Avulsion fractures are uncommon in adults.

A common way to observe osteoarthritis is to look for osteophyte formation. Osteophytes are also known as bone spurs. These spurs are bone growths that typically form as people age but may also form due to a traumatic event to the knee (ACL tear) [11]. In contrast to the previous study, the mice showed significant osteophyte formation after 12 to 16 weeks post-injury in both the high and low speed modes. These joints often times showed bone contact and significant erosion of the joint and cartilage. After quantification of joint biomechanics, the two modes were found to not have long term differences in bone structure, degradation of the cartilage, or laxity (joint hypermobility). However, larger osteophyte volumes were observed in the high-speed mice. Overall, it was determined that the differences in joint degradation between the high and low speed injuries is relatively insignificant beyond 12 to 16 weeks. The results of this study successfully defend the repeatability of using single tibial compression overload to induce ACL rupture, by midsubstance tears, causing consistent osteophyte formation around the joint capsule. With this information, an ideal machine would reliably reproduce the high-speed experiments.

Potential Safety Hazards

The main safety hazards surrounding this project relate to limbs being pinched by the apparatus. However, given the small loads and displacements involved (less than 20N and 3mm respectively), these concerns are extremely minimal. Additionally, in a broader sense, the main safety concern is interaction with animal specimens. There are no plans to interact with animal specimens at this time, so concerns such as bites and disease are not applicable. Finally, safety concerns related to the manufacturing of the apparatus are to be determined at this point. Standard concerns such as cuts from tools, eye injury from flying debris, injury related to loose clothing or free hair etc could potentially apply.

Regulations and Common Practices

Animal testing, "is a privilege granted by society to the research community with the expectation that such use will provide either significant new knowledge or lead to improvement in human and/or animal well-being.[13]" This principal is enforced by several regulatory bodies and with standard practices that ensure the humane treatment, and well-being of animal specimens.

PHS. The dominant policy governing animal testing in the united states is the Animal Wellness Act (AWA)[14]. Passed by congress in 1966, and amended several times since, the act still excludes rats, mice and birds. Where mice are protected, is under the policy of the Public Health Service (PHS). The PHS enforces the Health Research Extension Act, passed in 1985 which requires publicly funded research institutions to comply with "The Guide" [15] for their treatment of all invertebrate animals. Additionally, these institutions must maintain an Institutional Animal Care and Use Committee (IACUC), and report their AAALAC (Association for Assessment and Accreditation of Laboratory Animal Care) status.

IACUC. An Institutional Animal Care and Use Committee (IACUC) is established at each public institution that performs animal testing. A committee is generally made up of at least five members, with specific requirements regarding their qualifications (one must be Doctor of Veterinary Medicine, etc)[14.] The IACUC is responsible for reviewing protocols describing animal experimentation. These protocols address why animal models are necessary, and should provide a clear procedure for experimentation. Additionally, the number of animals necessary for a study should be stated and justified, and alternatives to animal models should be described. Finally, considerations related to animal well-being, such as anesthesia, post operation observation, and means of humane euthanasia and disposal should be described. This protocol is generally reviewed annually, and testing facilities are subject to twice annual inspection by the IACUC. Institutions are required to submit a new protocol, three months prior to the triennial review.

AAALAC. The Association for Assessment and Accreditation of Laboratory Animal Care is a Non-Profit organization responsible for accrediting research institutions that comply with "The Guide" in their treatment of animals [14]. Accreditation occurs on a three year basis, and is voluntary.

Three R's. One of the main tenants of the IACUC is the three R's; replacement, refinement, and reduction. Replacement requires that every effort be made to attain data without the use of animals. This could include "absolute replacement," using substitutes such as computer simulations, to completely remove animals, or "relative replacement" by utilizing animals lower on the phylogenetic scale. Reduction refers to obtaining more data per specimen, and reducing environmental variability (to reduce amount of data required). Finally, refinement addresses the well-being of animals that must undergo testing [14]. All effort should be made to ensure that minimum pain is experienced by the animal, and that necessary pain is experienced as shortly as possible. However, refinement does acknowledge that some testing procedures may cause the specimen pain, but aims to ensure that the testing remain as humane as possible.

U.S. Government Principle for the Utilization and Care of Vertebrate Animals Used In Testing, Research, and Training. This document describes nine policies related to the humane use of animals for research. Or chief concern to this project is the principal that any operation painful to a human should be considered painful to an animal, until proven otherwise. Standard indications of pain in a rodent include rapid or labored respiration, periocular and nasal porphyrin discharge, abnormal posture, and immobility.

Sterilization. Sterilization is an important ethical and clinical practice that ensures the well-being of a specimen, and the significance of data. Aseptic technique helps prevent infection of a specimen, and also serves to protect the colony. There are many different factors that contribute to sterility. Sterility of the specimen, instruments, surgeon (if applicable) and facility are all paramount. Instruments should be sterilized appropriately using such methods as autoclaving, plasma/gas, liquid chemicals, or dry heat. It is important to note that alcohol alone is not a sterilant.

Although it is common for animals to be tested outside of their care facility, some facilities, known as barrier facilities, do not allow animals to enter and exit. These facilities go to great lengths to avoid contamination of their colonies. Although each barrier facility has its own unique sterilization protocol, most are similar. Boston college barrier facility requires that testing apparatus are sterilized in a manner approved by the animal facility manager and the consulting veterinarian. Generally, a disinfectant such as Quatricide TB is acceptable [16].

Current Apparatus Design

The apparatus currently in use at UC Davis ruptures the specimen's ACL via the tibial compressive overload method. The ankle of the specimen is held at 30 degrees of flexion by a milled aluminum cradle. This cradle is milled from a block measuring 14mm by 50mm. Below, the knee is supported by a milled aluminum cup with a radius of 9mm and height of 6mm. This cup is milled from cylinder stock of 13mm diameter. This cup is held stationary while the ankle cradle is propelled downwards by a Bose ElectroForce 3200 table top tester. This compresses the tibia until the compressive force is seen to decrease significantly, which indicates injury and causes the machine to return to the nominal displacement position.

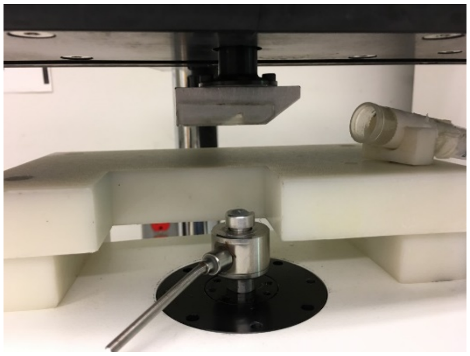

Figure 2: C*urrent apparatus, ankle cradle at top, knee cup below*

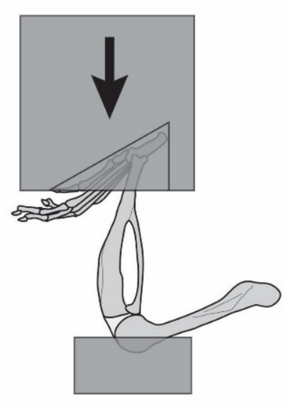

Figure 3*: Tibial compressive overload*

Table Top Tester. The Bose 3200 is capable of low force testing (up to 225N) with a response frequency of 300Hz (figure 4). The unit promises reliability to several billion cycles and is powered by "frictionless" electromagnetic motors that increase the accuracy for low load applications. Use of a High Accuracy Displacement Sensor allows resolution of 1nm and accuracy down to "a range of microns. [17]"

3220 Base System
Force Capacity
Peak/max sine : ± 225 N
Static or RMS: ± 160 N (continuous)
Frequency
0.00001 - 300 Hz
DMA max: 200 Hz
Displacement
+/- 6.5 mm
Motor Velocity
Static to 3.2 m/s
Min Ramp Rate
0.0065 micron/s
Test Space Size
Vertical = 0 - 43.1 cm
Horizontal = 35.5 cm

Figure 4: *Specifications of universal testing machine used for current procedure*

Chapter IV. Design Specifications

These specifications correlate with the level one requirements defined in Chapter II.

Prototype must:

- Cost less than $5000 to design and prototype.
- Be compliant with current IACUC protocol for study.
- Interface with the anesthesia set up.
- Have a displacement rate of 200 mm/s (+/- 10%).
- Collect sufficient data to detect and display force at injury.
- Prevent collateral injury (device must not exceed 2.25 mm tibial displacement or 14 Newtons of force).
- Be made with materials that can be sterilized when exposed to 70% Ethanol solution. Preferred sterilization, if possible, would be by an Autoclave (Heat resistant to 150C, 70psi).
    - 70% Ethanol solution indicated by the *Guideline for Disinfection and Sterilization in Healthcare Facilities* by the Centers for Disease Control and Prevention.
    - Autoclaves operate at 121C and 15 psi, according to several sources, including Princeton University.
- Be able to fit through a standard door and must weigh less than 50 lbs to meet National Institute for Occupational Safety and Health standards for what one person can lift.
- Fit a C57BL/6 mouse.
    - This is the species of mouse utilized in current studies.
- Include documentation for build and use, as well as downloadable files for any required code.
- Last 10,000 cycles with minimal user maintenance or component replacement.

Chapter V. Design Alternatives

Evalutation Matrix

	Cost	Ease of Use/Assembly	Performance	Durability/ Reliability	Portability	Sterilization	Zest	Total
Data Acquisition								
Strain Gauge Load Cell	5	4	3	4	3	1	8	**28**
Piezo Electric Load Cell	2	3	3	5	5	5	8	**31**
Hydraulic Load Cell	2	3	1	4	3	4	3	**20**
Linear Potentiometer	4	5	4	4	3	4	7	**31**
Laser Triangulation/Optical Displacement	2	4	5	3	3	2	10	**29**
Laser Counter	4	3	3	3	5	2	8	**28**
PreLoad Application								
Pneumatics "Barber Chair"	2	3	4	2		5	5	**21**
Lever	5	4	2	3		4	3	**21**
Mechanical Screw	5	5	4	5		5	3	**27**
Electromechanical Screw	2	3	5	5		3	4	**22**
Spring	5	3	2	3		4	3	**20**
Stopping								
Brake based off of final force	3	3	3	3			3	**15**
Brake based off of injury force (Feedback)	2	1	5	3			5	**16**
Displacement Stop (@2.25mm)	5	5	3	5			3	**21**
Manufacturing								
Milling/Turning	2	3	5	5	4	5	2	**26**
3D printing Plastic	3	3	4	3	5	2	5	**25**
3D printing Metals	3	3	4	4	4	3	5	**26**
Wood	5	2	2	2	5	1	1	**18**
Purchasing standard parts	4	4	5	5	5	3	3	**29**
Frame								
80/20 T-slotted aluminum framing system	3	4	5	5	5		5	**27**
Unibody frame with modular components	1	5	4	3	4		5	**22**
Pyramid	5	4	4	5	4		4	**26**
Stabilization								
Clamp to table	5	5	3	2	5		3	**23**
Critically damped base	2	3	5	3	4		5	**22**
Weight the base	4	5	5	4	2		4	**24**
Force Application								
Springs (and Dampers)	5	5	4	5	5	5	3	**32**
Mechanical Advantage (Lever or Screw)	5	3	3	5	4	5	2	**27**
Motor/Pulleys and Gear box	2	2	4	4	5	3	4	**24**
Pneumatics (with CO2)	2	4	3	5	4	5	5	**28**
Divine Intervention	5	5	5	0	5	5	5	**30**
Voice Coil Actuator	3	3	4	3	4	4	5	**26**
User Interface								
Raspberry Pi	4	1	4	5	5		4	**23**
Arduino	4	2	4	5	5		4	**24**
Microsoft Excel	5	5	3	3	3		1	**20**
MATLAB	1	4	3	3	3		2	**16**

Figure 5: *alternatives table from first iteration of design process, several design changes have occurred since*

Data Acquisition

Strain Gauge Load Cell. A strain gauge load cell utilizes Hooke's law to determine the applied force. By mounting strain gauges on a material with an accurately tabulated E value, such as aluminum, force can be derived after considering surface area. Generally, a Wheatstone bridge, or other means of signal amplification is utilized. This device is capable of 0.05% repeatability, and is fairly reliable given its simple design and no mechanical components. However, many cannot operate above 60 degrees Celsius and therefore would be impossible to autoclave. Load cells suitable for this application can be purchased for as little as $7.00.

Piezo Electric Load Cell. A piezo electric load cell utilizes the amount of voltage produced by a piezo electric cell to determine force applied. The device is very durable and can operate in temperatures up to 121 degrees Celsius. This would potentially allow for sterilization via autoclave. However, the nonlinearity of this device is 0.25% of FSO and would potentially be more difficult to calibrate. A high degree of accuracy and precision is possible (0.1% FSO). A typical piezo electric load cell that is suitable to this application should cost about $550.00.

Hydraulic Load Cell. A hydraulic load cell utilizes a hydraulic chamber to apply. pressure to a pressure sensitive transducer. This device is generally more applicable for high force applications. Additionally, hydraulic loads cells are generally more expensive. The repeatability of a hydraulic load cell is +/- 0.25% FSO.

Linear Potentiometer. A linear potentiometer modifies resistance with respect to displacement. Resolution is theoretically infinite, and many can withstand more than 500,000 cycles operating at temperatures up to 95 degrees Celsius. Additionally, many different displacement ranges are available, and an accuracy of +/- 0.01mm can be obtained with a maximum rate of displacement of 5 m/s. A device suitable for this application can be purchased for approximately $150.

Laser Triangulation/Optical Displacement. Laser triangulation utilizes trigonometry to determine the distance between the instrument and a surface. Laser triangulation can be an extremely accurate method and is non-contact, so there is no limit to how many cycles an instrument can withstand. However, these instruments are generally expensive, and can only withstand temperatures up to about 70 degrees Celsius. Additionally, the laser housing is generally somewhat large compared to other alternatives.

Laser Tachometer. A laser tachometer describes an interface between a laser, and a rotating object. We could relate this rotating object to the linear motion of the testing apparatus with a known gear ratio. The rotating object has several evenly spaced discontinuities that allow the laser beam to shine through.

Hall Effect Sensor. A hall effect sensor varies its analog voltage output based on the position of a magnetic field relative to it. This characteristic allows for displacement to be measured very accurately, and with no contact.

Preload Application

Pneumatics "Barber Chair". Similar to how barber chairs or office chairs work, this design would utilize simple pneumatic mechanisms to adjust the height of the mouse. CO2 canisters, which are regularly available in lab environments, could be used with a regulator as a replacement for an air compressor. This will allow for the fitting of different sized mice and would be a reliable way to apply a preload force.

Lever. A lever could have a predetermined displacement where it could be locked with a pin to apply the preload. It would be less tunable to different sized mice than the "barber chair". This could create some issues with preload accuracy (figure 6).

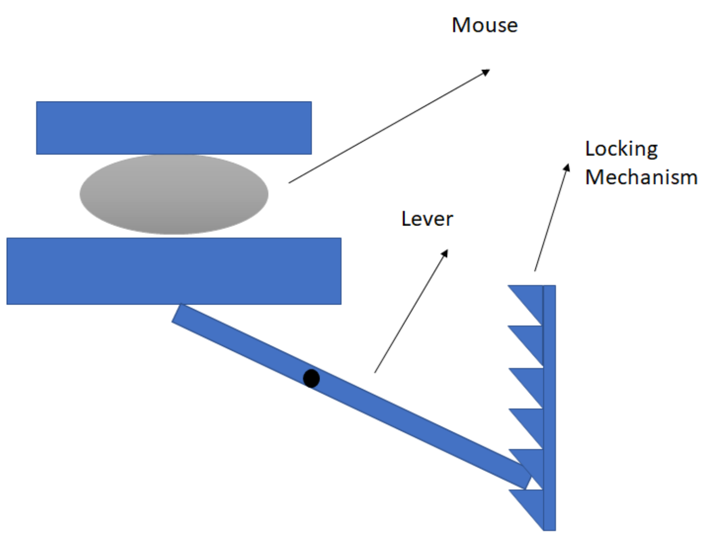

Figure 6: *Lever preload application method*

Screw. Similar to the "barber chair" idea, a mechanical screw could be used to raise and lower the mouse to position it into the optimal position and allow for an adjustable force application that could when utilized with a load cell to be very accurate (figure 7).

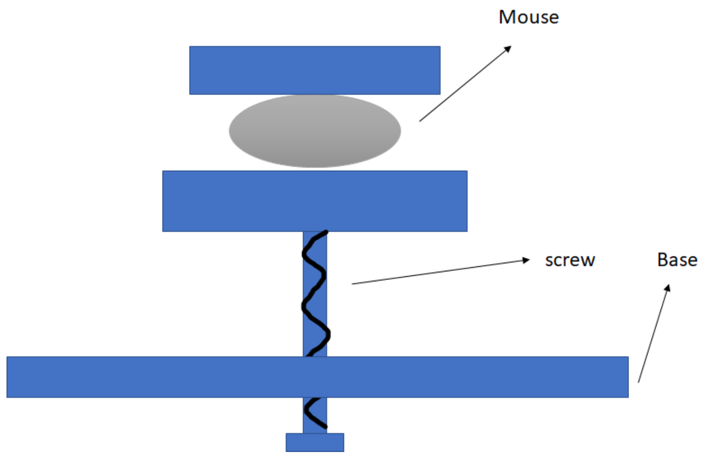

Figure 7: *Screw preload application method*

Electromechanical. Since speed is not a concern when applying the preload, and electromechanical option such as a motor could be very fitting. One concern with this option may be durability due to the impact from the force application to tear the ACL later. The force required (11N on average) is very low, however, and may not be too much of a problem.

Spring. A spring could be compressed to apply the preload force. This method, similar to the lever, may be less accurate than the other methods because it could need to have fixed locking points in place. This would limit the adjustability for differently sized mice.

Stopping

Brake based off of final force. This method would be based on stopping once a target force is reached. The procedure currently used has targets loads between 12 and 14 N that can be adjusted. For this method, a target load would be set, and once reached the system would be stopped using a method appropriate for the force application apparatus.

Brake based off of injury force (Feedback). A feedback loop would be utilized to monitor when injury occurs based on force time data. Injury occurs when the force drops significantly. Once this drop is detected the system would be stopped using and appropriate method based on the force application apparatus. The main benefit of this alternative is that the system would stop closer to injury than the other options. A downside to this system is that it depends on being able to accurately detect a drop in force.

Mechanical Stop (@2.25mm). This alternative involves placing a hard stop at a defined displacement to insure no further injury to the mouse (figures 8 and 9). This method would be very reliable and would involve few to no moving parts and would be purely mechanical (no data processing or electronic elements required). A softer, easily replaceable piece could be placed on top of the stop to help dampen the impact on the elements of the system.

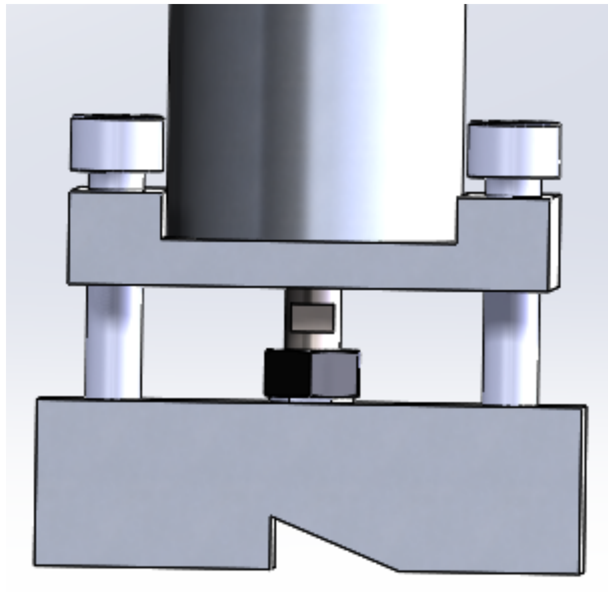

Figure 8: *Mechanical stop side profile*

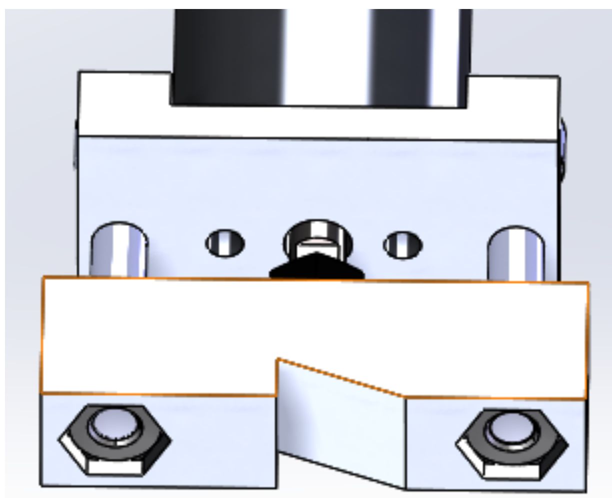

Figure 9: *Mechanical stop bottom profile*

Manufacturing

Milling/Turning. These basic machining process are likely all that would be needed to create parts for this system. Many universities have shops with this ability and if lab doesn't have access shops typically can be easily found anywhere across the US. Depending on the geometry and volume of a part, machining could be more expensive than the 3D printing options mentioned below. Utilizing these processes is beneficial because surface finishes can be much higher than 3D printing which would allow the part to be "clean" and "sterile". Another advantage is the wide range of materials that could be chosen from include 316 L SS which is surgical steel.

3D printing Plastic. 3D printing would allow for unique part geometries that would be otherwise difficult to achieve through traditional milling and turning processes. Utilizing 3D printing also provides the possibility for parts to be downloaded and printed in lab. Countless websites also exist to which parts could be uploaded, printed and then shipped. Printing with plastics would keep costs down but also provides challenges with sterilization. Most options could be sterilized using ethanol but the majority would not stand up to autoclaving. Ultem9085[18], however, has a high enough heat of deflection that it could be used. Unfortunately, it is significantly more expensive. Another downfall for anything 3D printed (in plastic or metal) is that porosity will exist where small particles may get stuck. This means that while a part may be "sterile" it may not be "clean".

3D Printing Metals. Printing with metals has many of the same benefits as printing with plastic but would have higher max operating temperatures which would make them generally better options for autoclaving. However, to print with metals very specific printers are required which would likely eliminate the benefit of being able to print parts in individual labs. Many online companies do have the ability to print with these materials at low costs and relatively quick turnaround times. The online supplier Shapeways boasts 12 business days.
Steel Material Information.

Wood. Wood is a very accessible cheap and lightweight material. However, this may not be a great option for areas where sterilization is key. Wood could however, be a good alternative for the frame. It can be easily processed with inexpensive equipment. A downfall, however, is that wood can warp and may require more maintenance than other options

Purchasing Standard Parts. In an ideal world, this system would be constructed solely using commercially available parts. This would aid in reproducing the system in the future in labs across the country. Another benefit of using standard parts is that many have been proven to be reliable in industry. Choosing proven components would increase the lifetime of this system. Unfortunately, some parts in this system (such as the applicators) will likely need to be custom made due to the specificity to this system.

Frame

80/20® T-Slotted Aluminum Framing System. Described as a "erector set for engineers". This slotted aluminum system would make for easy assembly in many different geometries. This material is stiff and strong which would ensure minimum frame deflection during testing (figure 10). A significant advantage to this system is that no welding or additional machining would be required. It would also be easy to take apart for sterilization and to make adjustments to the system. There is an immense variety of parts commercially available and 80/20® inc. offers assembly services.

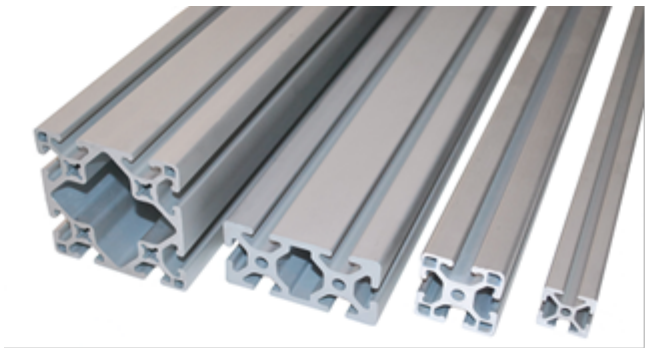

Figure 10: *80/20® T-slot aluminum framing*

Unibody Frame with Modular Components. Creating a frame that was all one piece would greatly simplify the assembly/maintenance process for the end user/lab. All the components could clip into place. This frame could be made using several manufacturing techniques including 3D printing and casting. This geometry could be more expensive to manufacture.

Pyramid. This alternative would take advantage of the structural stability of pyramids. This shape could save material and space while maintaining the structural integrity of the system. The force application method would attach to the top of the pyramid (figure 11).

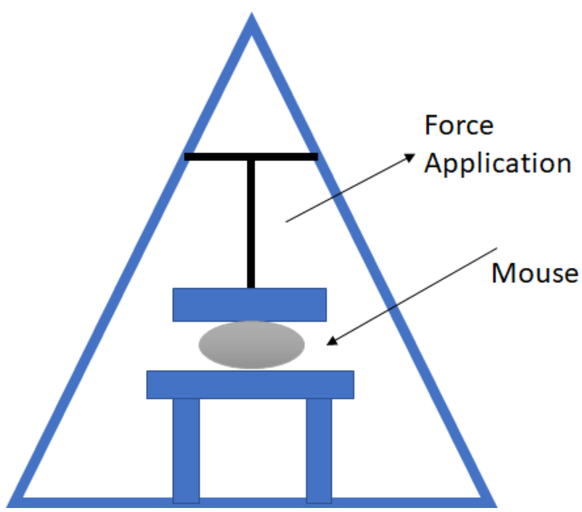

Figure 11: *Pyramid frame concept*

Stabilization

Clamp to table. Because the displacement in the mouse's knee needs to be carefully monitored it is important that the assembly doesn't move relative to the table it sits on when the force is applied and released. One way to accomplish this would be to simply clamp the system to the table it sits on. This however would put constraints on where the system sits on a table and there may be better options.

Critically Damped Base. By critically damping the base, vibrations will die out quicker than another system. This would be a very reliable system but may be more complicated to design than other options. It may also limit portability if more moving parts are required.

Weight the Base. If the base was weighted enough, motion from the force application would cause only negligible movement. This would be a very simple option that would require no maintenance or upkeep. A downfall of this option would be that it would add weight to the system which could lower the portability.

Force Application

Springs (and Dampers). Springs with known spring constants could be manually pressed into a compressed position with the known displacement resulting in a known amount of stored energy. The spring could then be released, exerting a known load rate onto the mouse with a damper controlling the displacement rate.

Mechanical Advantage (Lever or Screw). A lever or screw could be used to magnify a smaller force applicator onto the mouse tibia. With predetermined geometry a small displacement rate could be converted into the desired displacement rate of 500 mm/s with a lever. However, special considerations would be required to ensure that the lever applies force in a single axial direction and that it is not applying force in a circular path. Also, a screw could be employed to move plates together similar to a vice to provide the force on the knee.

Motor/Pulleys and Gear box. An electric motor could be amplified through a gear box and/or pulleys to produce high rotational speeds in order to quickly move components that compress the tibia. Gearing would require much consideration for gear sizes and friction but would be reliable in generating known output velocities with known input velocities.

Pneumatics (with CO2). Using compressed CO_2 to move pistons would be a quick way to induce force onto the mouse tibia. The displacement rate can also be controlled using PID controls that the group has already had experience with in the EMEC 361 lab. CO_2 is also easily accessible and can come in small cartridges or could be used from a large tank with a pressure regulator.

Voice Coil Actuator. A voice coil actuator utilizes a magnetic field to propel a permanent magnet in a controlled manner. The magnetic field is induced by running current through wire coils surrounding the permanent magnet. Voice coil actuators are best used in applications requiring rapid acceleration over a short displacement.

User Interface

Raspberry Pi. A Raspberry Pi microcomputer has a powerful processor relative to its small size, and can be purchased for a low price (under $100). Depending on the model of the Raspberry Pi, it offers the most versatility when considering displays, analog user interface devices, and software and operating systems. Operating in Windows 10, the Raspberry Pi is capable of running Microsoft Excel, or other third-party software that does not demand excessive processing power or RAM/SSD storage. The Rasberry Pi would be more difficult to program, and future software updates to the Pi and operating system could require updates to the code for the ACLR device.

Arduino. An Arduino is a low-cost microcontroller that utilizes open source software. The controller is ideal in repeatable applications that involve sensors mechatronic components. Arduinos are widely used in DIY projects and many downloadable libraries have been created to allow for ease of use with most sensors and devices. The Arduino MEGA should offer the clock-cycles needed for feedback control within the expected 4ms completion time to ACL rupture. Most display devices are easy to configure with Arduinos, but other user interface devices intended to alter the installed code would be difficult to use effectively.

Microsoft Excel. Excel or similar programs that open .xlsx files can be used on any computer. This allows for simple usage of data, and most researchers will be comfortable with interpreting data in these programs. Excel alone does not handle external devices as well, so another program would be needed to structure data from the device into a readable .xlsx file. This could be completed with a microcontroller, a microcomputer, or with software on a computer or laptop. The low cost and general populous' understanding of Excel make it a practical software for data interpretation.

MATLAB. MATLAB is a powerful software intended for mathematical modeling and data interpretation. MATLAB also has a number of libraries written to make interaction with external devices possible. MATLAB's high price makes it less feasible than other data specific software.

Chapter VI. Description of Project/Design

The final design uses a frame made of 80/20® 40x40 mm aluminum tubing and 90-degree corners 40-4302 fasteners to hold everything together and support the mouse, force applicator and electronics. The frame consists of 5x25cm pieces of tubing and 2x40cm pieces of tubing. See E. for engineering drawings of the frame. The frame was analyzed with both classical mechanical analysis (A.) and FEA in solid works (A.). The results give a safety factor with respect to deflection of 4.06 based off of a maximum allowable deflection of .035 mm. This maximum was set based off of five percent of the lowest injury displacement from previous data of .7 mm. The lowest factor of safety with respect to yielding in the frame was found to be 63.86. The fasteners were also analyzed based off of 80/20® fastener application tests (A.) and were found to be more than strong enough for this application. Since this system needs to last at least 10,000 cycles with minimum maintenance, fatigue in the frame was considered (A.). Based off of a minimum fatigue strength of 55 MPa and a maximum stress in the system of 3.774 MPa, the frame is expected to require no maintenance throughout and beyond the 10,000 cycles.

Next, there are three pieces that will actually come into contact with the mouse which are called the mouse platform (E.), the knee holster (E.) and the ankle holster (E.). Each of these parts will be 3-D printed. The mouse platform was designed based off of a roll in bracket from 80/20® so that the platform will hold itself in place without any additional fastening. Also, it can be easily removed from the frame without disassembly of the rest of the frame. An FEA analysis of this platform was performed to ensure that the piece does not yield and is stiff enough that it does not significantly deflect from the weight of the mouse (A.). This analysis gives a safety factor with respect to yield of 244.27 and a maximum deflection of 0.1448 mm, however this deflection is at the end of the platform and is not related to how far the knee will displace because it is supported by the load cell, not the platform. The knee holster and ankle holsters are based off of the design already in use in Dr. Christiansen's lab. The ankle holster will be attached to the end of the force applicator and the knee holster will be attached to the end of a strain gauge load cell. The strain gauge load cell will be attached to the bottom piece of the frame and will be purchased online and is said by the manufacturer (Uxcell) to withhold the loads (14 N maximum under the mouse knee) expected on it while maintaining an adequate level of accuracy.

The force applicator is a Voice Coil Actuator (VCA) from BEI Kimco. Originally, a pneumatic piston or a spring and damper was evaluated by the group to be the best force application methods. However, after suggestions from the Preliminary Design Review and further research a Voice Coil Actuator was determined to be more suitable to this application. The voice coil chosen is the LAS13-56 from BEI Kimco and the basis for this decsion can be found in (A.). The VCA has a stroke length of 12mm and will be able to reach the 200mm/s in the injury distance of 0.7mm. Another advantage of the voice coil actuator, is that the chosen model is sold with an embedded hall effect sensor for measuring displacement. This VCA will have a hard stop comprised of two socket head screws going into the ankle holster that can be adjusted to make sure that the VCA cannot push the ankle holster farther than 2.25mm. The VCA will be held onto the frame with a 3-D printed sleeve that is attached to the frame with a thumb screw. This way the sleeve, with the VCA on it, can manually be moved up and down the frame to apply the preload. The connection point will be the weak point of the collar. This connection will be the same as used in the rest of the frame and will be more than strong enough to with stand the load from the voice coil (see A. for frame connection analysis) Finally, the electronics to control the VCA and record the data will be placed onto one of the frame legs. The electronics will include a microcontroller, a motion controller and a power supply. These components and protective housing will be finalized in the future.

Chapter VII. Conclusions

After choosing design components the prototype apparatus will cost $2,868.61. The testing apparatus force applicator will move at a speed of 200mm/s and can apply up to 98N which is more than enough force required to rupture the ACL. The frame, platform and load cell have all been evaluated to ensure that the force exerted during the test will not cause enough displacement to affect the displacement being induced onto the mouse leg. The apparatus will weigh 13.19 pounds (with an unweighted base) which is well within the range of being easily lifted. The prototype also has a maximum dimension of 40cm which can easily fit through a door frame. Therefore, the current design is within the budget, portable and meets the desired specifications.

In the future, the prototype will be assembled once the parts arrive and the code for the electronics will be written. Then, testing can begin to ensure that the apparatus reaches the desired speed and force while not deforming and that it stops quickly and in response to a drop in force. Further work is also required in finalizing the choices for the microcontroller, motion controller and power supply. A protective case and mounting scheme will also be designed once these decisions have been made. Currently, the design is satisfactory and appears to meet all the specifications while avoiding potential problems that were foreseen by the group.

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APPENDIX A. Engineering Analysis

Material Properties

Table A.1: *Table of all the material properties for components analyzed. An important note is that the Nylon PA 12 will not be autoclavable (heat of deflection below the 121 C for autoclave). This means all 3D printed parts will need to be sterilized with ethanol. Labs will have the option to 3D print in stainless steel which will be autoclavable but costs significantly more. 3D printing with metal creates a part with porosity meaning they would have to be autoclaved and could not be sterilized using only ethanol.*

Material	Density (kg/m^3)	Yield Strength (MPa)	Modulus of Elasticity (MPa)	Melting/Max Operating Temperature (°C)
Aluminum (6105-T5)	2690	241.1	70,326.5	600
Nylon PA 12	1010	48 MPa	1700 MPa	197 (heat of deflection 95)

Frame Analysis

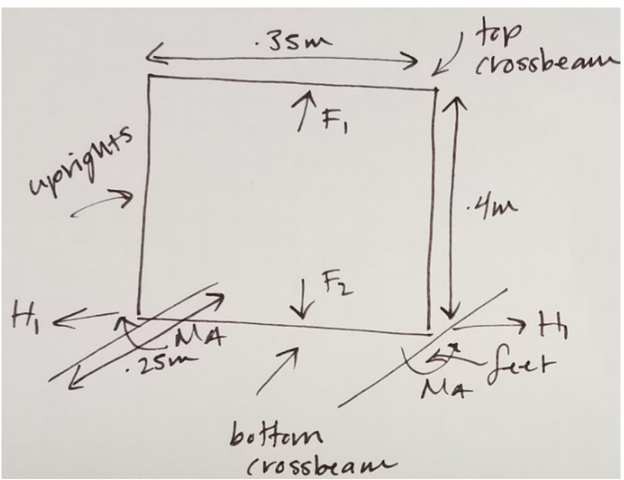


Figure A.1: *Schematic of simplified frame analyzed*

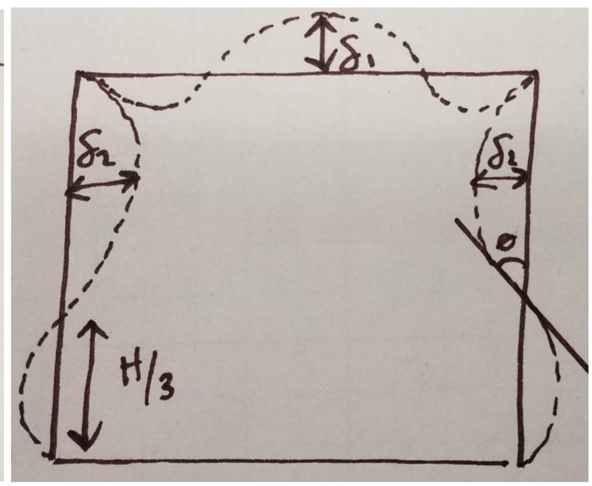


Figure A.2: *Schematic of deflection profile in frame*

Assumptions

- The feet weigh enough to act as fixed connections
- The cross-section is simplified as a solid square for any torsion analysis
- The frame acts as a portal frame
- The weight of the frame is ignored
- Deflection of the uprights was simplified as four similar right triangles as shown below in figure A.3

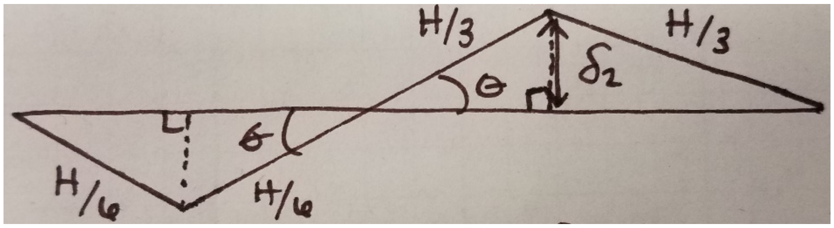
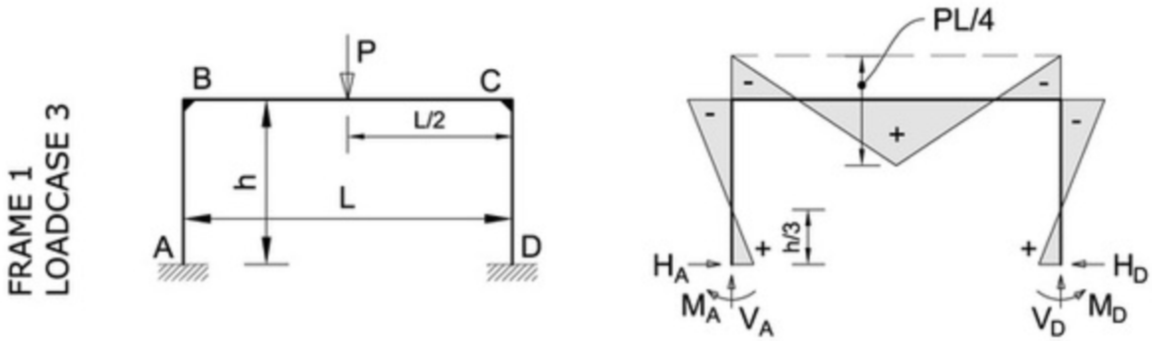


Figure A.3: *Approximated deflection profile for the uprights. The angle theta corresponds to Theta present in figure A.2.*

```
clear; clc
F1=100; %force from the voice coil N
F2=F1; %force felt by lower cross beam N (worst case scenario)
F3=(F1+F2)/2; %force felt by the feet crossbeams N
dallow=.05*.7; %maximum allowable displacement in any structural members mm
% based on 5 percent of the smallest displacement necissary for injury
```



$$M_A = M_D = \frac{PL}{8N_1}$$
$$M_B = M_C = -2M_A$$
$$V_A = V_D = \frac{P}{2}$$
$$H_A = H_D = \frac{3M_A}{h}$$

Figure A.4: *Portal frame analysis*[1]

Statically Indeterminate Rectangular frames

```
%assume fixed fixed at base (can't rotate or translate)
L=.25; %length of horizontal members m
H=.4; %height of vertical members m
ee1=H/L;
a=L/2; %location of applicator force
k=H/L;
N1=k+2;
N2=6*k+1;

%vertical reactions N
Ra1=F1/2;
Rb1=Ra1;
Ra2=F2/2;
Rb2=Ra2;

%Moments N-m
Mendsbot=F1*L/(8*N1); %moments at the base of the uprights MA,MD in figure A.4
Mendstop=2*Mendsbot; %moments at the ends of the top crossbeam MB,MC in figure A.4
Mcentertop=F1*L/4-Mendstop; %N-m from figure A.4
Mmaxtop=max(Mendstop,Mcentertop);
X=linspace(0,L/2);
Mmaxbot=max(Mendsbot+F2*X.^2/(2*L)); %max moment in bottom crossbeam
Mmaxfeet=Mendsbot/2; %max moment in the 'feet' causes a torque
```

```
%causes a torque in the 'feet' members

%Horizontal reactions N HA in figure A.4
Ha1=3*Mendsbot/H;
Hb1=Ha1;
Ha2=0; %pinned pinned with symetric point load so no additional...
%horrizontal reactions from bottom beam
Hb2=Ha2;
```

Analysis of Top Crossbeam

```
%Shear Diagram
X1=linspace(0,L/2);
X2=linspace(L/2,L);
figure(1); clf(1)
subplot(2,1,1)
plot(X1,F1/2*ones(length(X1)))
hold on
plot(X2,-F1/2*ones(length(X2)))
title('Shear Diagram for Top Crossbeam')
xlabel('x (m)')
ylabel('v (N)')
axis([0 0.35 -55 55])
hold off

%Moment Diagram
subplot(2,1,2)
plot(X1,-Mendstop+F1/2*X1)
hold on
plot(X2,-Mendstop+F1/2*L/2-F1/2*(X2-L/2))
title('Moment Diagram for Top Crossbeam')
xlabel('x (m)')
ylabel('M (N-m)')
hold off

%Stresses
%80/20 tubing https://8020.net/shop/40-4040.html
%#product_tabs_description_tabbed
h=40/1000; %height of cross-section of 40-4040 80/20 tubing m
I=13.770/100^4; %moment of inertia of 80/20 tubing m^4 from spec sheet
AC=8.742/100^2; %cross-sectional area of 80/20 tubing m^2 from spec sheet
E=70326.5; %Young's Modulus MPa from spec sheet
Sigyield=241.1; %yield stress of 80/20 tubing MPa from spec sheet
Q=69320.87/(1000^4); %from cad drawing m^4

Sigbend1=Mmaxtop*(h/2)/I*10^-6; %max bend stress in the top crossbeam MPa
Sigaxial1=Ha1/AC*10^-6; %axial stress in the top crossbeam MPa (tensile)
Sigshear1=((F1/2)*Q)/(I*h)*10^-6; %bending shear stress in top crossbeam MPa
Sigx1=Sigbend1+Sigaxial1; %stress on outside of the beam (no shear)
Sigyx1=Sigshear1;
Sigvon1=sqrt(1/2*(2*Sigx1^2)+3*Sigyx1^2); %vonmises stress criterion for
%center of bottom beam 'y=0' where there is both max shear stress and axial
%stress from the axial force
```

```
max(Sigx1,Sigvon1)
SF1=Sigyield/max(Sigx1,Sigvon1)

%Deflection²
%http://structsource.com/analysis/types/beam.html
L1=L-2*(3*L/(4*N1)); %length between "hinges" in the top crossbeam m
%the "hinges" are locations of zero moments in the beam
b1=L1/2; %force acts at the midpoint of the beam
a1=b1;
x1=L1/2; %max deflection will occur and the midpoint of the beam
del1=-((F1/2)/(6*E*10^6*I)*(b1*x1^3/L1-a1*b1*x1/L1*(2*L1-a1))*10^3) %mm
```

```
Max stress in top crossbeam MPa
ans =

    0.6631

Safety factor with respect to yielding in top crossbeam
SF1 =

  363.6170

Max vertical deflection in top crossbeam mm
del1 =

   3.3362e-04
```

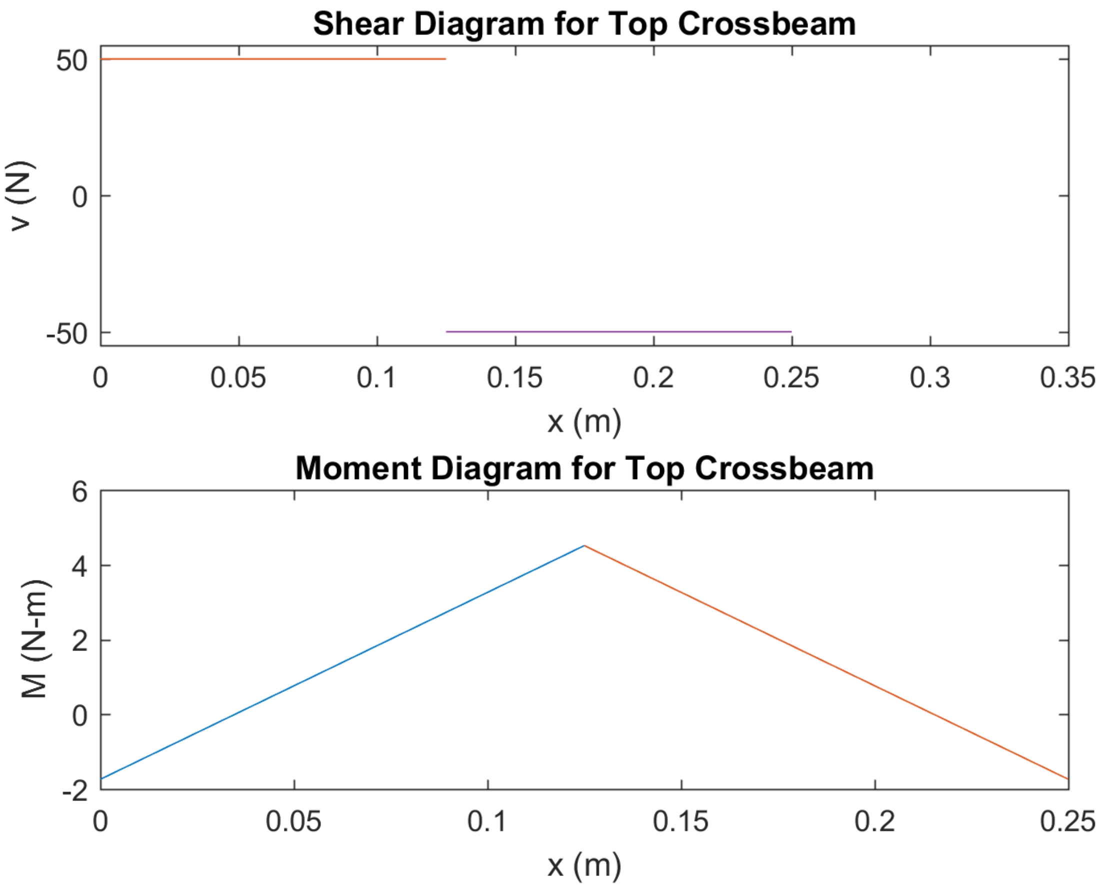


Figure A.5: *Shear moment diagram for the top crossbeam*

Analysis of Uprights

```
%Stresses
Sigaxial2=-Ra1/AC*10^-6; %axial stress in uprights MPa (compressive)
Sigbend2=-Mendstop*(h/2)/I*10^-6; %max bending stress in uprights MPa
%(compressive)
Sigshear2=Ha1*Q/(I*h)*10^-6; %bending shear stress in uprights MPA
Sigy2=Sigaxial2+Sigbend2; %stress on outside of the beam (no shear)
Sigyx2=Sigshear2;
Sigvon2=sqrt(1/2*(2*Sigaxial2^2)+3*Sigyx2^2); %vonmises stress criterion for
%center of bottom beam 'y=0' where there is both max shear stress and axial
%stress from the axial force
SF2=Sigyield/max(Sigy2,Sigvon2)

%Buckling of uprights3
```

End Condition:	Pinned-Pinned	Fixed-Fixed	Fixed-Pinned	Fixed-Free
Illustration:				
Theoretical Effective Length Factor, K:	1	0.5	$1/\sqrt{2}$	2
Recommended Effective Length Factor, K:	1	0.9	0.9	2.1

Figure A.6: *Theoretical and recommended length factors for end condtions for vertical columns under compressive loads*

Columns with Eccentric Loading

	Using Effective Length Factor, K
Max Deflection:	$\delta_{max} = e\left[\sec\left(\frac{KL}{2r}\sqrt{\frac{P}{AE}}\right) - 1\right]$
Max Compressive Stress:	$\sigma_{c,max} = \frac{P}{A}\left[1 + \frac{ec}{r^2}\sec\left(\frac{KL}{2r}\sqrt{\frac{P}{AE}}\right)\right]$

Figure A.7: *Summary of equations for columns under eccentric loads in terms of the length factor K from figure A.6.*

```
k=.9; %assuming pinned fixed conection. Actual value will be slightly less
%since there is some stiffness in the joint from the top crossbeam. From figure A.6
r=sqrt(I/AC); %radius of Gyration square memebers so it is the same across
%either axis
%the moment acts as an eccentric load M=P*e
e=L/(2*N1); % eccentricity of the load (location of "hinge" in top
%crossbeam m
P=F1/2; %N
c=h/2; %centroidal distance in members m
Sigcolmax=P/AC*(1+e*c/r^2*sec(k*H/(2*r)*sqrt(P/(AC*E*10^6))))*10^-6; %MPa from figure A.6
SFbuckle=Sigyield/Sigcolmax %SF wrt the critical compressive stress from figure A.6
```

```
%Deflection
del2=e*(sec(k*H/(2*r)*sqrt(P/(AC*E*10^6)))-1)  %m
%deflection creats an arc. The member is assumed to not stretch so the
%length of the arc equals to H the original height of the uprights the
%chord of the arc (a) needs to be calculated and is the "new" height of the
%uprights. The vertical deflection is then calucled as H-a
%approximate as four similar right triangles as depicted in assumptions
xx=sqrt((H/3)^2-del2^2); %m
Hprime=3*xx; %approximate veritical distance from bottom to top cross m
del2prime=-(H-Hprime)*1000 %approximate vertical deflection mm
```

```
Safety factor with respect to yielding in uprights
SF2 =

   4.2154e+03

Safety factor with respect to buckling in uprights
SFbuckle =

  779.3138

Maximum horizontal deflection in uprights mm
del2 =

   2.9045e-06

Maximum vertical deflection in uprights mm
del2prime =

  -9.4906e-08
```

Analysis of Bottom Crossbeam

```
%Shear Diagram
X3=linspace(0,L/2);
X33=linspace(L/2,L);
figure(2); clf(2)
subplot(2,1,1)
plot(X3,F2/L*X3)
hold on
plot(X33,F2/L*X33-F2)
title('Shear Diagram for Bottom Crossbeam')
xlabel('x (m)')
ylabel('v (N)')
hold off

%Moment Diagram
subplot(2,1,2)
plot(X3,Mendsbot+F2*X3.^2/(2*L))
hold on
plot(X33,Mendsbot-F2*(X33-L/2-X33.^2/(2*L)))
title('Moment Diagram for Bottom Crossbeam')
xlabel('x (m)')
```

```
ylabel('M (N-m)')
hold off

%Stresses
Sigbend3=Mmaxbot*(h/2)/I*10^-6; %max bend stress in the bott crossbeam MPa
Sigaxial3=-Ha1/AC*10^-6; %axial stress in the bott cross MPa (compressive)
Vmaxbot=F2/2; %max shear felt in the bottom crossbeam N
Sigshear3=((Vmaxbot)*Q)/(I*h)*10^-6; %bending shear stress in bott crossbeam MPa
Sigx3=Sigbend3+Sigaxial3; %stress on outside of the beam (no shear)
Sigyx3=Sigshear3;
Sigvon3=sqrt(1/2*(2*Sigaxial3^2)+3*Sigyx3^2); %vonmises stress criterion for
%center of bottom beam 'y=0' where there is both max shear stress and axial
%stress from the axial force
SF3=Sigyield/max(Sigx3,Sigvon3)

%Deflection
%flat on table so no deflection possible
del3=0;
```

```
Safety factor with respect to yielding for bottom crossbeam
SF3 =

  421.1227
```

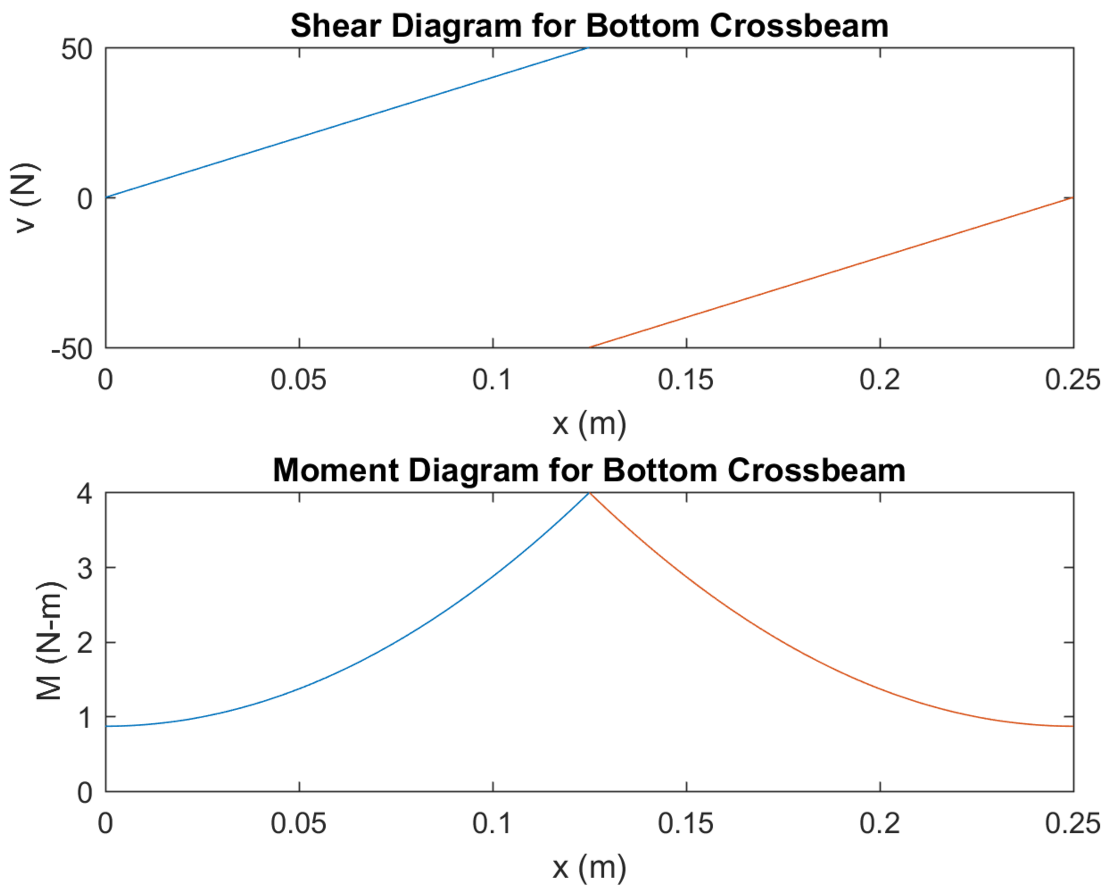


Figure A.8: *Shear and Moment Diagrams of Bottom Crossbeams*

Analysis of Feet

```
Lfeet=.25; %length of the feet crossbeams m

%Shear Diagram
X4=linspace(0,Lfeet/2);
X5=linspace(Lfeet/2,Lfeet);
figure(3); clf(3)
subplot(2,2,1)
plot(X4,F1/Lfeet*X4)
hold on
plot(X5,F1/Lfeet*X5-F1)
hold on
plot(X4,Ha1/Lfeet*X4,'--')
hold on
plot(X5,Ha1/Lfeet*X5-Ha1,'--')
title('Shear Diagram for Feet Crossbeams')
xlabel('x (m)')
ylabel('v (N)')
hold off

%Moment Diagram
```

```
subplot(2,2,2)
plot(X4,F1/2*X4)
hold on
plot(X5,F1/2*Lfeet/2-F1/2*(X5-Lfeet/2))
hold on
plot(X4,Ha1/2*X4,'--')
hold on
plot(X5,Ha1/2*Lfeet/2-Ha1/2*(X5-Lfeet/2),'--')
title('Moment Diagram for Feet Crossbeams')
xlabel('x (m)')
ylabel('M (N-m)')
hold off

%Torque Diagram
subplot(2,2,3)
plot(X4,Mendsbot/2*ones(length(X4)))
hold on
plot(X5,-Mendsbot/2*ones(length(X5)))
title('Torque Diagram for Feet Crossbeams')
xlabel('x (m)')
ylabel('T (N-m)')
hold off

%Stresses
 %approximate as a solid square cross for torsion analasys4
```

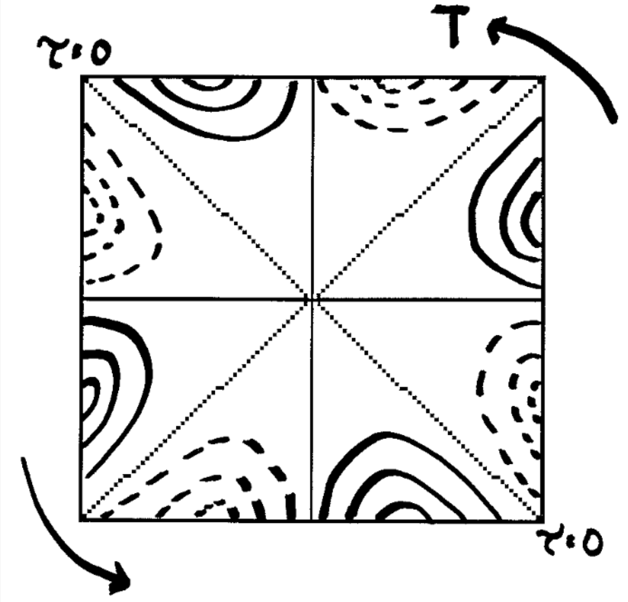


Figure A.9: *Torsional Stress distribution of square solid.*

```
M1=F1*Lfeet/8; %moment caused by the application force F1 N-m;
M2=Ha1*Lfeet/8; %moment caused by the reaction force Ha1 N-m;
SigbendM1=M1*(h/2)/I*10^-6;
SigbendM2=M2*(h/2)/I*10^-6;
a=.208; %a and b are parameters
b=.141;
Sigtorque4=Mmaxfeet/(a*b*h^2); %torsional stress in the feet Pa
Sigshear41=((Ha1/2)*Q)/(I*h); %bending shear stress case 1 Pa
```

```
Sigshear42=((F1/2)*Q)/(I*h); %bending shear stress case 2 Pa
Sigx41=SigbendM1; %case 1 middle of horizontal side
Sigx42=SigbendM2; %case 2 middle of vertical side
Sigx43=SigbendM1+SigbendM1; %case 3 corner
Sigyx41=Sigshear41+Sigtorque4; %case 1
Sigyx42=Sigshear42+Sigtorque4; %case 2
Sigyx43=0; %case 3 %shear stress from torque is 0 at corners see figure A.9
Sigvon41=sqrt(1/2*(2*Sigx41^2)+3*Sigyx41^2)*10^-6; %vonmises stress criterion
Sigvon42=sqrt(1/2*(2*Sigx42^2)+3*Sigyx42^2)*10^-6; %case 2
Sigvon43=sqrt(1/2*(2*Sigx43^2)+3*Sigyx43^2)*10^-6; %case 3
Sig=[Sigvon41,Sigvon42,Sigvon43];
SF4=Sigyield/max(Sig)

%Deflection
del4=0 %mm
```

```
Safety factor with respect to yielding for "feet"
SF4 =

   1.4091e+04
```

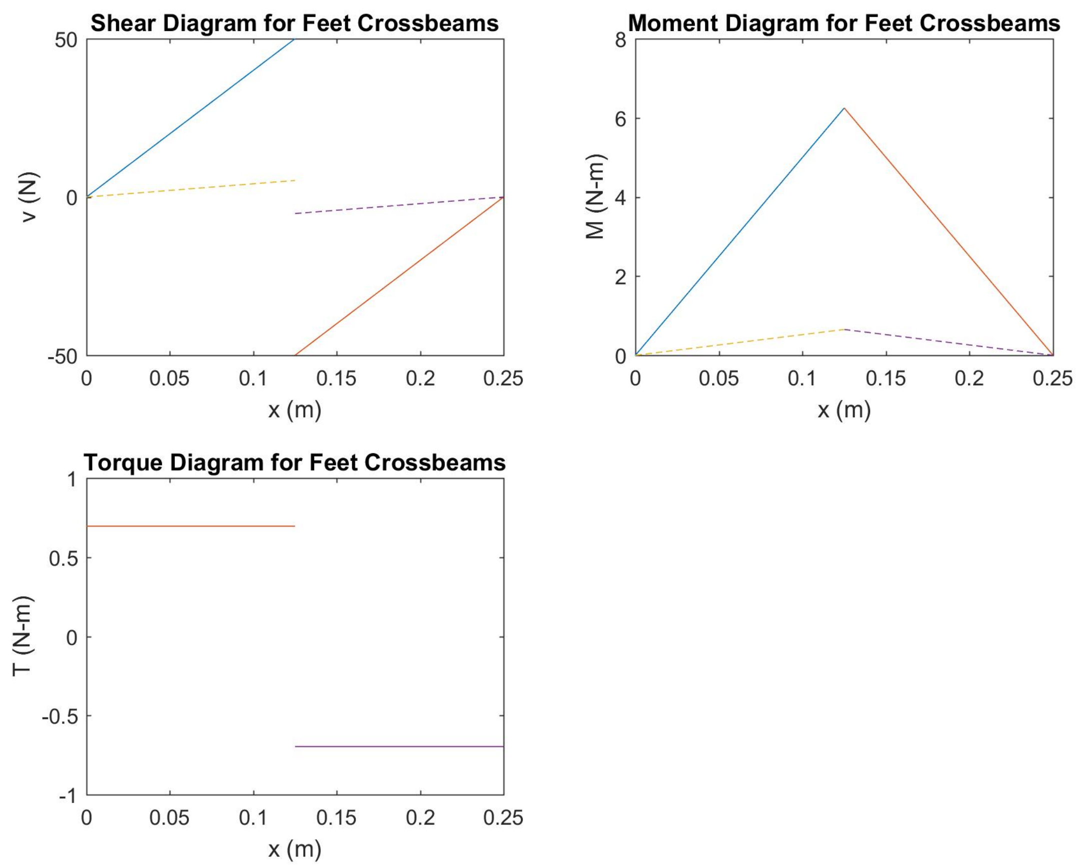


Figure A.10: *Shear, Moment and Torque Diagrams for Feet Crossbeams.*

Total Displacement

```
del=abs(del1+del2prime+del3+del4)
SFdeflect=dallow/del
```

```
Total vertical displacement mm
del =

  3.3352e-04

Safety factor with respect to maximum allowable vertical deflection
SFdeflect =

  104.9410
```

Analysis of Weights

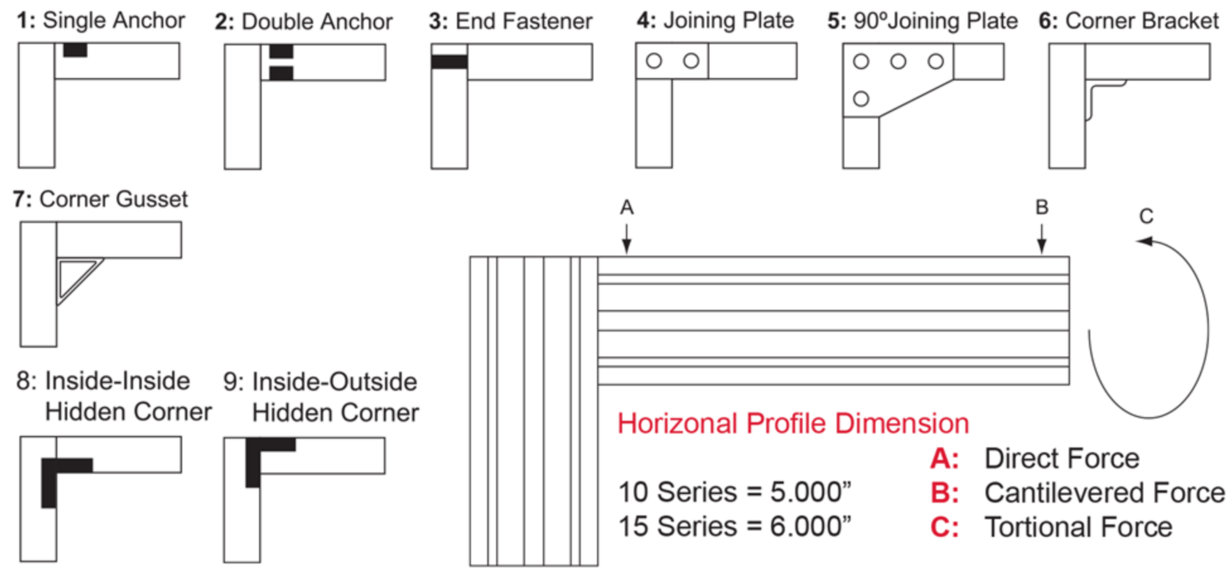
```
%will be placed under the 'feet' and bottom crossbeam
%weight must be enough to overcome the upward force from deceleration
%assume to be equal to F1;
weight_frame=F1/9.81 %weight of the frame neccissary kg
```

```
Total weight the frame must weigh kg. Additional weight will be added to excede the value
weight_frame =

   10.1937
```

Fasteners[5]

The 40-4302 90 degree corner fasteners were chosen using information from 80/20® fastener application tests. The application test did not test the 4040 (40 mm by 40 mm) profile used in this frame, however the 1515 (1.5 in by 1.5 in) profile that is very close in size to the 4040 was tested. The loads reported are the connection failure point. Focusing on the 1515 profile data in the figure A.11 below for case 6: Corner Bracket, failure occurred when the cantilevered load B reached 225 lbs which coresponds to a moment of 1125 in-lbs from the 5 inch moment arm between the load and the joint. The maximum moment in the frame is 39.83 in-lbs (4.5 N-m) and is located in the top crossbeam and is significantly less then the failure moment. Looking at the direct force A, the connection failed at 575 lbs. The applied load in the frame will reach no more than 22.48 lbs (100 N) which is significantly lower than the failure force. Given this data, the selected fasteners are expected to be more than strong enough for this application



Fastener	1010 Profile			1515-Lite Profile			1515 Profile		
	A (lbs.)	B (lbs.)	C (Inch-lbs.)	A (lbs.)	B (lbs.)	C (Inch-lbs.)	A (lbs.)	B (lbs.)	C (Inch-lbs.)
1	500	250	180	950	625	540	950	1,000	700
2	900	250	260	1,200	700	1,150	1,200	1,200	2,000
3	450	200	325	1,000	500	680	1,000	820	1,150
4	175	50	400	225	200	1,000	225	200	1,100
5	175	50	500	250	200	1,120	250	200	1,260
6	325	75	180	375	225	500	575	225	500
7	325	220	260	375	750	500	575	750	500
8	N/A	N/A	N/A	50	50	50	N/A	N/A	N/A
9	N/A	N/A	N/A	240	220	240	N/A	N/A	N/A

Note: Plates, brackets and gussets were attached with 80/20® recommended bolt kits. Fasteners were tightened according to 80/20 torque specifications.

Test results reflect the connection failure point. Loads at or above these points are not recommended.

Figure A.11: *Styles and Dimensions of 80/20® Fasteners.*

FEA

Frame

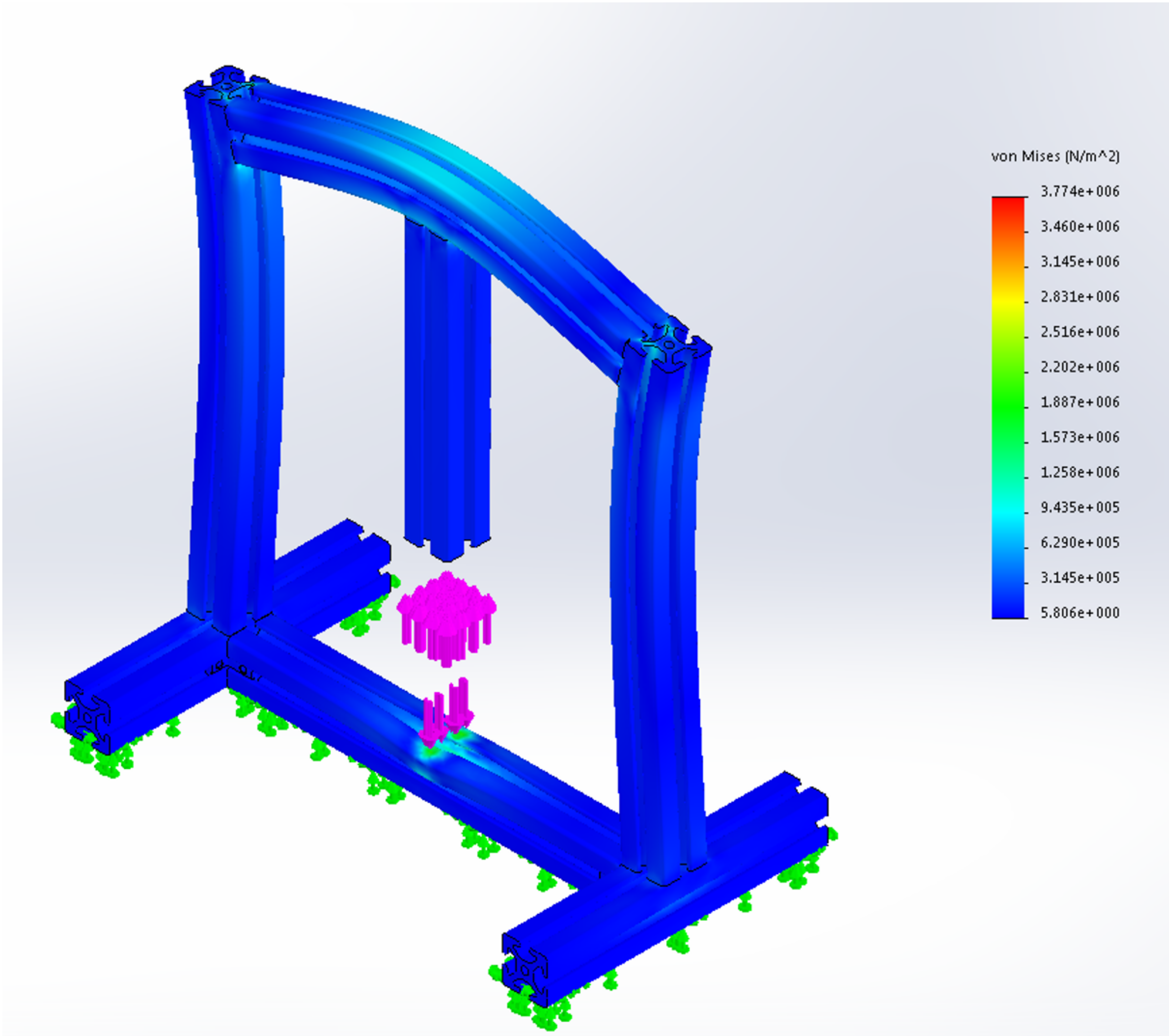


Figure A.12: *Von Mises stress distribution in the frame. The stress present in the center of the top crossbeam is approximately .8 MPa from the figure above. Calculations for the top crossbeam gave a stress of .6631 MPa which is of the same magnitude. The largest stress seen in the frame from the FEA is 3.774 MPa which is much higher than anything calculated previously. These high stresses occur at the stress concentrations which were not analysesed in the previous code. Dividing the yield stress of 241.1 MPa by the larger value of 3.774 MPa results in a safety factor of 63.86 which is still very high.*

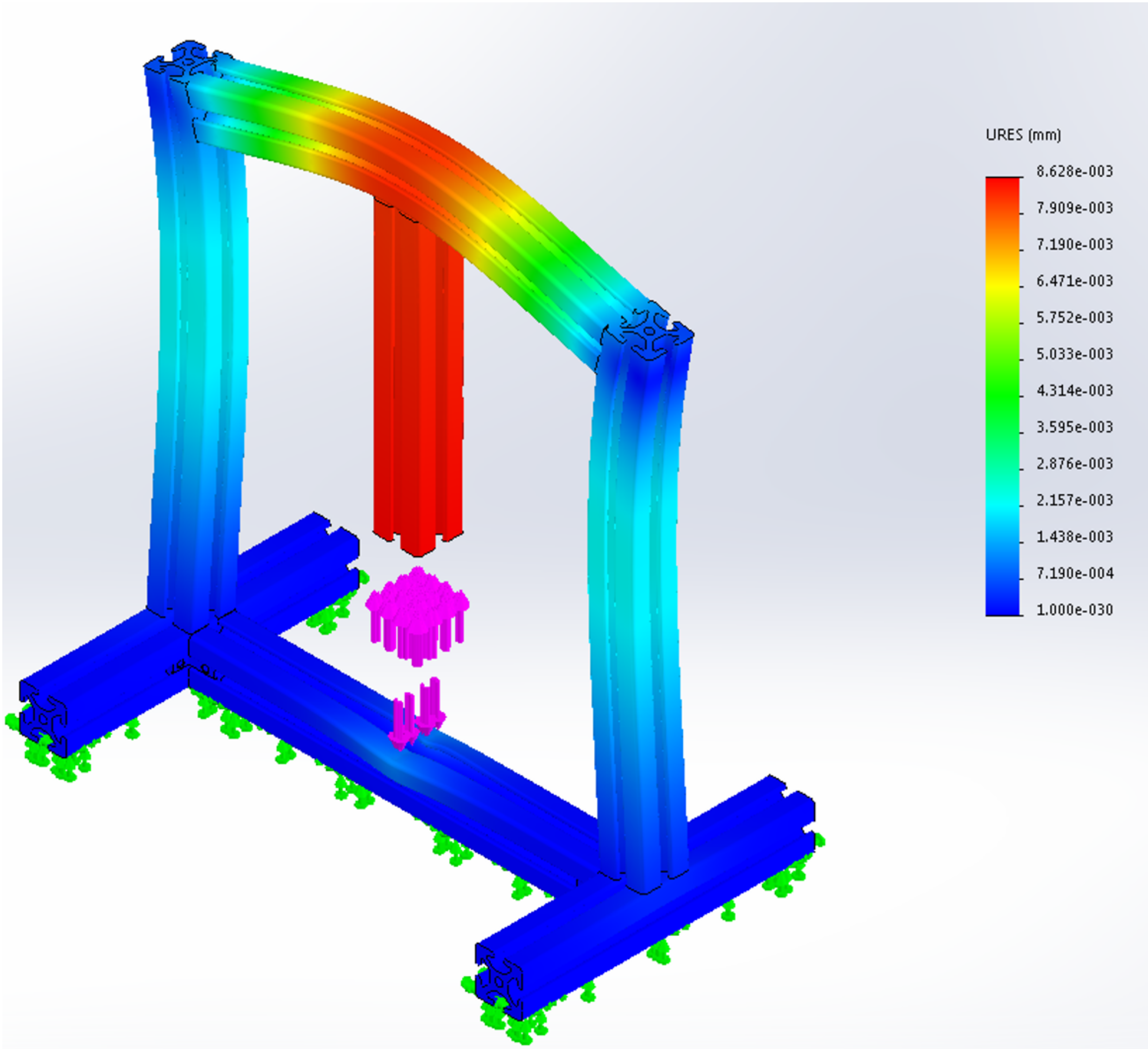


Figure A.13: *Deflection profile in the frame. The largest displacement present is 8.628e-3 mm which is an order of magnitude larger than the total displacement calculated of 3.3352e-4. This difference is likely due to assumptions made for the vertical deflection of the uprights (approximating as four similar right triangles). The differences could also be attributed to the assumptions of a fixed-pinned connection for buckling. In actuality the connection is between fixed-fixed and pinned-fixed because of the portal frame assumption. However, dividing the larger 8.628e-3 mm displacement by the max allowable displacement of .035 mm still gives a safety factor of 4.06. This will be slightly higher because the uprights are in compression and thus have a deflection downwards. These results show that deflection is the dominating consideration for the frame design.*

Mouse Platform

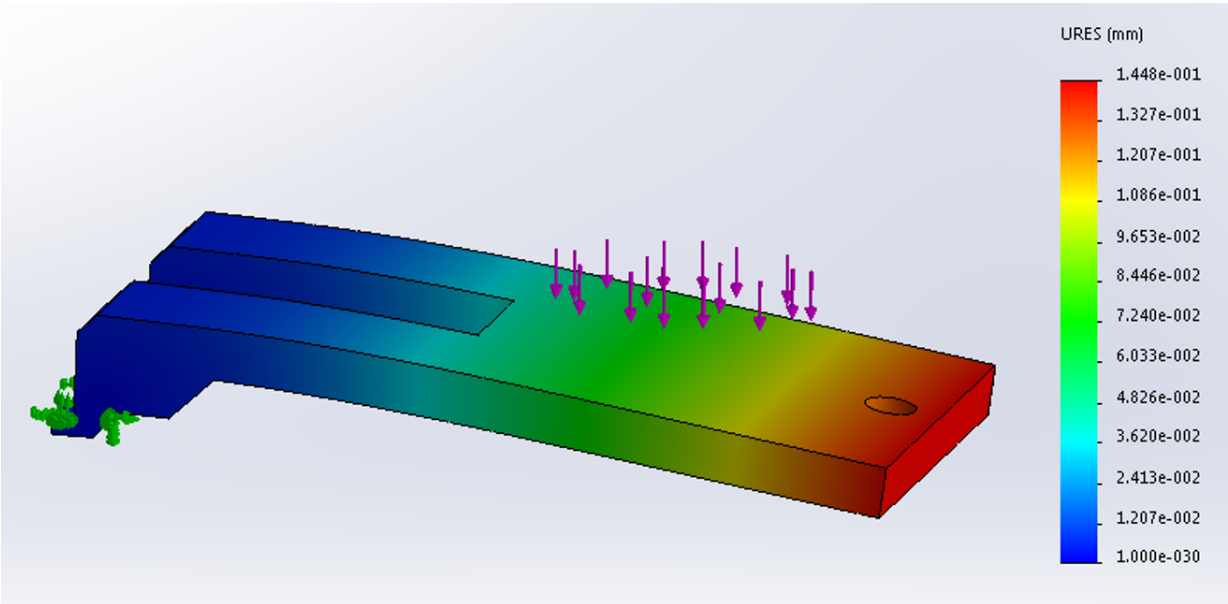


Figure A.14: *Deflection profile of the Nylon 3D printed mouse platform. The platform supports only the mouse and the measurement will be independent of this deflection (the load cell is attached directly to the frame and will fit into the cut out of this platform). This displacement profile simply shows that the platform will not significantly deform under the weight of a mouse (deflecting only .1448 mm).*

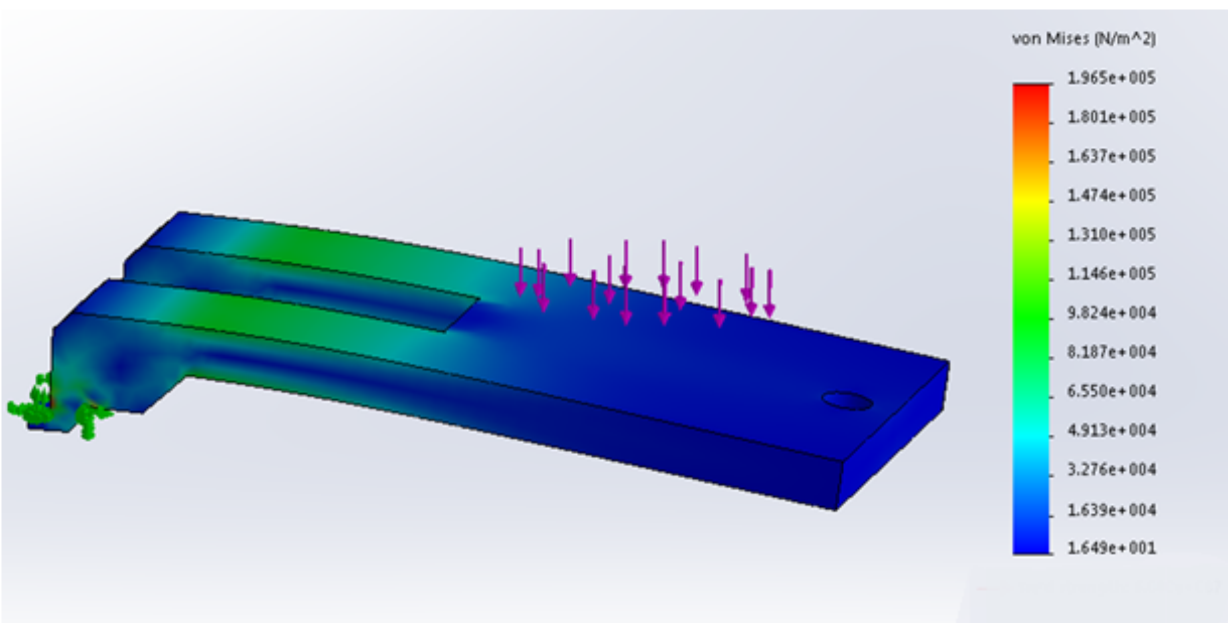


Figure A.15: *Von Mises stress profile for the mouse platform. The highest stress present is located at the stress concentration located at the frame insert. The yield strength of 48 MPa divided by this max stress of .1965 MPa gives a safety factor of 244.27.*

Displacement Stop

Fatigue

All components need to be designed to withstand 10,000 cycles or more.

Frame

MatWeb[6] gives a fatigue strength for 6000 series aluminumn as a range of 55 to 375 MPa. The max stress in the frame is 3.774 MPa which is an order of magnitude below the lower value of 55 MPa. Therefore, the system is expected to last far beyond 10,000 cycles.

VCA

BEI Kimco claims that the VCA was life cylce tested to an excess of 500 million cycles[7].

Load Cell

If the load cell malfunctions or breaks it is a very inexpensive part ($7) and will be very simple to replace if need be.

Electronics

Mouse Knee Spring Constant

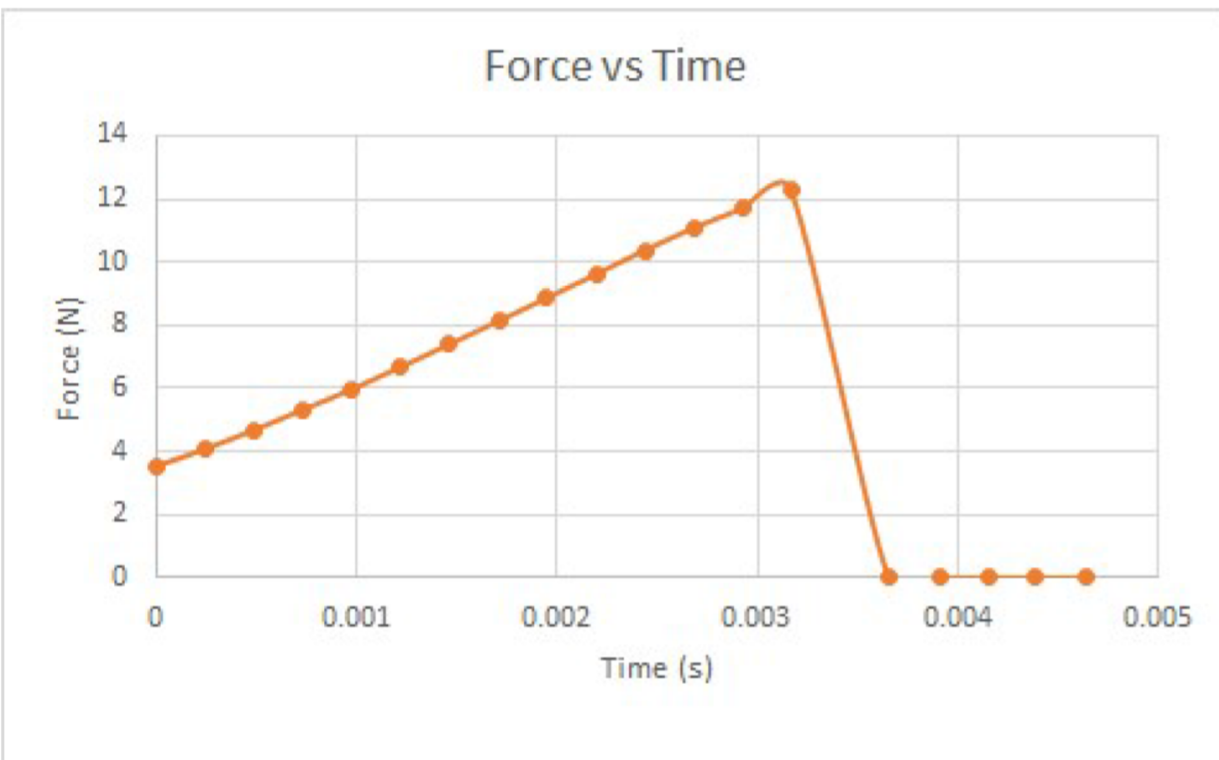


Figure A.16: *Force time curve from previous experimental data. This graph shows how quickly the force application needs to reach 200 mm/s. It also depicts the drop in force that will be seen at injury. This drop is what the feedback loop will look for to stop the VCA.*

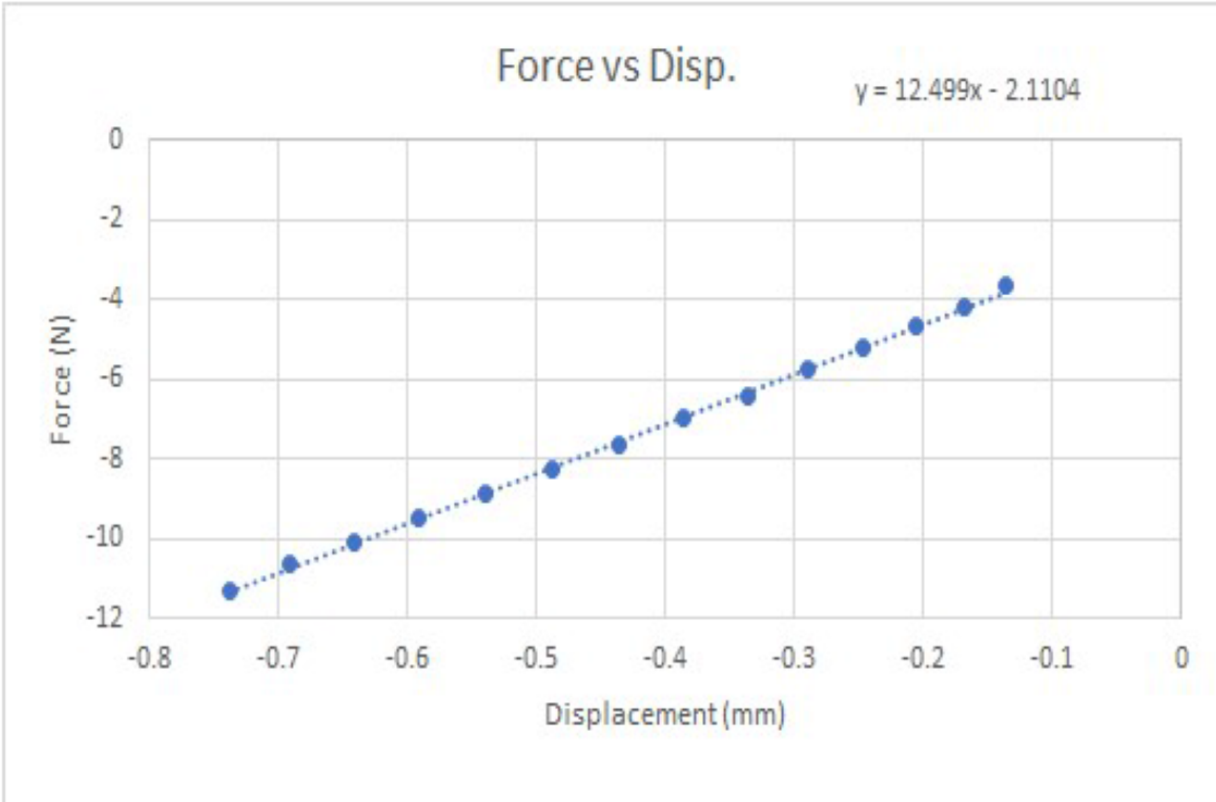


Figure A.17: *Force displacement curve plotted from a previous experiment. This is an example of how the spring constants were obtained. Here the spring constant from the fitted line is 12.499 N/mm.*

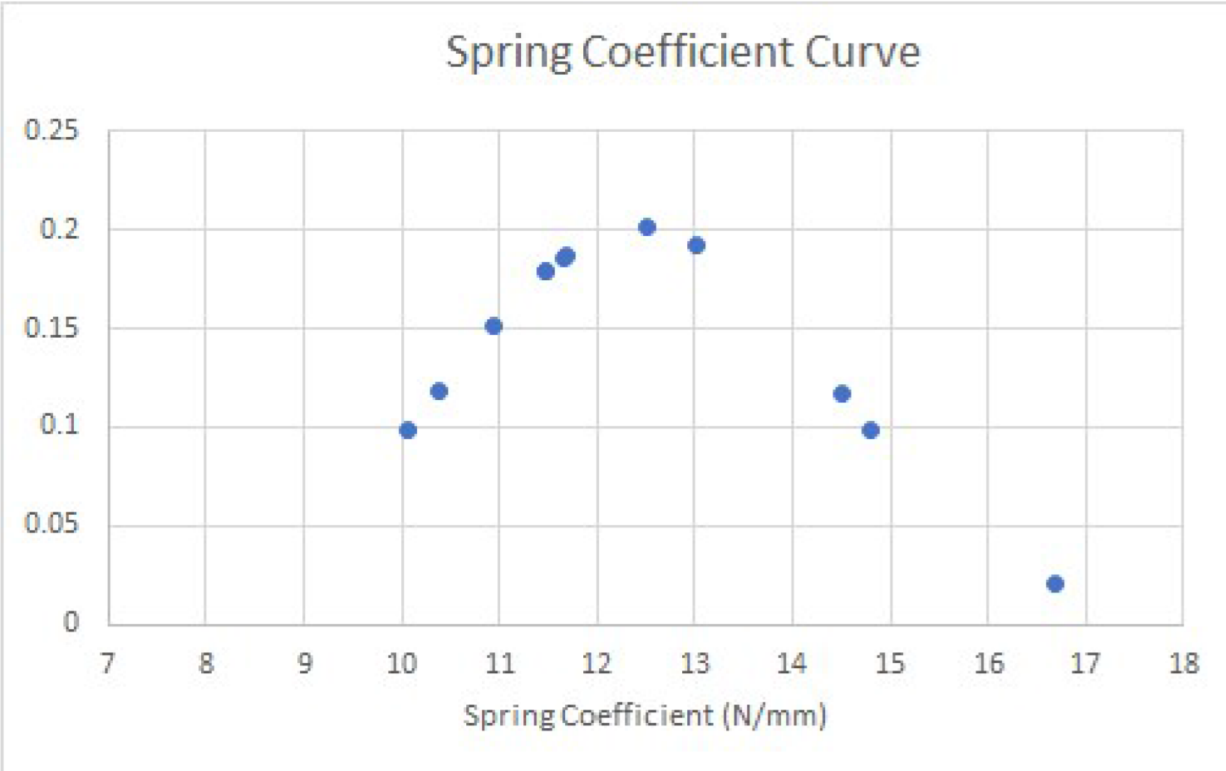


Figure A.18: *Normal distribution of knee spring constants. Each constant was calculated form a force displacement graph (. The mean spring constant was found to be 12.4 N/mm with a standard deviation of 1.98 N/mm.*

Force Application Analysis

Analysis was performed to determine the minimum load required to accelerate a given mass to the specified 0.2m/s velocity within a displacement of 0.5mm. A simulink model was constructed based on the equation F=ma+kx. The mass was assumed to be the moving magnet mass and the mass of the ankle holster. The k constant was determined to be 15 N/mm (an overestimate from the average of the k values found above in figure A.18). Using this model, it was determined that the LAS13-56 is the smallest VCA appropriate for the application. This VCA accelerates its magnet, and the knee holster to 0.2 m/s within 0.1mm. Additionally, this VCA has a large factor of safety, which will be beneficial given unknown factors, and a larger deceleration once injury has been induced. Figure A.19 illustrates the solution of the second order differential equation, such that theoretical displacement and velocity data can be determined. Additionally, this data is plotted in Figure A.20 and shows that the ankle holster is expected to accelerate to 0.2 m/s within 0.0001m of displacement. This proves that the chosen VCA should perform well within specs, with a reasonable margin of safety, should unknown factors impact the system.

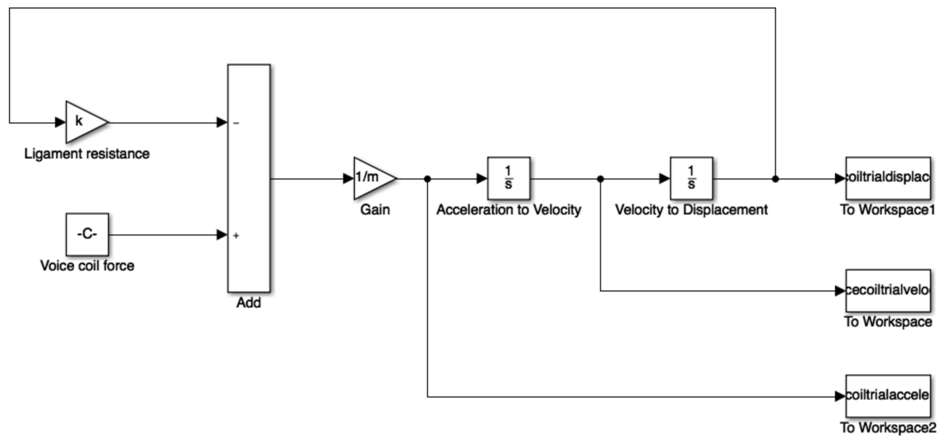


Figure A.19: *Simulink Model Architecture*

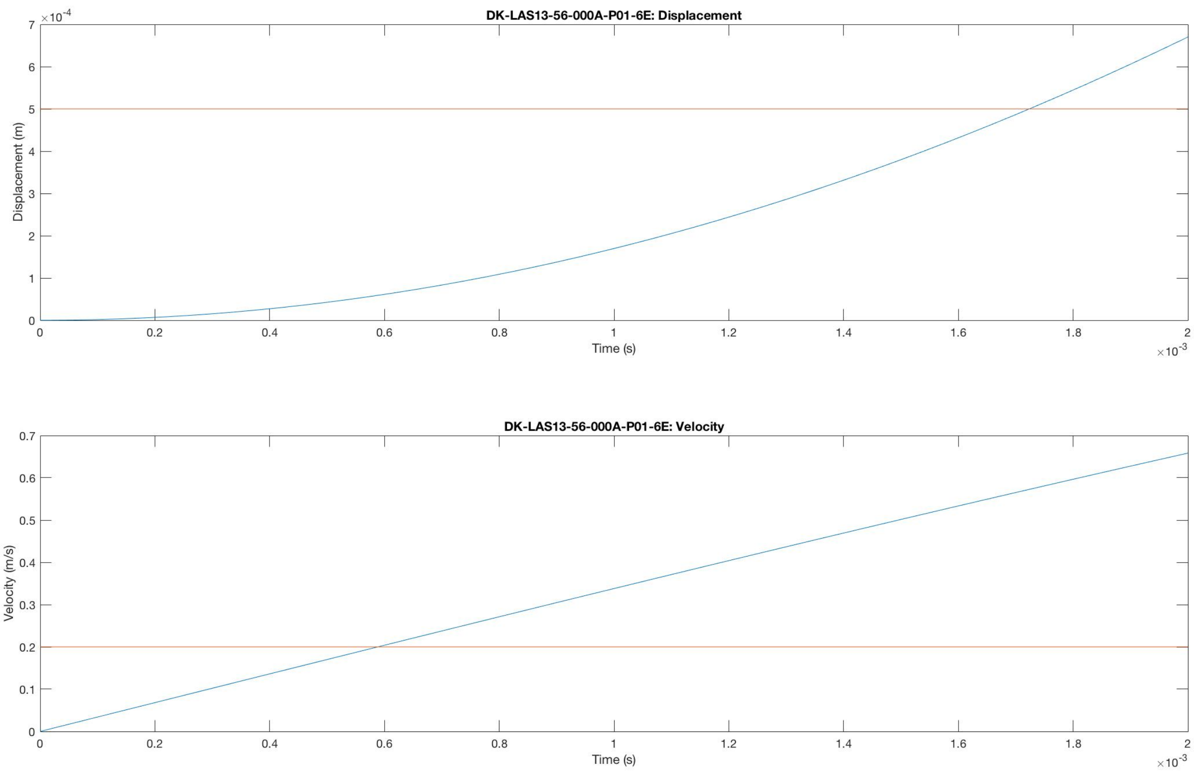


Figure A.20: *Simulink Results for LAS13-56*

References

1. Rigid Frame Formulae. (n.d.). Retrieved December 10, 2017, from http://www.yourspreadsheets.co.uk/rigid-frame-formulae.html
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3. Column Buckling. (n.d.). Retrieved December 08, 2017, from https://mechanicalc.com/reference/column-buckling
4. Elder, J. (n.d.). TORSION OF MEMBERS WITH RECTANGULAR CROSS-SECTIONS. Retrieved December 10, 2017, from http://emweb.unl.edu/Mechanics-Pages/J-Elder/torsion.html
5. The Glue That Holds. (n.d.). Retrieved December 10, 2017, from https://8020.net/university-fastening-options
6. Overview of materials for 6000 Series Aluminum Alloy . (n.d.). Retrieved December 10, 2017, from http://www.matweb.com/search/DataSheet.aspx?MatGUID=26d19f2d20654a489aefc0d9c247cebf
7. Cylindrical Housed Linear VCA with an Integrated Sensor. (n.d.). Retrieved December 10, 2017, from http://www.beikimco.com/motor-products/VCA-linear-voice-coil-actuator-all/actuator-with-integrated-feedback

APPENDIX B. Manufacturing Plan

Manufacturing Plan

Simplifying construction was a large consideration for this testing apparatus. As such, no fabrication is expected of the consumer, and all components are purchased from vendors. Once these components have been obtained, assembly is completed with minimal tools, other than a five millimeter allen wrench, and a phillips/flat head screw driver. The details of this manufacturing process are elaborated on below.

Purchase

Purchase components specified on bill of materials. Vendors include: 80/20®, Shapeways, Amazon, McMaster Carr, BEI Kimco, and Moticont. Lead times should not exceed 10 days, with the exception of the VCA which potentially has a four-week lead time. Orders will be submitted to Shapeways via CAD files stored on grabcad.com. These files will be clearly labeled, and will all be printed in HP Nylon plastic. The 80/20® frame will be purchased by submitting a CAD file, and specifying the 40-4040 frame material. The frame will come precut, and potentially preassembled. If not, the frame will be easily assembled using the slide in fasteners. For simplicity, the design uses only two frame piece lengths.

Assembly

The 80/20® frame may be shipped preassembled. If this is cost prohibitive, the frame will come cut to length. Assemble the frame in accordance to drawings provided. The only tools required will be a tape measure, and a 4mm hex wrench.

Slide the VCA collar onto the central vertical column. Mount the VCA to the VCA collar by pulling the wires through the upper port, and screwing in the two phillips/flathead screws. Attach the upper plate of the mechanical stop to the bottom face of the VCA using the other two phillips/flathead screws.

Thread a hex nut onto the threaded VCA shaft until it is most of the way up the thread. Push the barbed threaded insert into the ankle holster and thread the ankle holster until snug. Back the ankle holster off the thread until it is oriented properly. Advance the nut positioned above, down onto the top of the ankle holster, to secure it in place.

Attach the microcontroller, load cell, power supply, and hall effect sensor to the motion controller as shown in the circuit diagram. Press the user interface LCD/button panel onto the microcontroller with the integrated pins. Copy and paste code for microcontroller, and load onto microcontroller memory.

After completing the calibration section (which will instruct on the installation and calibration of the load cell), install the mouse platform by rotating the curved end of the component down, and pushing it into the top groove of the 80/20® frame. Then pivot the platform to its final cantilevered position. Finally, push the nose cone mount into the hole in the platform, and push a modified test tube into it, such that the nose cone/test tube and rotate and translate to accommodate different sized mice.

APPENDIX C. Project Management Plan and Project Schedule

Project Management Plan

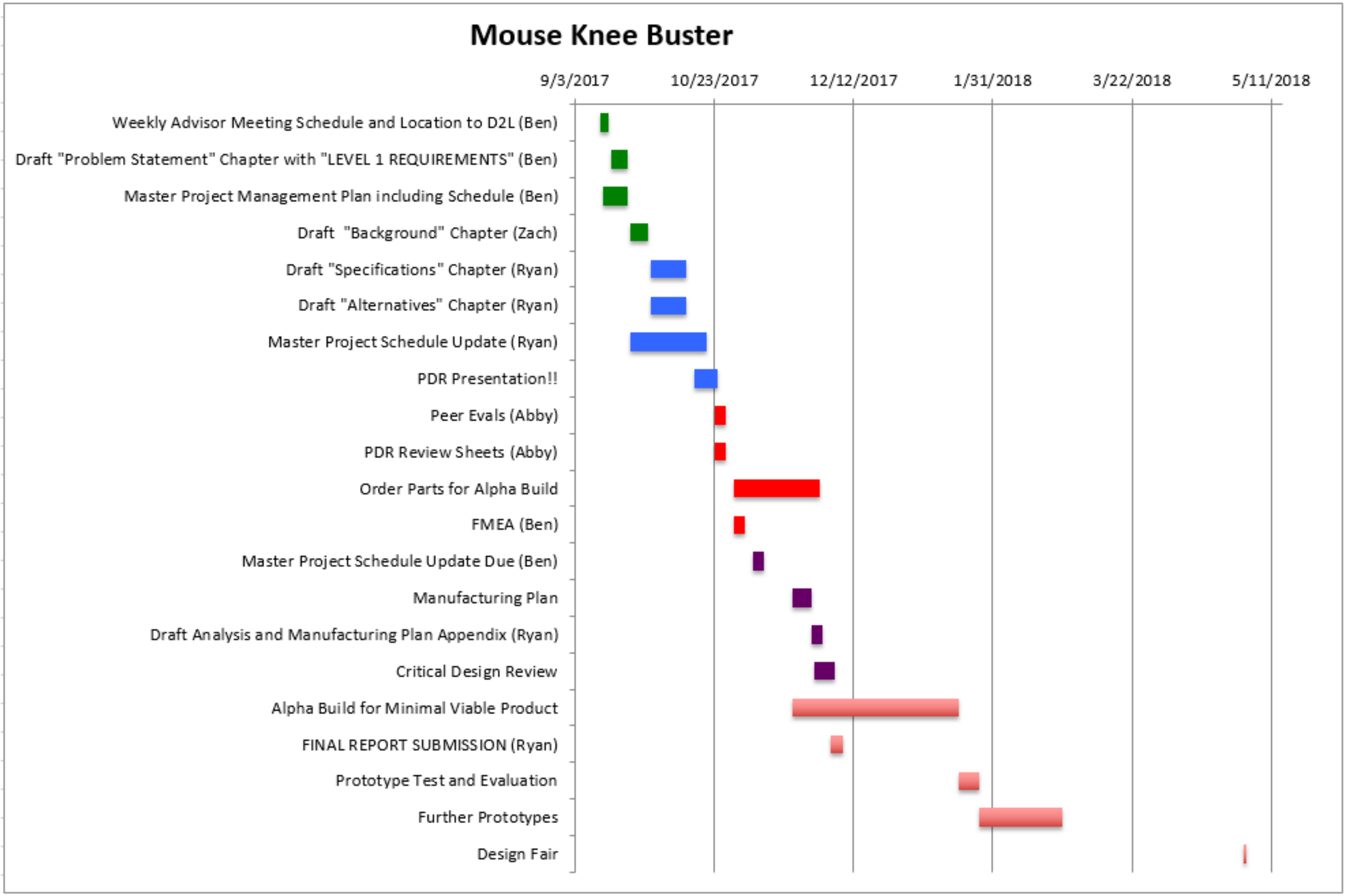
Introduction. For the next nine months this project will focus on producing a viable instrument setup to induce ACL rupture via tibial compressive overload in mice and potentially rats. Group members must be in communication with each other and the advisor weekly and the sponsor as needed.

Project Management Approach. Document nomenclature will be followed for organization. These documents will be made and shared over Microsoft Box. A Gantt chart will be managed to keep track of deadlines. This chart will have all individual tasks and names of responsible group members. It will be updated regularly. Gantt charts will be downloaded as PDFs before any changes are made. These PDFs will be named in the format Gantt MM/DD/YYYY_#. PDFs will be saved in the Gantt chart archives folder. Past deliverables will be saved in the completed deliverables archive folder. Meeting notes will be taken in individual's bound design journals.

Group Interactions. A chairperson (nicknamed the commissioner) will be in charge of submitting required deliverables every week before 5pm on Friday during their rotation. The rotation will be every two weeks alphabetically by last name at the beginning of the advisor meeting. The advisor meeting is scheduled for every Monday beginning at 8:15 am (MDT until Nov. 5th at 2am which will then switch to MST) in Dr. June's office (Roberts 411). Group meetings will be scheduled as needed likely after capstone on Tuesdays. Additional meetings will be scheduled as needed.

Conflicts will be brought to the chairperson and will be dealt with in a professional open discussion between group members. During the brainstorming phase, every idea is a good idea. Further on in the design phase ideas will be voted on and discussions will use constructive criticism. Every member will be expected to do timely, quality work. Failure to do so will be reflected on peer evaluations. A 16" rule will be employed during standard business hours for a healthy work life balance. Group me and email will be the main forms of communications.

Project Schedule


Mouse Knee Buster
9/3/2017
10/23/2017
12/12/2017
1/31/2018
3/22/2018
5/11/2018
Weekly Advisor Meeting Schedule and Location to D2L (Ben)
Draft "Problem Statement" Chapter with "LEVEL 1 REQUIREMENTS" (Ben)
Master Project Management Plan including Schedule (Ben)
Draft "Background" Chapter (Zach)
Draft "Specifications" Chapter (Ryan)
Draft "Alternatives" Chapter (Ryan)
Master Project Schedule Update (Ryan)
PDR Presentation!!
Peer Evals (Abby)
PDR Review Sheets (Abby)
Order Parts for Alpha Build
FMEA (Ben)
Master Project Schedule Update Due (Ben)
Manufacturing Plan
Draft Analysis and Manufacturing Plan Appendix (Ryan)
Critical Design Review
Alpha Build for Minimal Viable Product
FINAL REPORT SUBMISSION (Ryan)
Prototype Test and Evaluation
Further Prototypes
Design Fair

APPENDIX D. Purchased Parts List

Figure D.1: *Bill of materials for all parts to be purchased and 3D printing*

Part	Quantity	Cost	Mass (g)	Link
BEI Kimco LAS13-56 (VCA)	1	$1650	534 g	http://www.beikimco.com/motor-products/VCA-linear-voice-coil-actuator-all/actuator-with-integrated-feedback
Moticont 510-01 (Motion controller)	1	$796.84	159 g	http://www.moticont.com/510-series.htm
Adhesive Strips ½" x 36" 1/16" thick (# 1466N12 from McMaster	36''	$5.79	Negligible	https://www.mcmaster.com/#silicone-rubber-sheets/=1afklr4
Arduino Due (Micro controller)	1	$37.40	36 g	https://store.arduino.cc/usa/arduino-due
40mm 80/20®	180cm	$0.34/cm and $1.95 per cut=$125.20	23.59 g/cm=4246.2 g	https://8020.net/shop/40-4040.html
80/20® fasteners 90 degree corners 40-4302	10	$2.95/per corner $29.5	Negligible	https://8020.net/40-4302.html

80/20® bolt assembly 75-3422	20	$0.67/per assembly $13.4	Negligible	https://8020.net/75-3422.html
80/20® M5 Self-Aligning Roll-in T-Nut for load cell, VCA, Electronics mount 13090	4	$1.40/per part $5.60	Negligible	https://8020.net/13090.html
80/20® bolt for load cell and electronics mount placement 13-5520	3	$0.20	Negligible	https://8020.net/shop/13-5520.html
Knakro 5 kg Load Cell	1	$8.50	46 g	https://www.amazon.com/KNACRO-Converter-Breakout-Portable-Electronic/dp/B07469KSJC/ref=sr_1_4?ie=UTF8&qid=1511557048&sr=8-4&keywords=5kg+load+cell
24vdc Power Supply	1	$25.99	498.95g	https://www.amazon.com/transformer-Universal-Regulated-Switching-110-240V/dp/B00QCJ9FAY/ref=sr_1_5?s=hi&ie=UTF8&qid=1512354051&sr=1-5&keywords=24vdc+10a+power+supply
110vac Power Cord	1	7.99	204.117 g	https://www.amazon.com/5-15P-Standard-Power-Black-Conductor/dp/B00I0VL96U/ref=sr_1_fkmr2_1?ie=UTF8&qid=1512354601&sr=8-1-fkmr2&keywords=110v+power+cord+bare+leads

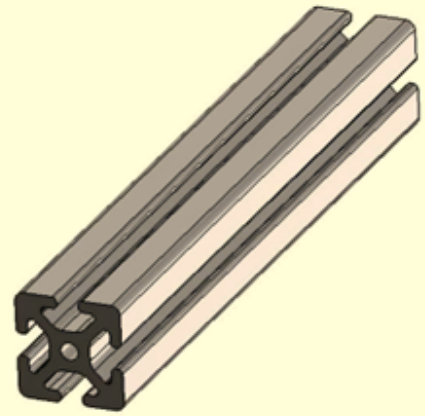
Mouse Platform	1	\$5/part \$0.56/cm^3 \$89.73	151.3g	https://www.shapeways.com/materials/hp-jet-fusion
Mouse knee cup	1	\$5/part \$0.56/cm^3 \$ 5.39	2g	https://www.shapeways.com/materials/hp-jet-fusion
Anesthesia Pivot	1	\$5/part \$0.56/cm^3 \$5.96	1.71g	https://www.shapeways.com/materials/hp-jet-fusion
VCA collar	1	\$5/part \$0.56/cm^3 \$59.52	98.33g	https://www.shapeways.com/materials/hp-jet-fusion
Ankle Holster	1	\$5/part \$0.56/cm^3 \$7.27	4.097g	https://www.shapeways.com/materials/hp-jet-fusion
Socket Head Screw ¼"-20 90128A301	2	\$6.45 (for 25)		https://www.mcmaster.com/#catalog/123/3110/=1aj3nkv

Mechanical Stop Bolts 11-6540 From 80/20®	2	$0.62 each ($1.24)	negligible	https://8020.net/shop/11-6540.html
M6 Hex Nut 11-6065	3	$0.13		https://8020.net/freetextsearch/search/result/?keyword=11-6065
Test tube for anesthesia interface	1	Common already owned lab equipment	Negligible	https://www.fishersci.com/shop/products/fisherbrand-higher-speed-easy-reader-plastic-centrifuge-tubes-8/p-193269
VCA collar locking knob 2907T52	1	$6.00	Negligible	https://www.mcmaster.com/#catalog/123/2238/=1ah5txp
Stainless Steel Twist Resistant Hex Shape Insert 92398A127	1	$7.06 (for 10)	1g	https://www.mcmaster.com/#catalog/123/3328/=1aj3d8d
Total	52	$2868.61	5982.704g	

			(13.19lbs)	

APPENDIX E. Engineering Drawings

L	QNT
25cm	3
35cm	2
40cm	2



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NEXT ASSY

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
ALL UNSPECIFIED TOLERANCES ARE IN ACCORDANCE WITH 3D-PRINTER LAYER THICKNESS OF 0.05mm OR LESS
INTERPRET GEOMETRIC TOLERANCING PER:
COMMENTS:
DO NOT SCALE DRAWING

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		

MATERIAL

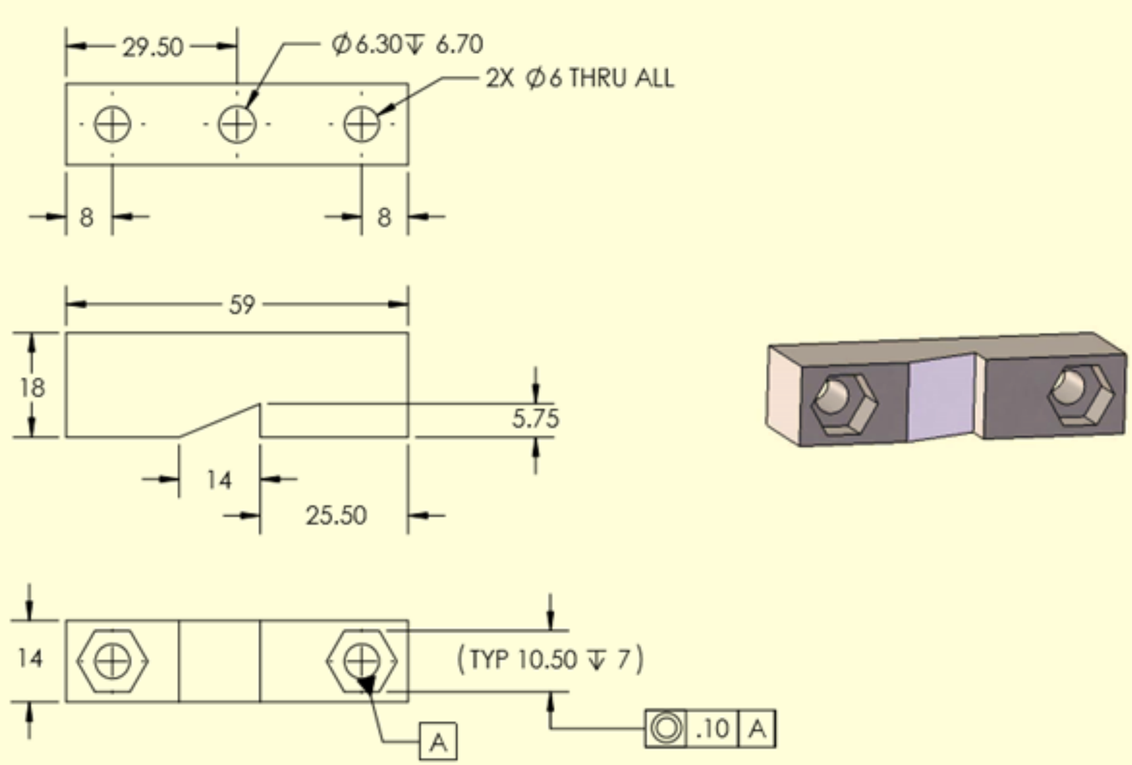
MSU M.& I.E. DEPT.

TITLE:
80-20 40series T-SLOTTED

SIZE A | DWG. NO. | REV

SCALE: | WEIGHT: | SHEET 1 OF 1

5 4 3 2 1



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APPLICATION	

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DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
ALL UNSPECIFIED TOLERANCES ARE IN ACCORDANCE WITH 3D-PRINTER LAYER THICKNESS OF 0.05mm OR LESS
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL -
FINISH
DO NOT SCALE DRAWING

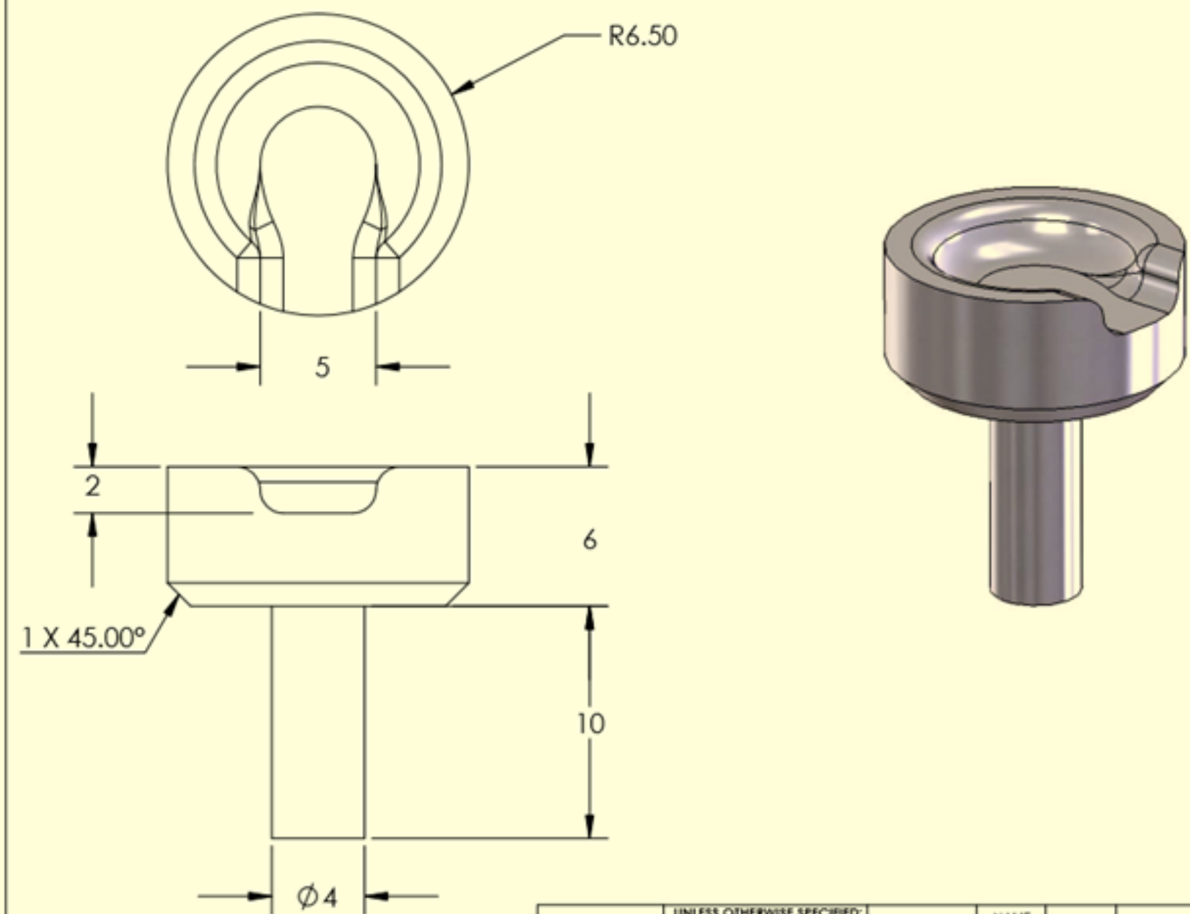
	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		
COMMENTS:		

MSU M&I.E. DEPT.

TITLE:

Ankle holster2.0

SIZE	DWG. NO.	REV
A		
SCALE:	WEIGHT: 32.77	SHEET 1 OF 1



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TOLERANCES:
ALL UNSPECIFIED TOLERANCES ARE IN ACCORDANCE WITH 3D-PRINTER LAYER THICKNESS OF 0.05mm OR LESS
INTERPRET GEOMETRIC TOLERANCING PER:
COMMENTS:
DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	-	-
CHECKED		
ENG APPR.		
MFG APPR.		

MATERIAL
-
-

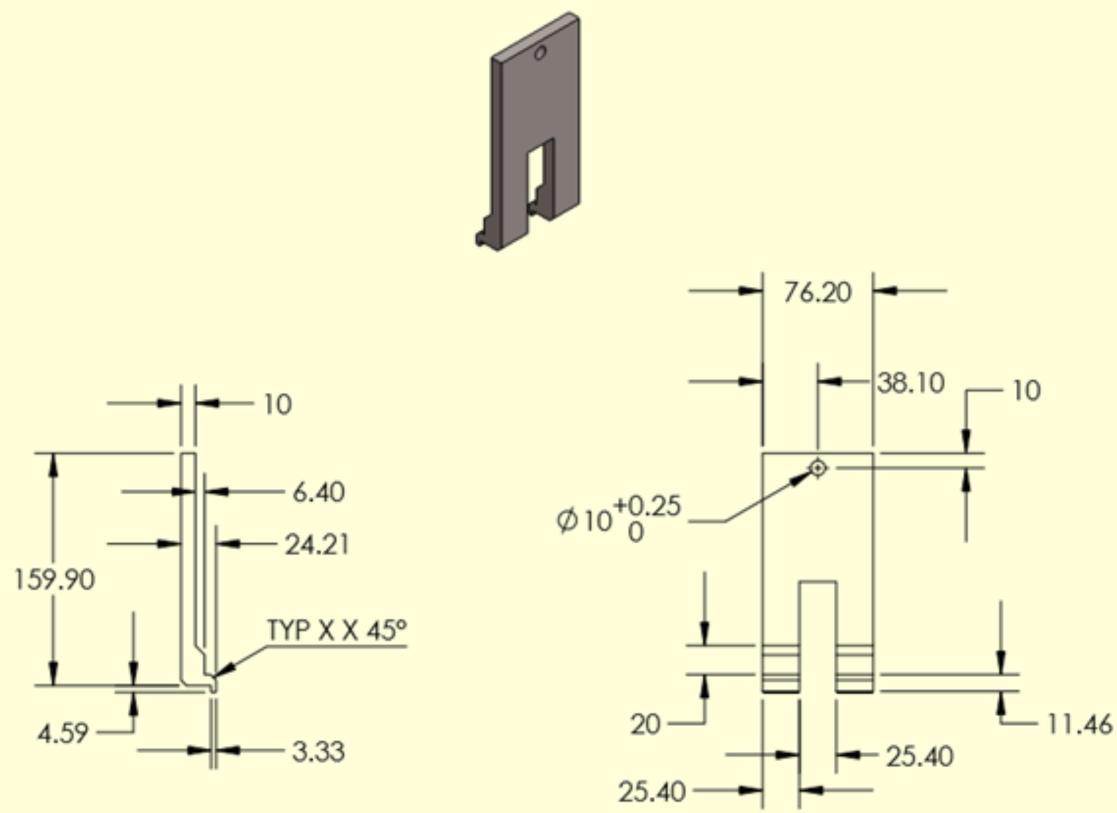
MSU M.& I.E. DEPT.

TITLE: - **Knee holster**

SIZE **A** | DWG. NO. | REV

SCALE: | WEIGHT: 2.08 | SHEET 1 OF 1

5 4 3 2 1



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
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INTERPRET GEOMETRIC TOLERANCING PER:
COMMENTS:

NEXT ASSY
DO NOT SCALE DRAWING

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
MATERIAL		

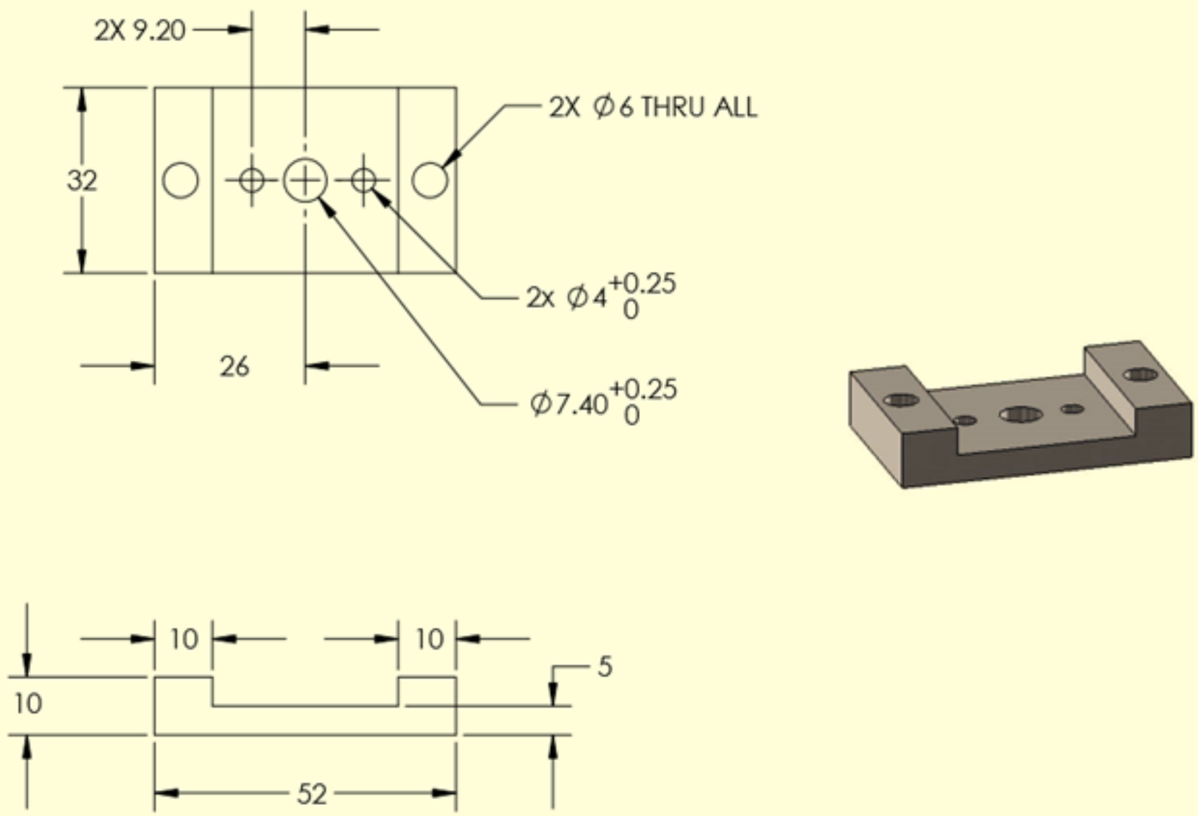
MSU M.& I.E. DEPT.

TITLE:
MOUSE PLATFORM

SIZE A | DWG. NO. | REV

SCALE: | WEIGHT: | SHEET 1 OF 1

5 4 3 2 1



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COMMENTS:
DO NOT SCALE DRAWING

	NAME	DATE
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ENG APPR.		
MFG APPR.		
MATERIAL		

MSU M.& I.E. DEPT.

TITLE: Top Slider

SIZE A | DWG. NO. | REV

SCALE: | WEIGHT: | SHEET 1 OF 1

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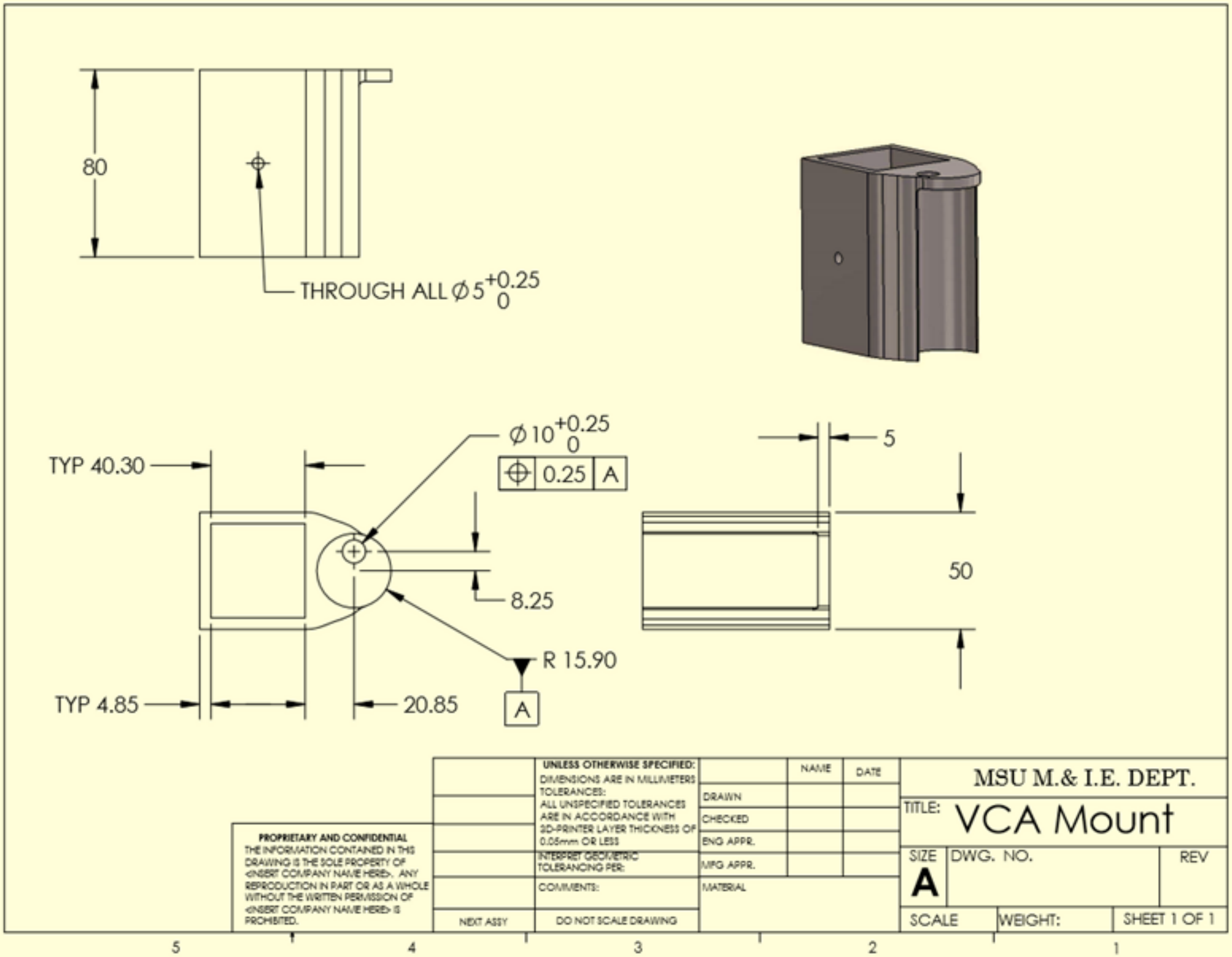
80
THROUGH ALL ⌀5 +0.25 / 0
TYP 40.30
TYP 4.85
20.85
8.25
⌀10 +0.25 / 0
0.25 A
R 15.90
A
5
50
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COMMENTS:
DO NOT SCALE DRAWING
NAME
DATE
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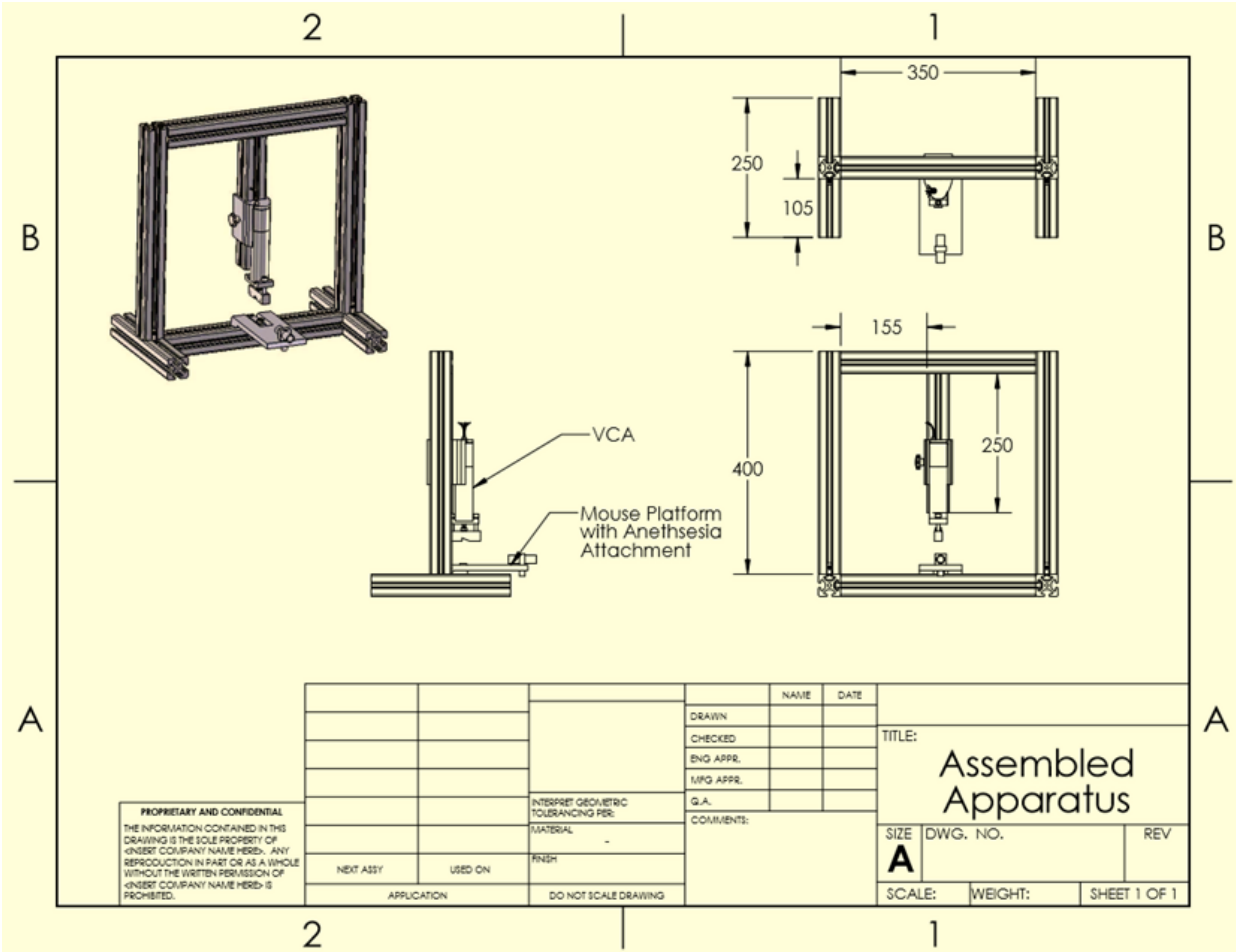
CHECKED
ENG APPR.
MFG APPR.
MATERIAL
MSU M.& I.E. DEPT.
TITLE:
VCA Mount
SIZE
A
DWG. NO.
REV
SCALE
WEIGHT:
SHEET 1 OF 1
5
4
3
2
1



350
250
105
155
400
250
VCA
Mouse Platform
with Anethsesia
Attachment
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Assembled
Apparatus
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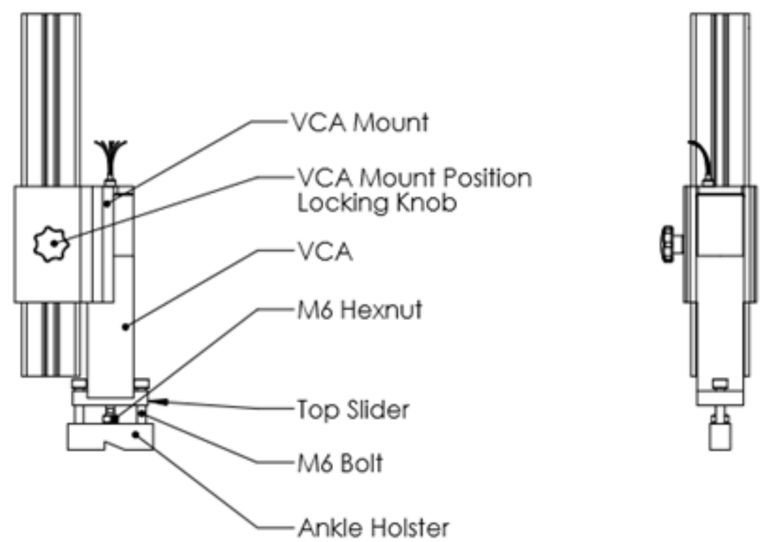
REV
SCALE:
WEIGHT:
SHEET 1 OF 1



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DO NOT SCALE DRAWING

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ENG APPR.		
MFG APPR.		
Q.A.		

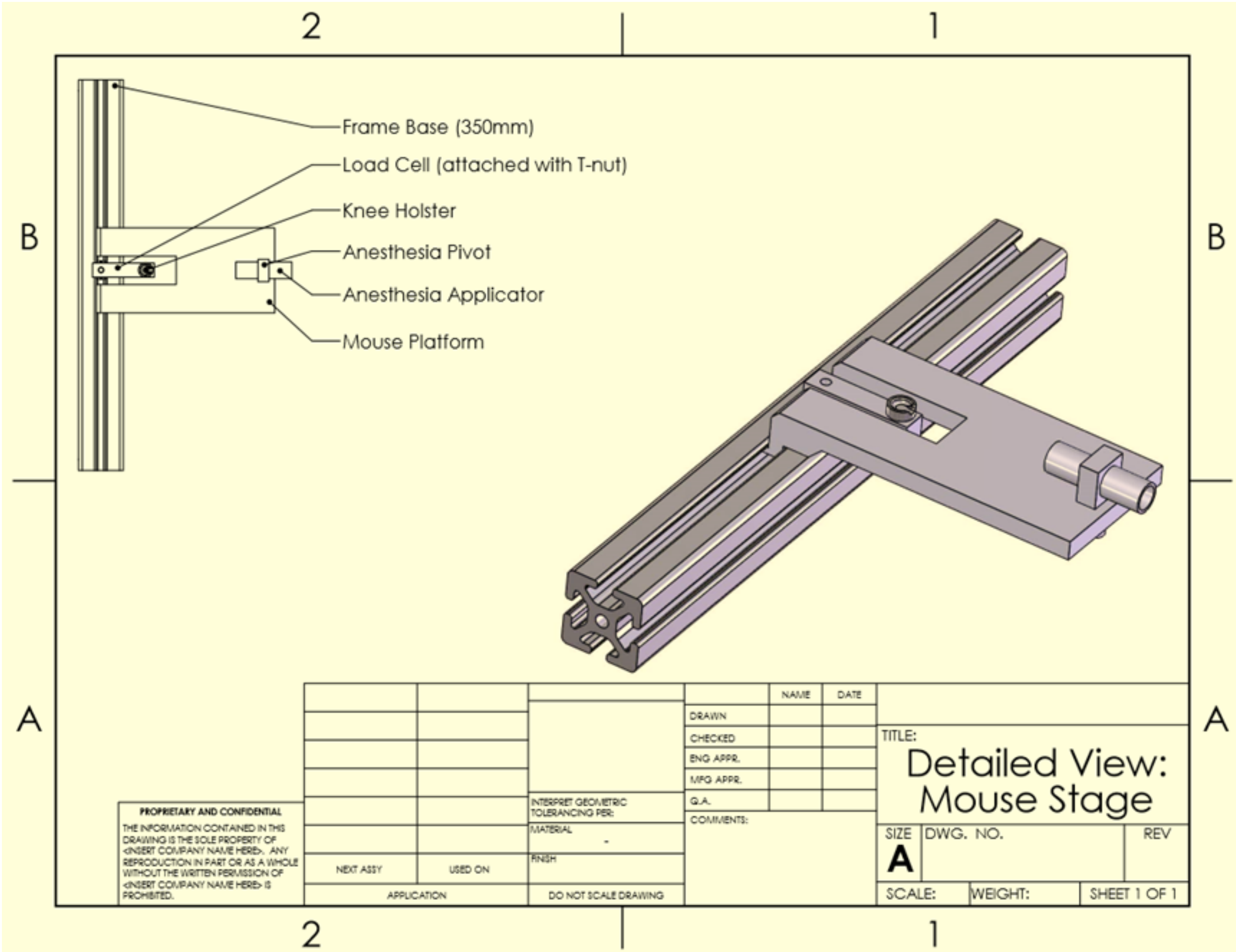
COMMENTS:

TITLE:

Detailed View: VCA System

SIZE **A** DWG. NO. REV

SCALE: WEIGHT: SHEET 1 OF 1


2
1
B
A
Frame Base (350mm)
Load Cell (attached with T-nut)
Knee Holster
Anesthesia Pivot
Anesthesia Applicator
Mouse Platform
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NEXT ASSY
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INTERPRET GEOMETRIC TOLERANCING PER:
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ENG APPR.
MFG APPR.
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COMMENTS:
TITLE:
Detailed View:
Mouse Stage
SIZE
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SCALE:
WEIGHT:
SHEET 1 OF 1

APPENDIX F. Project Economics Analysis and Budget

Economics Analysis and Budget

Current practices for producing animal models of ACLR to study osteoarthritis involve using Bose ElectroForce 3200 that costs nearly $100,000. One goal of this project is to make this research more affordable. For this reason, the budget was set to $5,000 for the project, with a goal of producing a design that would cost around $3,000 for the end users. Table F.1 (below) shows a cost break-down of all parts needed for the design. Not included in this table are shipping ($200 has been conservatively estimated) and labor needed to assemble the device.

Table F.1: *Cost Structure for design.*

Part	Supplier	Quantity	Total Cost
LAS13-56 (VCA)	BEI Kimco	1	$1650
Moticont510-01 (Motion controller)	Moticont	1	$796.84
Adhesive Strips ½" x 36" 1/16" thick Part#: 1466N12	McMaster-Carr	36"	$5.79
Arduino Due (Micro controller)	Arduino	1	$37.40
40mmX40mm T-Slotted Profile Part#:40-4040 $0.34/cm and $1.95 per cut	80/20®	180cm	125.2
fasteners 90 degree corners Part#:40-4302 $2.95/per corner	80/20®	10	$29.5
bolt assembly Part#:75-3422 $0.67/per assembly	80/20®	20	$13.4
M5 Self-Aligning Roll-in T-Nut Part#:13090 $1.40/per part	80/20®	4	$5.60
Bolt (for load cell and electronics mount placement) Part#:13-5520	80/20®	3	$0.20
5kg Load Cell	Knakro (Amazon)	1	$8.50
24vdc Power Supply	SingPad (Amazon)	1	$25.99
110vac Power Cord	Offex Wholesale (Amazon)	1	7.99
Mouse Platform $5/part + $0.56/cm^3	Shapeways	1	$73.72
Mouse knee cup $5/part + $0.56/cm^3	Shapeways	1	$ 5.39
Anesthesia Pivot $5/part + $0.56/cm^3	Shapeways	1	$6.45
VCA collar $5/part + $0.56/cm^3	Shapeways	1	$59.52
Ankle Holster $5/part + $0.56/cm^3	Shapeways	1	$7.27
Socket Head Screw ¼"-20 Part#:90128A301 (Pack of 25)	McMaster-Carr	1 Pack	6.45
Mechanical Stop Bolts Part#:1695032 $0.62 each	80/20®	2	1.24
M6 Hex Nut Part#:1521542	80/20®	3	0.13
Test tube for anesthesia interface		1	Common lab equipment
VCA collar locking knob Part#:2907T52	McMaster-Carr	1	6.00

Stainless Steel Twist Resistant Hex Shape Insert Part#:92398A127 (Pack of 10)	McMaster-Carr	1	7.06
Total			2853.09

In order to facilitate ease of ordering parts as mentioned in Appendix B, all custom parts will be printed from Shapeways. This will allow the lab building the device to order the custom parts as a package directly from Shapeways' website, instead of finding a custom manufacturer and working with them to produce parts. All other parts can be purchased from the suppliers listed in Table F.1. Assembly of the device is assumed to take 1-3 hours once the user has all of the components.

It is important to note that if the device does not behave correctly and impacts the mechanical stop, the VCA could be damaged. This would result in a $1650+ expense, however it is not expected that the situation would ever happen. The microcontroller will be programmed to not allow a VCA displacement that would result in mechanical stop impact, but the stop was included to facilitate added safety for the animal model being produced.

APPENDIX G. Project Academic Assessment

Academic Assessment

Several aspects of the mechanical engineering curriculum have been exercised during this design process.

Table G.1: *Table*

Class	Description	Degree (1-5)
EGEN 205: Mechanics of Materials	This course was instrumental to understanding how to go about the structural analysis of the frame and other components.	3
EMEC 405: Finite Element Analysis	Although Solidworks was used for FEA, skills learned in the FEA course, taught with ANSYS, were relevant, including assessing whether or not results were reasonable (converged).	1
EELE 371: Microprocess HW and SW Systems	The implementation of microcontrollers and assembly language will be integral parts of this project during the build of the design. Without this class, decisions about the necessary electronic components could not have been made.	5
EMEC 403: Design Integration	This course was useful in teaching how to run an FEA in SolidWorks.	4
EMEC 360: Measurements and Instrumentation	The measurements course covered several subjects relevant to this project, such as the basics of data acquisition/Arduino, strain gauge load cells, and LVDT.	3
EMEC 303: Systems Analysis	This course was very helpful in teaching how to use MATLAB for the analysis of the frame.	4
EMEC 103: Engineering Graphical Communications	Basic SolidWorks drawing skills were needed in order to accurately communicate the design to the project's advisor and sponsor. These drawings were also used in the FEA.	4

EGEN 310: Multidisciplinary Engineering Design	This team design class helped teach how to work in a team while making a design.	2

APPENDIX H. Failure Modes Effects and Analysis (FMEA)

FMEA Chart

Item	Function	Failure Mode	Causes	Occurance	Effects	Severity	Method of Detection	Detection	RPN
Force Application	Provides the force required to accelerate applicator to specified velocity, within specified displacement	Shaft side load	Mode applied in more than one axis	1	Force not applied directly to the ACL - possibly to other tendons or bones, potential damage to VCA	10	Visual Inspection	2	20
		Excessive force	Feedback controls not regulating motion properly	3	Difficult to stop force applicator, failure to meet specifications	6	Data inspection from test run	1	18
		Insufficient force	Not enough pressure/power	2	Avulsion injury instead of clean ACL rupture (if under 180 mm/s)	9	Data inspection from test run	2	36
Physical Stop	Ensures that no collateral injury in mouse occurs	Breaks from multiple impacts	Fatigue fracture	2	Damage to other knee structures such as the femoral condyles	10	Visual Inspection	4	80
Anesthesia Interface	Keeps mouse sedated	Mouse wakes up and escapes	Fixture inhibits proper anesthesia flow	1	Improper handling and treatment of mice	10	Visual inspection of Anesthesia hoses/valves	1	10
Feedback Loop	Govern motion of applicator	Feedback loop response is too slow	Feedback loop update frequency is insuffient	8	Applicator is not arrested within specified displacement, impacts physical stop	7	Test run without mouse, displacement data, high speed footage	2	112
Frame	Holds all components in place, ensuring precision	Not stiff enough	Poor geometry or material selection	2	Data will not represent relative, not absolute results	5	Classical mechanics, potentially FEA or high speed footage	7	70
		Assembled incorrectly	Poor instructions or confusing assembly	2	Improper dimensions for components to work properly/structural instability	8	Visual inspection/Secondary check with instructions	2	32
Applicators	Holds mouse in correct position throughout entire force application	Misalignment	Placed in frame improperly after sterilization	3	Mouse leg could slip out of testing area and mouse could receive injury besides ACL rupture/force application could be concentrated on other knee structures besides ACL	10	Visual Inspection	2	60
Electrical Circuitry/Wiring	Relay data from measurement devices to Arduino to be stored and send feedback signals	Unplugging, shorting, EMI/RFI	Wires getting tugged while moving device/poorly labeled wire ports/cold solders	5	Experiment does not take place or data is not collected and experiment was for naught	8	Visual inspection of wires/Code test without running actual test/potential use of ferrites I/O	10	400
Microcontroler	Collects and manipulates data	Code doesn't work, gets deleted or corrupted	Poor instructions for uploading code	3	System does not function	10	Code test without running actual test	8	240
		Compromised by environmental factors such as water, temperature (operates at -40 to 85 degrees celsius), power surge, etc	Arduino not properly covered in a waterproof shell, or exposed to excessive temperatures (autoclave)	2	Arduino destroyed, loss of time and money	6	Incorporate controller status into code to indicate if the controller is functional	8	96

Rank

1. Electrical Circuitry/Wiring
2. Microcontroller
3. Feedback Loop
4. Physical Stop
5. Force Application
6. Mouse Contacting Plates
7. Anesthesia Interface

Action Plan

1. ***Electrical Circuitry/Wiring.*** Extensive documentation will be provided with a detailed wire diagram and proper procedures for soldering. Circuits will be made as simple as reasonably possible. Both of these considerations are important since the end user may have little to no electronics experience. Videos may also be included with the documentation to aid in the assembly.
2. ***Microcontroller.*** A protective shell will be designed to protect the microcontroller from any moisture and sterilization. It will also be thoroughly state in documentation and potentially on the case itself not to autoclave or place in extreme environments. If necessary heat sinks can be incorporated into this shell if overheating becomes a concern.
3. ***Frame.*** Extensive mechanical analysis will be performed to ensure the frame is structurally stable and stiff enough. A "portal" frame analysis will be performed along with FEA in solid works to ensure that the total vertical deflection in the frame is no more than 5% of the smallest displacement to failure that has been observed in past experiments. Stiffness is the main concern since the maximum loading on the frame is to be 100 N. However, a stress analysis will be performed to ensure that nowhere in the frame yields. Quality products will be purchased to limit material and manufacturing defects. Supporting Documentation and possible videos will detail the correct assembly procedure. Instructions will also be provided on how to properly visually inspect the structure.
4. ***Force Application.*** Maximum side load values will be observed for the VCA. High quality fasteners will be chosen to ensure the force application remains in the correct position over many cycles. A simulation will be completed to ensure a chosen VCA produces enough force to meet specifications.
5. ***Physical Stop.*** This stop is for a "worst case scenario" meaning that if it is used something went wrong with the feedback loop. The stop will be designed to be inexpensive with replacement in mind. A classical mechanics analysis and solid works FEA will be performed to insure it does not fracture from the impact. Vertical deformation will also be analyzed to ensure that the force applicator will be stopped before the 2.25 mm mark.

6. ***Feedback Loop.*** When choosing components, processing speed will be of high concern. The mass of the applicators will be limited as much as possible to reduce momentum.
7. ***Mouse Contacting Plates.*** These plates will be 3D printed from nylon which is stiff (Flexural Modulus of 1.4 GPa), low cost, and easily sterilized with ethanol. An option to 3D print in metal will also be provided if the end user would rather autoclave, however this is significantly more expensive. FEA in solid works will also be performed to ensure that there is no yielding present in the parts. The connections of the applicators to the remainder of the system will be user friendly and such that it would be extremely difficult to replace them incorrectly.
8. ***Anesthesia Interface.*** Care will be taken in designing the interface so that any kinks in tubing or other factors that could inhibit flow are highly unlikely to occur. The nose cone will also be designed with adjustment in mind for different sized mice.

APPENDIX I. Data Sheets

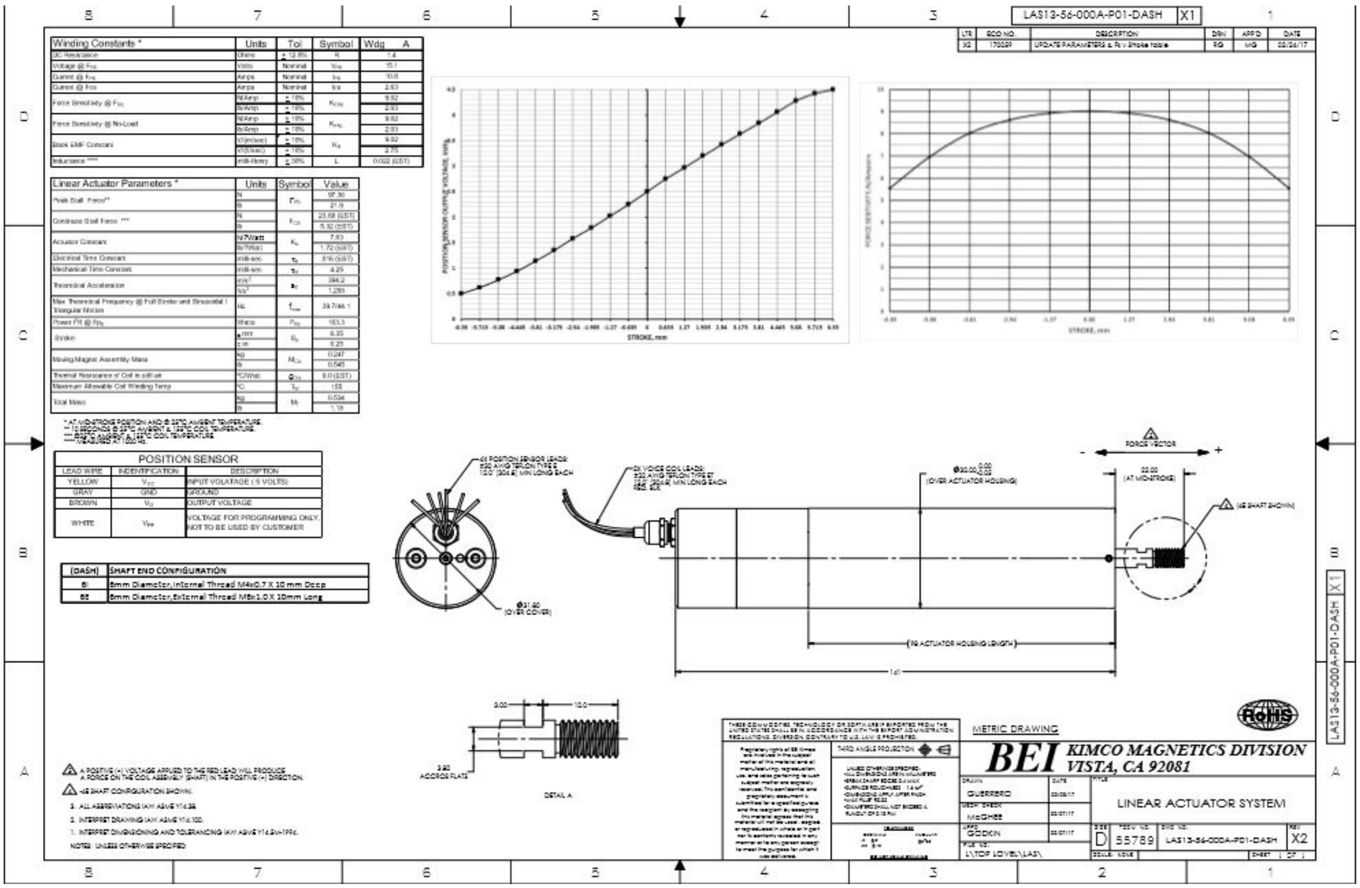

Figure I.1: *VCA Data Sheet*

Power Specifications		
Description	**Units**	**Value**
DC Supply Voltage Range	VDC	20 - 80
DC Bus Over Voltage Limit	VDC	86
DC Bus Under Voltage Limit	VDC	17
Logic Supply Voltage	VDC	5
Maximum Peak Output Current	A (Arms)	12 (8.5)
Maximum Continuous Output Current	A (Arms)	6 (4.2)
Internal Bus Capacitance	µF	330
Minimum Load Inductance (Line-To-Line)[1]	µH	250
Switching Frequency	kHz	20
Control Specifications		
Description	**Units**	**Value**
Communication Interfaces	-	RS-232
Command Sources	-	±10 V Analog, 5V Step and Direction, Encoder Following
Feedback Supported	-	±10 V Analog, Auxiliary Incremental Encoder, Halls, Incremental Encoder
Commutation Methods	-	Sinusoidal, Trapezoidal
Modes of Operation	-	Current, Position, Velocity
Motors Supported	-	Brushed, Brushless, Voice Coil
Hardware Protection	-	40+ Configurable Functions, Over Current, Over Temperature (Drive & Motor), Over Voltage, Short Circuit (Phase-Phase & Phase-Ground), Under Voltage
Programmable Digital Inputs	-	2
Programmable Analog Inputs	-	1
Current Loop Sample Time	µs	50
Velocity Loop Sample Time	µs	100
Position Loop Sample Time	µs	100
Maximum Encoder Frequency	MHz	20 (5 pre-quadrature)
Mechanical Specifications		
Description	**Units**	**Value**
Weight	g (oz)	159 (5.6)
Heatsink (Base) Temperature Range[2]	°C (°F)	0 - 65 (32 - 149)
Storage Temperature Range	°C (°F)	-40 - 85 (-40 - 185)
Cooling System	-	Natural Convection
Form Factor	-	Chassis Mounted

Figure I.2: *Motion Controller Data Sheet*

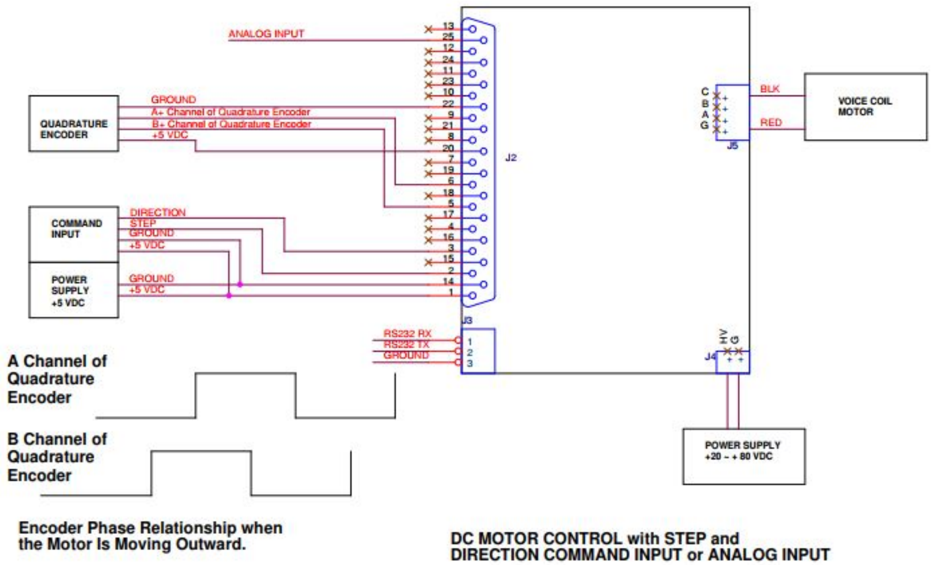

Figure I.3: *Motion Controller Circuit Schematic*