Final Report

Concussion Simulation Team

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Contents

1 Problem Statement

A major issue right now, especially in athletics, is the long term effects of a concussion on a person even after they have been cleared to return to work. There are many speculations as to what causes these long term effects and what can be done to reduce them. While the brain itself may receive damage from a concussion, the nerves are what allow the brain to function properly. Therefore, long term damage to the functionality of nerves will directly affect the functionality of the brain. Research into nerve impact will hopefully help to gain a better understanding of the extent of long term nerve damage due to various concussions.

Our goal is to create a device for the Oklahoma State University Chemical Engineering department that can expose petri dishes (containing synthesized neural tissue in sterile conditions) to angular accelerations that the human head experiences during a concussive injury. High angular accelerations due to an impact cause the brain to shift inside the skull and this abrupt motion is responsible for causing neural tissue damage to the brain. The forces will be applied mechanically so that there will be a greater amount of precision in both the forces applied and the overall process of inducing a concussion.

To do this, a device will be constructed incorporating accelerometers, motors, electromagnets, and other computer-controlled components that will take as many variables out of the impact scenario as possible. After the mechanical force is applied to the synthesized neural tissue, the functionality of the tissue will be evaluated and compared to that of known neural tissue degradation to act as a baseline for further tests. The tissue will then be evaluated daily to determine the time it takes for the tissue to become fully functional again, as well as to determine the line or curve of the percent recovery vs. time along with other secondary data. This procedure will be repeated at different impact forces all above that of a concussion grade force and the data for each test will be compared. With this data, the goal is to determine a baseline for recovery time from a concussion injury based on the degradation of the nerve tissue. This device is also intended to serve the Chemical Engineering department in future experiments regarding mechanical applications of force.

2 Deliverables

Our goal this semester was to create an automated machine that would induce a concussion force onto nervous tissue sample with exceptional accuracy and precision. This device needed to be fully automated, of high quality, and be easily operated by someone with a basic engineering background. All of these things were to be delivered under a budget of $6000. This budget, determined by our sponsor, was one that included any licenses as well as specialized sensors that would need to be purchased. Though our budget was high, our sponsor employed upon us that we try to save money where possible and to make wise decisions when making purchases.

Along with all of the structural progress we have made, we have also been responsible for logging our information and logging all progress made for the project, and preparing our work for possible publications in the future. Because of this, we have also participated in the OSU Research Week Symposium's Poster Contest and in the University of Kansas's Regional Chemical Engineering Research Competition. All of our logged information will be used as reference for publication, and our instruction manual will allow those doing further research with our machine to have proper the proper documentation they need to get reliable results.

3 Work Completed

3.1 Materials

3.1.1 Accelerometer

The high frequency accelerometer was by far the most difficult piece of equipment to select. This was because of the many difficulties setting up our instrumentation system. We first looked into previous research on concussions and found that angular accelerations between 2000-9000 rad/s^2 and linear acceleration above 97gs would produce concussions to the human brain. With these numbers we were able to determine the specifications of our required accelerometer. When we developed our first prototype, we measured our acceleration using high speed cameras in order to determine the impact time between our hammer and our specimen arm as well as the tangential acceleration and rotational acceleration of the specimen arm. We were able to determine that the impact time lasted around 3ms when our rotational acceleration exceeded 5000 rad/s^2. With this data, we were able to determine that we needed an accelerometer with a sampling rate of at least 5000Hz, has a measurement range of ±250gs, and has a sensitivity of 9.8 mV/g.

Initially, we found models that had already been used in concussion testing. These accelerometers had been used in helmet impacts for football as well as applied to the skin for real world impacts. The accelerometers met our requirements but they were reaching the top of our budget in the $4000+ dollar range and all of them required some other software to run and would require a large amount of coding in order to make them work with LabView. Because of this, we decided to move on to accelerometers that were not specifically labeled as “concussion accelerometers” and would still meet our needs.

We next found about 10 different brands of accelerometers that we compared against each other based on their specification sheets as well as calls to the respective companies as well. When calling each of the companies, we made sure that the accelerometer would work well with LabView, would not require any extra amplification or filtering to work, and would not be paired with any unforeseen costs associated with purchasing the accelerometer. After calling companies, we then passed those that met our standards by Dr. Conner in order to determine if the accelerometer would meet our needs.

This got us down to four main accelerometers that we strongly considered and that Dr. Conner had approved. To narrow our search down a final time we called each of the companies again and asked pointed questions about how well each accelerometer would work without an additional power source and specifics on the wiring and extra labor that would be required to make them work. We determined that many of the high frequency accelerometers had a 4 wire setup which caused many problems of their own (detailed figures in Appendix). 4 wire accelerometers had wires for ground and the x, y and z axis but had no additional wiring for power. These accelerometers required us to either buy either an additional 4 wire specific power source, or upgrade our data acquisition device so that it could power our accelerometer.

The final model we have chosen was the Model 356A33 Triaxial Accelerometer from PCB Piezotronics. While this model does require an additional power source, we will be able to make it work with our DAQ device and the total cost for all of the components required will be well within our budget. This model will sample at up to 10000 Hz and has a ± 500g measurement range. The fact that this accelerometer is affordable enough to include the power source is also a strong benefit because it will give us extra filtering for our signal and more accurate results. Also, all of the components that go with this accelerometer have a lifetime warranty which will allow our sponsor to confidently conduct tests knowing that he is covered for any manufacturing or calibration imperfections caused by the company.

3.1.2 Stepper Motor/ Stepper Drive

To determine how to lift our impact arm, we first calculated the force needed on our specimen arm in order to create the accelerations we needed. We calculated this using the momentum equation as well as our energy conservation equation knowing that our coefficient of restitution between steel and aluminum was 0.56.

$$\boldsymbol{e = \frac{Va2 - Vh2}{Vh1 - Va1} = \frac{Va2 - Vh2}{Vh1}} \tag{1}$$

$$\boldsymbol{e = \sqrt{\frac{KE\ after\ impact}{KE\ before\ impact}} = \sqrt{\frac{\frac{1}{2}Mh\,Vh2^2 + \frac{1}{2}Ma\,Va2^2}{\frac{1}{2}Mh\,Vh1^2}} = \sqrt{\frac{Mh\,Vh2^2 + Ma\,Va2^2}{Mh\,Vh1^2}}} \tag{2}$$

Using these equations we determined that a hammer weight of 8 lbs with a length of 3.5ft would suffice if it was rotating at 95 RPM by impact. Using torque calculations we determined that the hammer would be exhibit a maximum torque of 25 Nm if it was directly connected to a motor shaft and lifted to a horizontal level.

We decided that we had two options when determining what motor would work with our design. The first was a gear motor that would pull up our arm by winding up an attached string as shown in Figure 1.

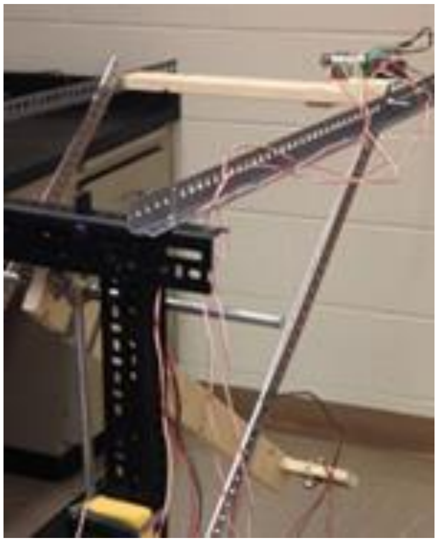


Figure 1 Mechatronics system for swing-hammer impact

While this method would allow the motor to impose a lower torque on the swing hammer, there were many factors that were introduced that could have caused inconsistencies such as trouble winding the string and also releasing the hammer. Because of this we decided our second option was the better choice. Our second option was to go with a stepper motor. With a stepper motor, our weight can be driven into our specimen arm by rotating our motor at the desired RPMs. This will allow for a larger variance of impact forces possible in the amount of space there is to raise the arm when compared to just releasing the swing hammer and letting gravity control the force. Also because the motor raises our arm at 1.8° per turn, it will allow us to have another check on our height logged along with the data gained from our rotary motion sensor.

When deciding the size of the motor we had two options. The first was to go with a smaller stepper motor but then use a gearbox so that the torque would not all be felt on the motor. This option was a good option due to the ease of replacement parts and the lower cost of motor but with our time constraints we were unable to allot enough time to designing and ordering the entire system. For this reason, we decided to go with a larger, more expensive stepper motor and have our swing hammer attached directly to the shaft through coupling. In this setup, our motor would feel the entire 25 Nm torque but would be rated to handle a torque above that.

This decision led us to decide on a NEMA 42 stepper drive with 30 Nm of holding torque. This motor will meet our needs of lifting a hammer swing arm of 3.5 feet with a weight of 8 pounds and then releasing it at the exact height we want. Along with our stepper motor we have also selected the appropriate stepper drive and power supply.

3.1.3 Data Acquisition Device

For data acquisition we found a DAQ Device with 8 analog channels and 13 digital channels. This would allow us to use 6 of the analog channels for the x, y and z directions (as differential channels) and then use 3 digital channels for our stepper motor and rotary motion sensor. The DAQ will also give us some natural filtering to our accelerometer signal which will give us better readings from tests. This DAQ will also run smoothly with LabView because it is a National Instruments device.

We had a choice between two National Instrument DAQ devices. Both had the same number of channels but one had double the sampling capability of the other for about a 20% raise in cost. After discussing these options with Dr. Conner, we determined that the DAQ with the higher sampling rate would be much better for our money because of how many devices we were running through it as well as how high the sampling might be through our accelerometer.

It should also be noted that there were several accelerometers that came with their own DAQ devices which worked optimally with the sensor. While these DAQ devices offered many various advantages such as independently powering the accelerometer or offering extra filtering of the signal, the DAQs came with a very large price tag that often exceeded that of the accelerometer. After discussions with our sponsor and other professors, it was determined that using the NI DAQ device would meet all of our testing needs and that the extra filtering and other options were not worth the extra cost they carried.

3.1.4 Rotary Motion Sensor

We will be using a simple rotary motion sensor that will be attached to the other end of our extension form the motor shaft. This sensor will serve as a second check to make sure that the height of our swing arm is correct. All data logged from this sensor will be in LabView and can be seen in real time when running the experiment. The model we finally picked was the Vernier rotary motion sensor. After corresponding with Dr. Joseph Conner about the device and inspecting the spec sheet we concluded that this model is not only feasible price-wise, but also sufficiently accurate as it can record angle offsets which are as small as 0.25 degrees at our rotating speed. We have calculated from our kinematic impacts calculations that we will not need to rotate the shaft at more than 100 RPM, which is well below the maximum rotation that can be recorded by our sensor.

The only other option considered for logging the height of our swing arm was an inclinometer attached to the swing-arm, which would indirectly give us the angle of the device by recording the gravitational acceleration and calculating the angle based on that acceleration value. This device was considered in the very early stages of research but was quickly thrown out because the rotary motion sensor selected was more accurate and easier to use, and the price difference between the two devices was not enough to validate going with the cheaper option. After ordering the rotary motion sensor, we drilled a 5/16 inch diameter hole through the side of our metal frame and bolted the sensor to the inside of the frame so it aligns perfectly with the shaft that is coupled with our stepper motor.

3.2 Solidworks Design/Manually Machined Structure

3.2.1 Previous Frame Designs

Several previous Solidworks designs were drafted before we arrived at the current dimensions and design that we have for our device. We started off with the goal of having a swing hammer with a 3.5 feet radius, as that was the optimal radius for giving us the desired range of dynamic impacts in our previous prototypes for the device. Initially, we wanted to have a cubic shaped frame for containing the system. The motor was to be attached to a top edge of the box and would reel in the swing hammer from the opposite and lower edge of the frame using string/rope of some sort. The Solidworks model for this design can be seen in Figure 2.

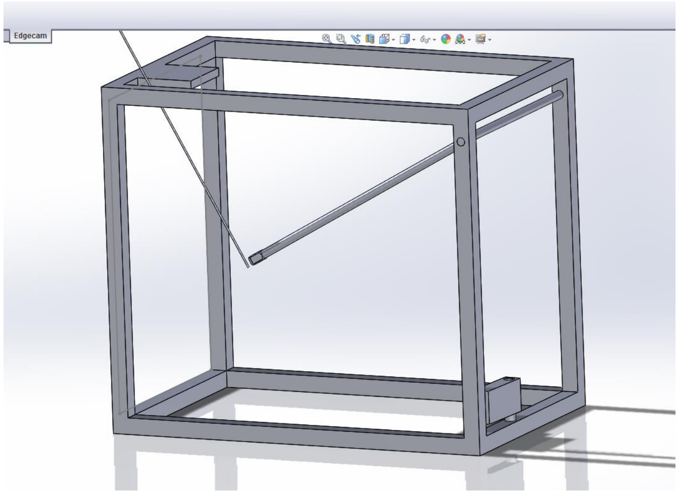


Figure 2 Solidworks frame for initial frame design

As soon as we decided to directly rotate the swing-hammer using a high-torque motor instead of using a weaker one to reel it up, our design parameters became simpler. We no longer needed a box-like frame. We decided to have frame that looks like an upside-down T from a side-view. The motor and the rotary motion sensor were to be placed at the top of the frame, where they would rotate the swing-hammer arm and measure the angle of rotation at the same time. The length of the frame was selected to be 6 feet. Although it does not cover the entire swing diameter of 7 feet, the length is high enough to keep those using the device out of harm's way during experimentation, as we are never expecting the hammer to be elevated to close to 90 degrees on either sides.

3.2.2 Steel Frame

After consulting with our course instructor about our models we made further improvements. We determined the right width for the frame, so that it doesn't topple over easily even when it is not bolted to a heavy base. We decided to connect the top of the frame using a bar on the top to make our frame sturdier than it was before. We also moved the motor from the side of the frame to a spot closer to the center. As the motor is of significant weight (12.5 kg), keeping it as close to the center as possible will make the device less likely to topple over under any circumstances.

As soon as we decided to directly rotate the swing-hammer using a high-torque motor instead of using a weaker one to reel it up, our design parameters became simpler. We no longer needed a box-like frame. We decided to have a frame that looks like an upside-down T from a side-view. The length of the frame was selected to be 6 feet (72 inches). Although it did not cover the entire swing diameter of 7 feet, the length is high enough to keep those using the device out of harm's way during experimentation, as we are never expecting the hammer to be elevated to close to 90 degrees on either sides. We also set the width of the frame to be 30 inches and the height to be a little more than 49 inches. All dimensions can be seen in the Solidworks drawing in Figure 3 in the appendix. We initially considered building the frame out of aluminum using T-Slots but we discarded that plan when we realized it would be unnecessarily expensive. We finally decided to build a structure out of 1 inch by 1 inch hollow steel tubing with 1/8 inch thickness, and have it professionally welded to ensure it is built perfectly.

We had our design constructed by Stillwater Steel Services with funding from our sponsor. The final weight of the steel frame was 67 lbs and from toppling moment calculations we found at least a 30 lbf horizontal force would be needed to topple the frame over, which was satisfactory for our purposes. We had 5/16 inch diameter holes drilled on the side of the frame for our rotary motion sensor placement, on one of the plates to attach a pillow block that supports the weight of the hammer, and at the bottom of the frame to attach our specimen arm holder to. The final picture of our painted frame can be seen in Figure 3. The motor and the rotary motion sensor were placed at the top of the frame, where they would rotate the swing-hammer arm and measure the angle of rotation at the same time.

Figure 3 Final painted frame

3.2.3 Impact swing-hammer

We started off with the goal of having a swing hammer with a 3.5 feet (42 inches) radius, as that was the optimal radius for giving us the desired range of dynamic impacts in our previous prototypes for the device. After doing some further kinematic calculations we came to conclude that 40 inches would be a better length from top of the shaft to the bottom of the hammer, and modeled our frame around that number. From our impact calculations we found that going with an 8 lb (3.63 kg) hammer would be ideal for the desired final speed. We ordered a steel shaft and a steel block for the hammer-head. We machined the hammer head and shaved off edges until it was the right weight and welded them together. We also found the hammer would produce a 25.0 Nm torque when lifted to a horizontal level, which is below our motor's torque capacity. The Solidworks model of our hammer the final welded hammer is shown in Figure 4 below.

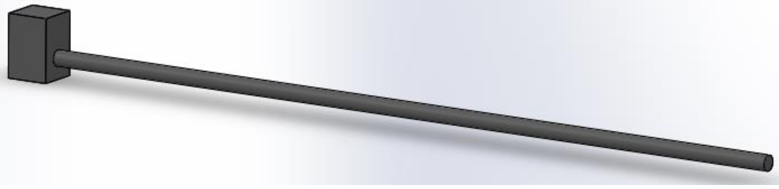


Figure 4 Solidworks model of hammer

3.2.4 Specimen arm

We had to make many factors into consideration for designing our specimen arm. The damping system we were initially planning to implement affected our initial designs. When we discarded the plan for damping, the design became a lot simpler. We used kinematic calculations to figure out the ideal radius and ideal mass of the specimen arm. The radius of the specimen arm was also influenced by the radius of rotation of the human head upon impact. The coefficient of restitution also determined the material properties of the specimen arm we created. Since we needed a fairly light arm which weighed less than 1 lb (0.45 kg) to meet with our rotational acceleration requirements, we went with a light yet strong aluminum alloy, Aluminum 6061 for our modeling. We decided its dimensions to be 1 in x 1 in x 8.66 in to meet the mass and radius requirements. We had the specimen arm set to rotate on another aluminum block that would be bolted to the bottom cross-bar in our steel frame. After designing it and finding the right distance the specimen arm needed to be from the side of the frame we started building it in the Design and Manufacturing Lab.

We machined the specimen arm holder and bolted it to our frame as planned. Next we designed the specimen arm from aluminum. And placed the bolt inside it which would serve as the pivot shaft around which the specimen arm was to rotate. The bolt was screwed into a tapped hole in the specimen arm holder to keep it sturdy and static through the impacts. There were two small bearings with an inner diameter of 0.3125 inch and outer diameter of 0.867 inch which was placed in the specimen arm to allow it to rotate without any frictional resistance. Finally, a nylon sleeve was used to hold the specimen arm up to the top of the bolt without allowing it to slide down. The picture of our specimen arm model can be seen in Figure 5 below.

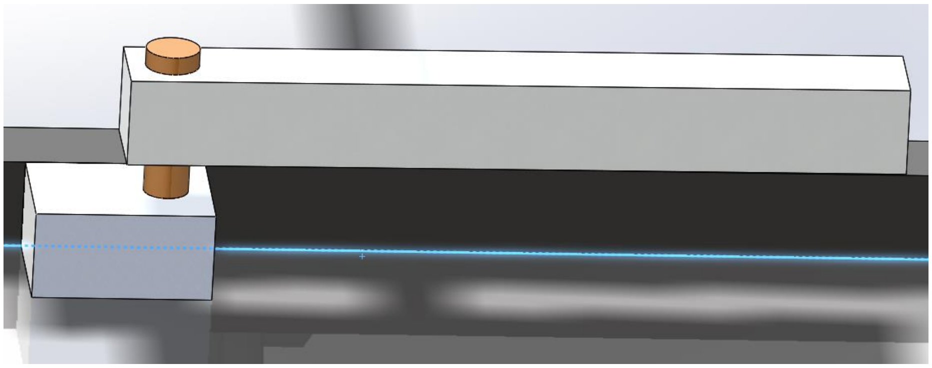


Figure 5 Solidworks model of specimen arm

3.2.5 Damping system

One of our initial goals was to design a damping system that accurately models the deceleration of the human head after the initial impact which causes very high acceleration. We looked at several possible options throughout the semester. We first considered using a one way frictional bearing that would slow down the rotation in only one direction, but ended up moving away from that idea as we couldn't find the right bearing. Next, we considered implementing a magnetic resistance system to slow down the rotational velocity, but discarded that option as well because it would make the system more complicated than it needed to be. Finally, after consulting Dr. Joseph Conner, we decided we wanted to go with an Airpot Dashpot, a device that slowed the motion of a system by using the compressibility of air. We thought it would be ideal as the damping coefficient of the device can be easily changed using a tuner at the back of the dashpot.

We designed a Solidworks model for the system to incorporate the linear motion damper to stop our rotating arm and we calculated the necessary dimensions for the system if it were to be implanted. However after the modeling, as we looked into further research regarding the standard deceleration curve of the human head due to physiological factors after an impact, we realized that there was no concrete data on this motion. So we realized that we could build the system and not be sure of what damping coefficient to use on our specimen arm. Because of this uncertainty we decided to not machine and implement the damping system that we designed, and leave the implementation of this system for the future when more data is available on the desired damping motion

3.3 Calculations

Numerous calculations went into creating the device that we have now. We had to pick our motor carefully because we needed it to be of a high enough torque capability to rotate a 5-8 lb swing-hammer with ease. After calculations on the torque needed we selected a 4200 oz-in stepper motor. The selection of an accelerometer involved more calculations than any other part. Because of the very low times of impact we needed something that would capture the data well over a 2-3 ms time-span, and we decided that any accelerometer that records at a sampling rate higher than 5 kHz would suffice. We also calculated that the DAQ Device had to have a collecting frequency of higher than 10 kHz to avoid aliasing. Moving to the frame dimensions, we tried selecting different widths for the frame and then calculated how strong of a force it would take from the side opposite to the motor and 2.5 ft vertically off the ground to actually topple over the device. Even using a light aluminum alloy we found that 25 lbs of forces would be needed to lift/topple the device, provided that it did not slide, when the width of the frame was 2.5 ft. Hence we concluded that 2.5 ft will serve as a good width for the frame of the device. We also eventually chose to switch to a heavier steel frame to have a higher safety factor.

3.4 Log Book

We have included pictures and figures of the models we have worked with so far in our log books and included some of the important calculations that we have done in this project so far in the log book as well. We have also logged in ideas that we have come up with during team brainstorming and recorded all important ideas we have considered throughout the project.

4 Detailed Description of Final Design

4.1 What does it do

Our machine allows the user to truly combine both the biological and mechanical applications of concussions that to this point have been limited to separate testing. Biologically, the machine allows the user to use a wide variety of tissues and cultures into the specimen arm for testing. Those biological specimens can then be impacted accurately and with the exact amount of force that the user wants.

Apart from manually inserting and removing the biological tissue, the rest of the device is fully automated. By using LabVIEW software to control all the devices and data capture on the device, results can be accurately obtained and errors due to the user will be held to a minimum.

The user will run the machine by using LabVIEW to start collecting data with the accelerometer as well as to raise the swing hammer to the correct height. The software will then drive the motor at the correct RPMs to impact the specimen arm at the users' desired force. LabVIEW will then stop the swing hammer so that it does not swing back to impact the specimen arm. The specimen arm will spin after impact and slow down to a stop. The user will then be able to remove the tissue from the machine to physically analyze it as well as analyze the accelerations the tissue experienced.

4.2 Manufacturing and Materials

Our steel frame was cut and welded professionally by Stillwater Steel. The cost with parts and labor is $250. The frame was then spray painted to protect against corrosion and for aesthetics. Our T-joint, swing hammer, specimen arm and motor shaft were all custom machined at the DML and the cost of the parts collectively was about $100. All drilling and into the steel frame to add customization was done manually with a hand drill. Instruments such as the accelerometer, stepper motor, and Vernier rotary motion sensor were purchased as is and no modifications were made except for sanding down the key size of the stepper motor so that it would couple well with our shaft. While many of the machining and customization we did took us weeks to do, we believe that the time it would take to build and replicate the entire machine would be about 20 work hours.

4.3 Materials for Key Components

To make our full system work cohesively additional components were machined or purchased. To connect our motor to our motor shaft we purchased a coupling that would connect the two using set screws. We had to slightly modify the key size of the motor shaft since it was not the standard size to fit in the coupling. To attach our swing hammer to our motor shaft, a custom t-joint was machined. This t-joint was welded on to the swing hammer at the bottom and then was attached with set screws to the motor shaft. The described set-up can be seen in Figure 6.

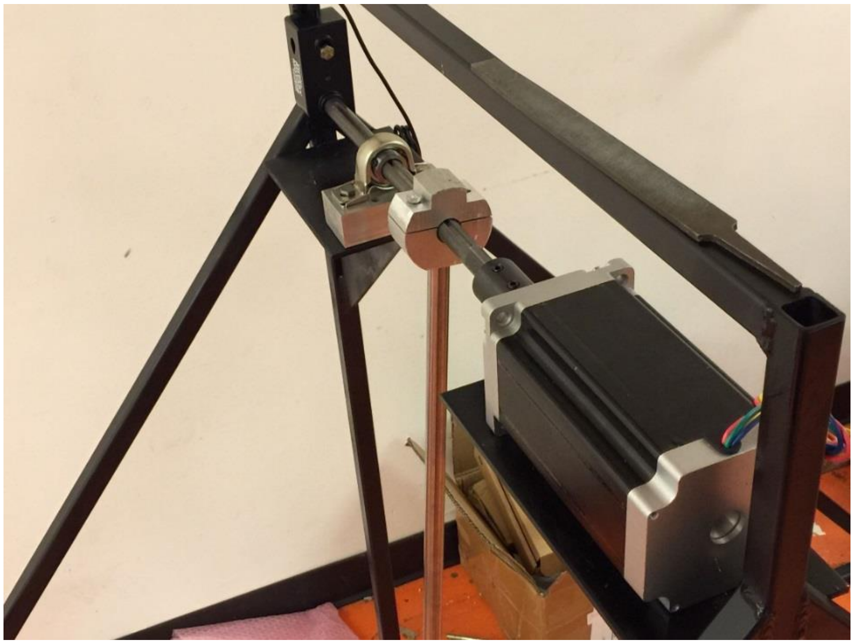


Figure 6 Set-up of the swing-hammer, motor and rotary motion sensor

To prevent the motor from feeling the shear force felt by the weight of the swing hammer, a pillow block was used to support the extended shaft. This pillow block required being raised on an aluminum block to the correct height so that the motor shaft could be level and not be slanted in any direction. Another modification we made to our motor shaft was to hollow out the end opposite of the motor in order to insert the Vernier rotary motion sensor encoder into it and use a set screw to secure the shaft to our rotary motion sensor. This set screw would make sure there was not slipping between the motor shaft and the rotary motion sensor so that the most accurate degrees of rotation could be measured. The final component of our device that we built was the specimen arm holder and the specimen arm itself. The specimen arm holder was a block of aluminum that was bolted to the crossbar after drilling a 5/16 inch diameter hold through the crossbar. The small shaft that served as the pivot for our specimen arm was screwed into another tapped hole on the specimen arm. A nylon sleeve was put between the specimen arm and the arm holding block to ensure that the specimen arm stays at the top of its pivot shaft.

5 Evaluation

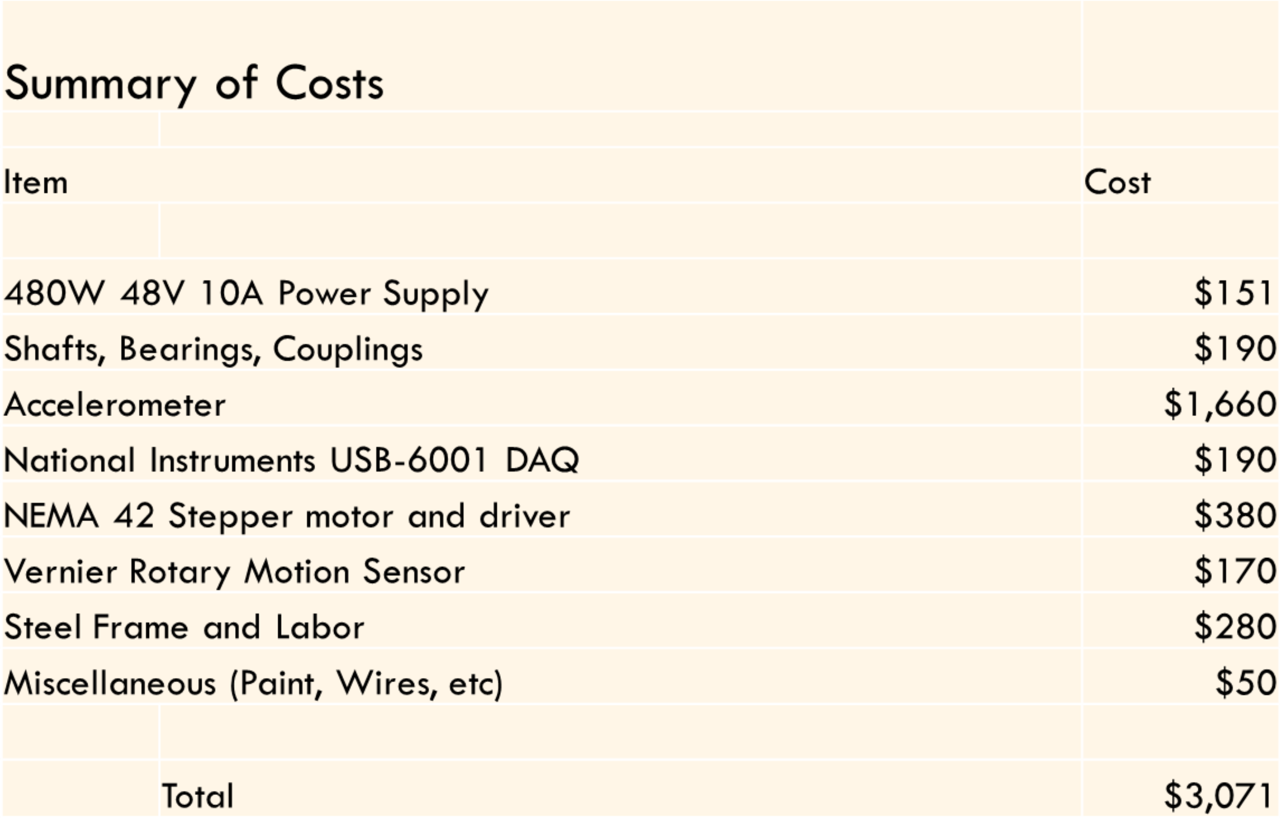
Evaluating the total progress that we have made as a team this semester and considering the things that we have made happen, it is safe to say that we have made satisfactory gains with the project. Our primary goal was to create an automated device that will be able to produce concussion-like impacts on cultured cells. We have our final design constructed mechanically and assembled, and all we need to do is set up electrical components and a Labview interface which we will need the help of electrical engineers to complete. Our secondary goal was to Increase repeatability of impact force as well as allow application of different impacts. By having the system digitally controlled and by having a precise stepper motor introduced to system we have met our needs. We needed a single user-friendly interface for the end-user. By communicating with National Instruments throughout the project and ensuring every part we got worked with Labview, we have met that purpose as well.

We needed to make a specimen arm that mimics the motion of the human head and allows the synthesized neural tissue to experience the required shear forces and accelerations. We calculated the dimensions of the specimen arm using kinematic equations and tweaking values until we found the ideal numbers, and then machined that arm in the Design and Manufacturing lab using those dimensions. We needed a long-lasting device that our sponsors could use for many years to come, and we have compiled just that with every important part having a lengthy or life-time guarantee. We wanted a damping system to provide a standard concussion acceleration/deceleration curve. Even though we modeled a damping system on Solidworks, we deemed Implementing a damping system as unnecessary at this part of the project because we do not have concrete data on what the ideal deceleration would look like. We intended to have high-performance sensors to get reliable data and we have certainly gotten the best parts that we could have bought for our project.

6 Recommendations for future work

The first recommendation that we have for the end-user is to test the device as soon as all the electronic components have been put together to ensure all the Labview components are working as intended and giving the user the data that it is supposed to. This is important because if Labview is malfunctioning the device is not usable, and proper resources will have to be contacted to fix the problem. Once the data that be recorded from the device, the resulting data needs to be compared with data from the same tests that have been collected with another method of motion analysis, for example, by comparing it with the results from high-speed video analysis using Tracker. After sufficient testing has been done on the prototype, the damping system that we have modeled in Solidworks using an airpot dashpot should be implemented to the machine and further testing should be done (be it with an arbitrary damping ratio) to study how damping affects the results. Finally one thing the user can keep in mind is that if they wish to use heavier specimen arms, and consequently a heavier swing hammer, then a system to use gear ratios to have the motion support a higher torque should be a prudent move. Testing it out for publication values. The final step should be to test out the device on synthesized neural tissue. The effects on the synthesized neural tissue can be catalogued to ensure that the device is performing the way it was meant to be. If there are any issues, further adjustments can be made to our device to make it a better finished model.

7 Budget Table



Summary of Costs

Item	Cost
480W 48V 10A Power Supply	$151
Shafts, Bearings, Couplings	$190
Accelerometer	$1,660
National Instruments USB-6001 DAQ	$190
NEMA 42 Stepper motor and driver	$380
Vernier Rotary Motion Sensor	$170
Steel Frame and Labor	$280
Miscellaneous (Paint, Wires, etc)	$50
Total	$3,071

8 Appendices

8.1 Frame Models

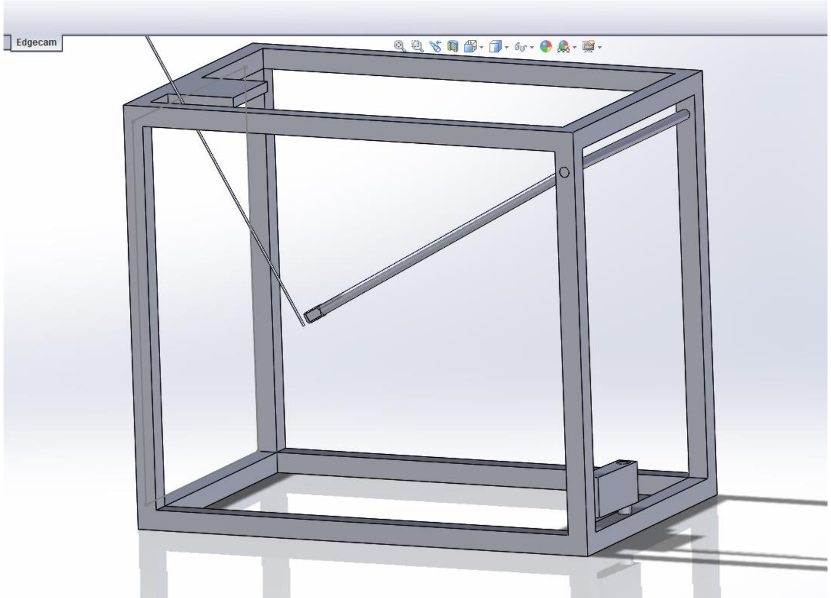


Figure 7: Preliminary Solidworks Design

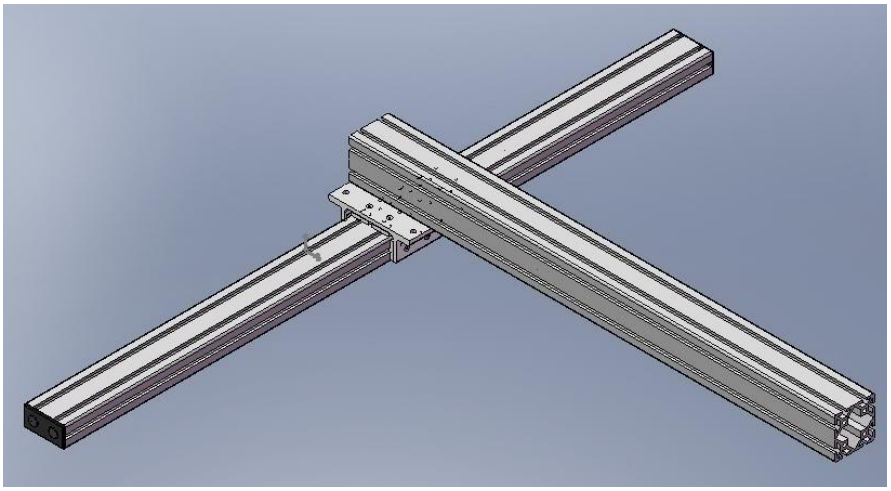


Figure 8: T-Slots Initial Modeling

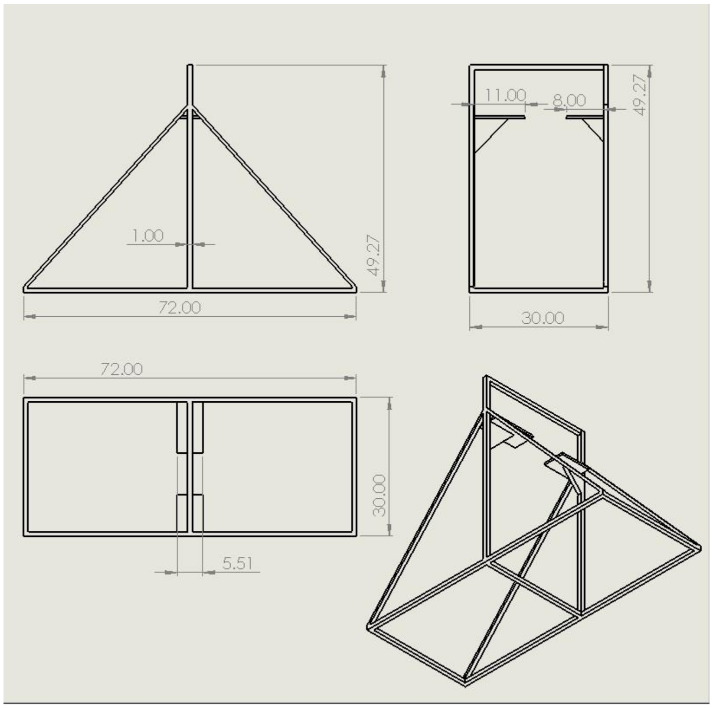


Figure 9: Final Solidworks drawing with dimensions

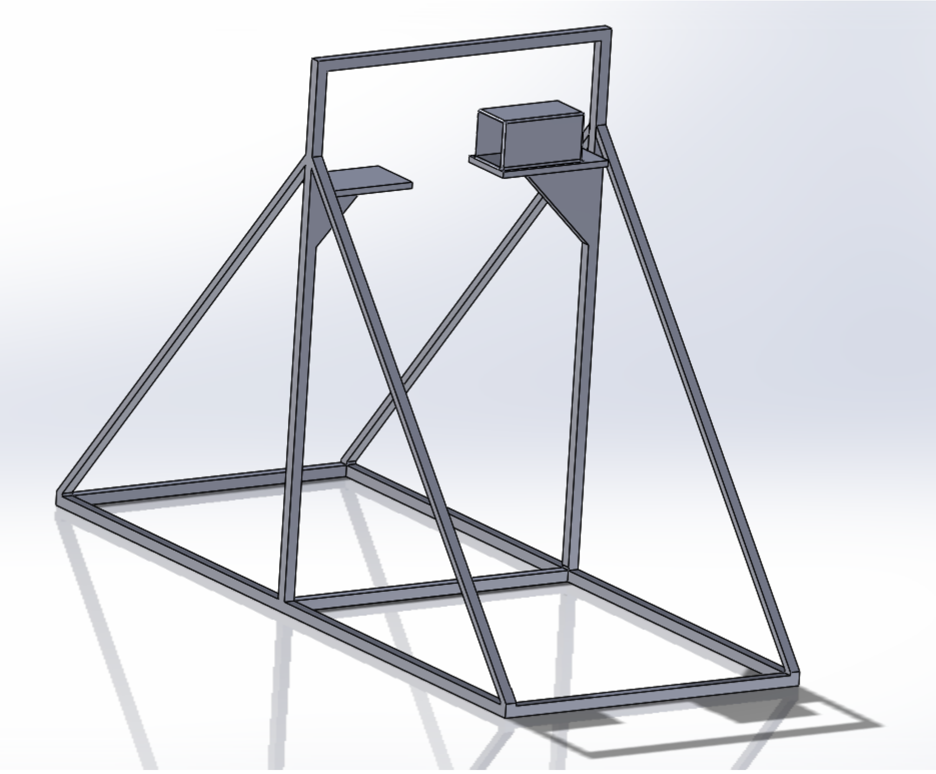


Figure 10: Final Solidworks Model

Figure 11: Constructed steel frame

8.2 Impact hammer

Figure 102: Solidworks model for hammer (left) and final machined hammer (right)

8.3 Specimen arm and damping system

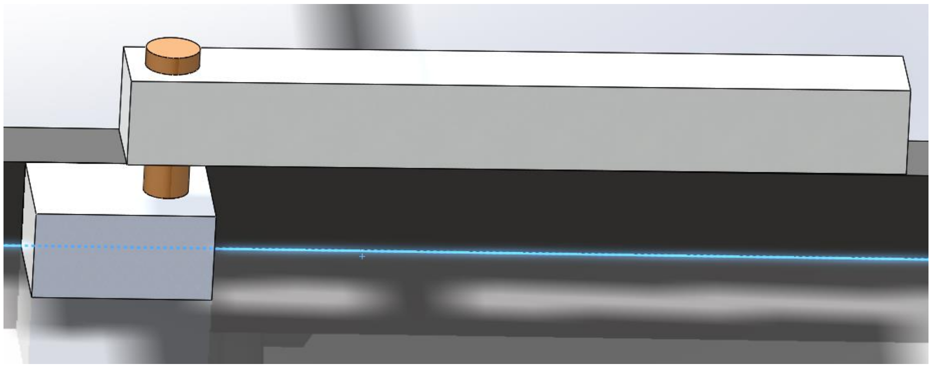


Figure 113: Solidworks model of specimen arm

Figure 124: Airpot Dashpot

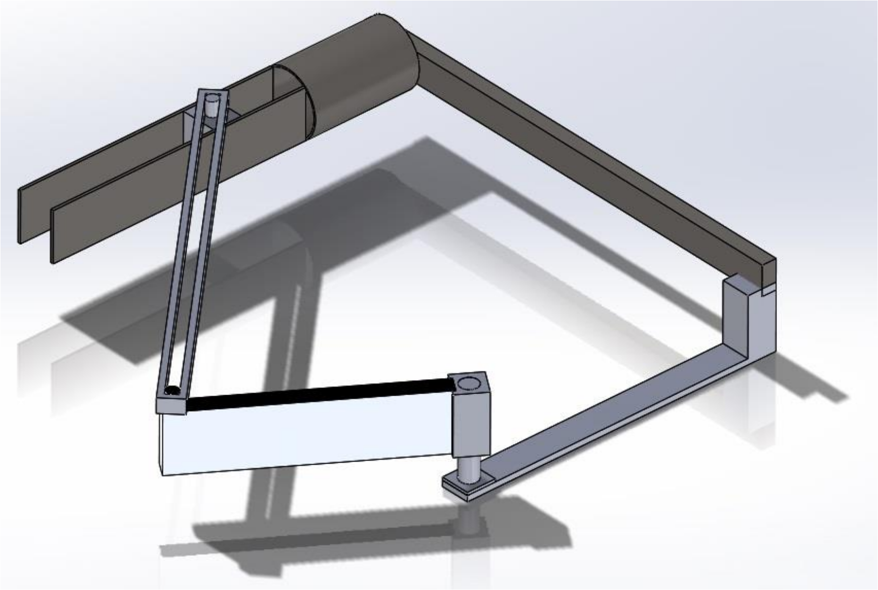


Figure 135: Solidworks model of damping set up

8.4 Accelerometers

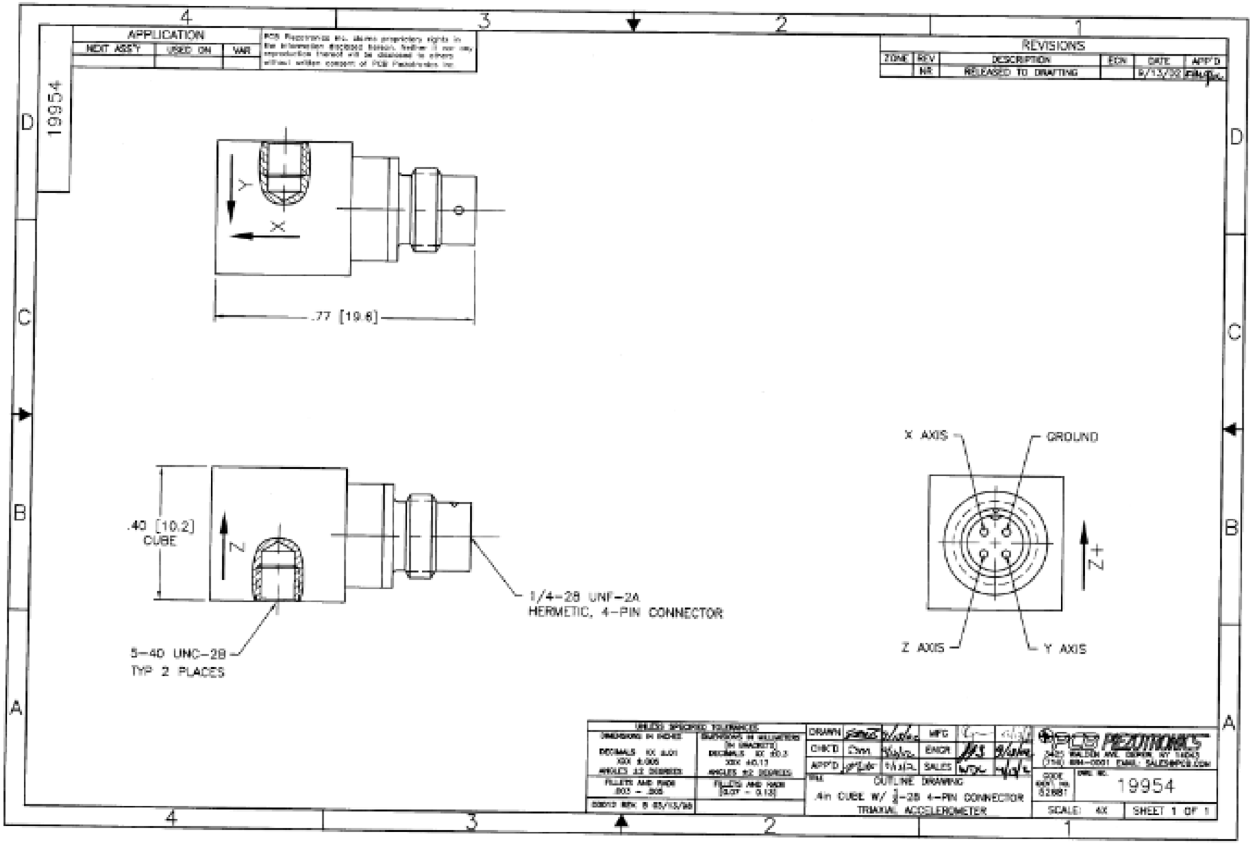


Figure 16: PCB Accelerometer Sketch

Figure 17: Connection Wiring to Signal Conditioner

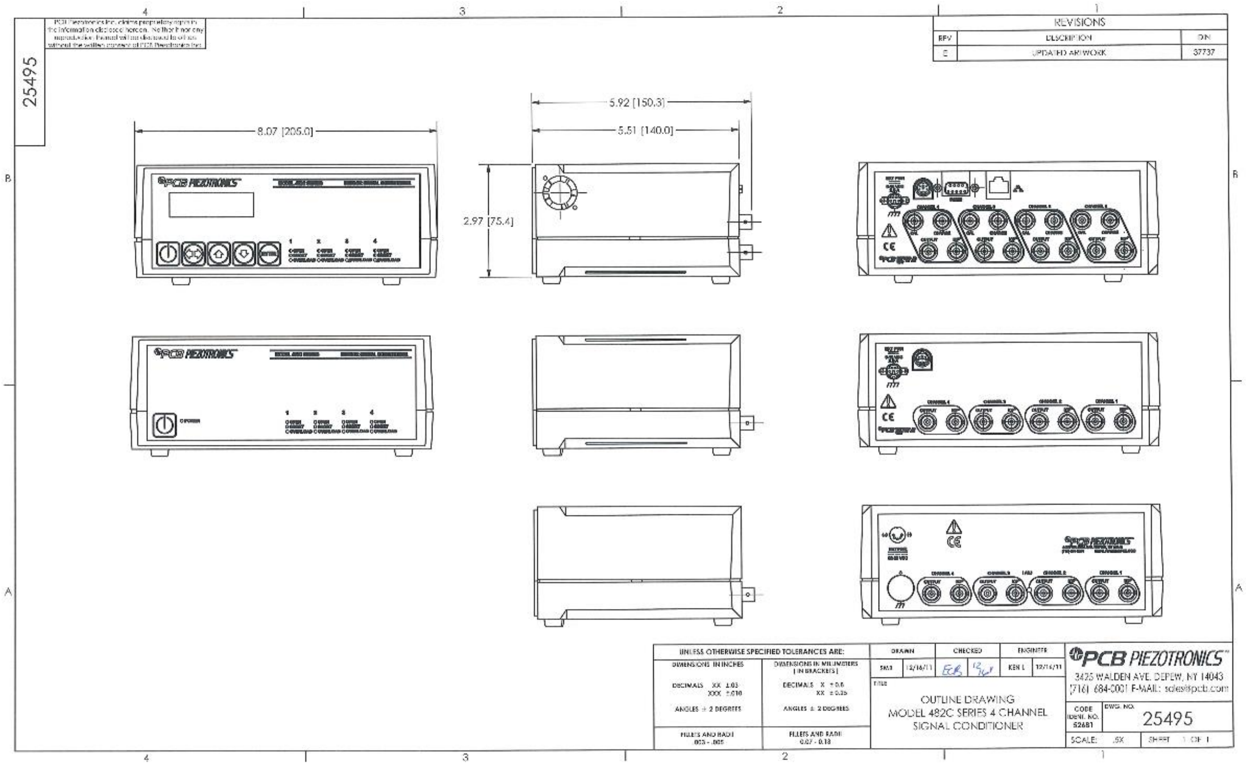


Figure 18: Signal Conditioner Sketch

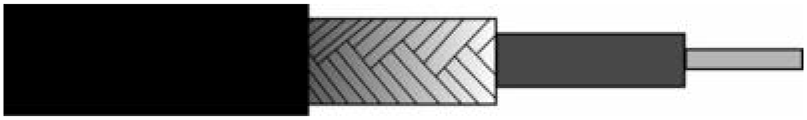


Figure 19: Wire Connection to DAQ

8.5 Stepper Motor/ Stepper Drive

Figure 20: NEMA 42 Stepper Motor

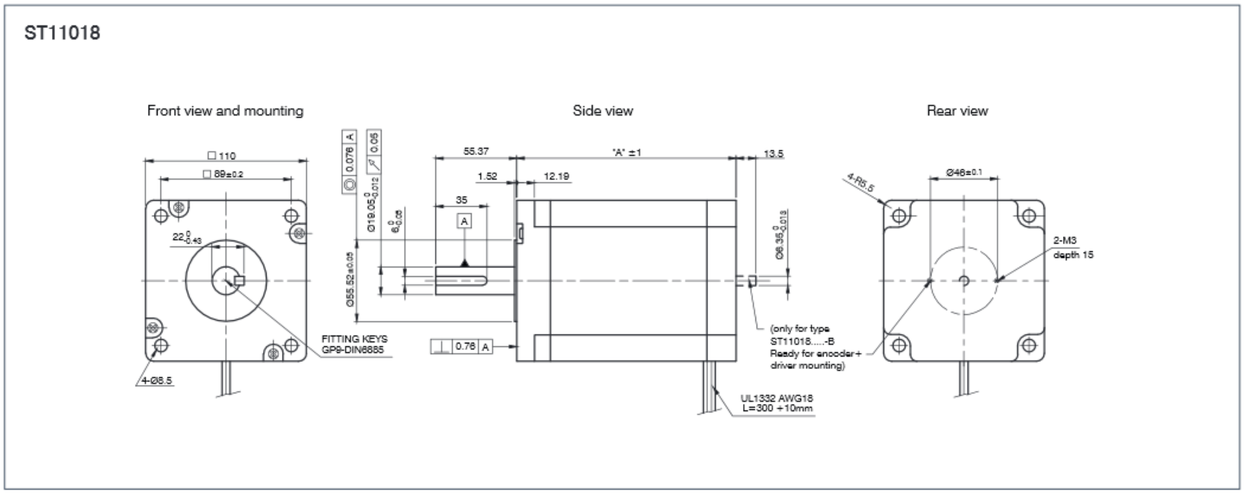


Figure 21: Stepper Motor Specifications

Current Table (Peak=RMS×1.4)

Peak	RMS	SW1	SW2	SW3
Default		off	off	off
2.2A	1.6A	on	off	off
3.2A	2.3A	off	on	off
4.5A	3.2A	on	on	off
5.2A	3.7A	off	off	on
6.2A	4.4A	on	off	on
7.3A	5.2A	off	on	on
8.2A	5.9A	on	on	on

SW4: Standstill current setting
off = Half Current; on = Full Current.

SW4: Self-test and Auto-configuration
Turn SW4 2 times switch in 1 second.

FLT LED Codes (RD = Red LED blinks):

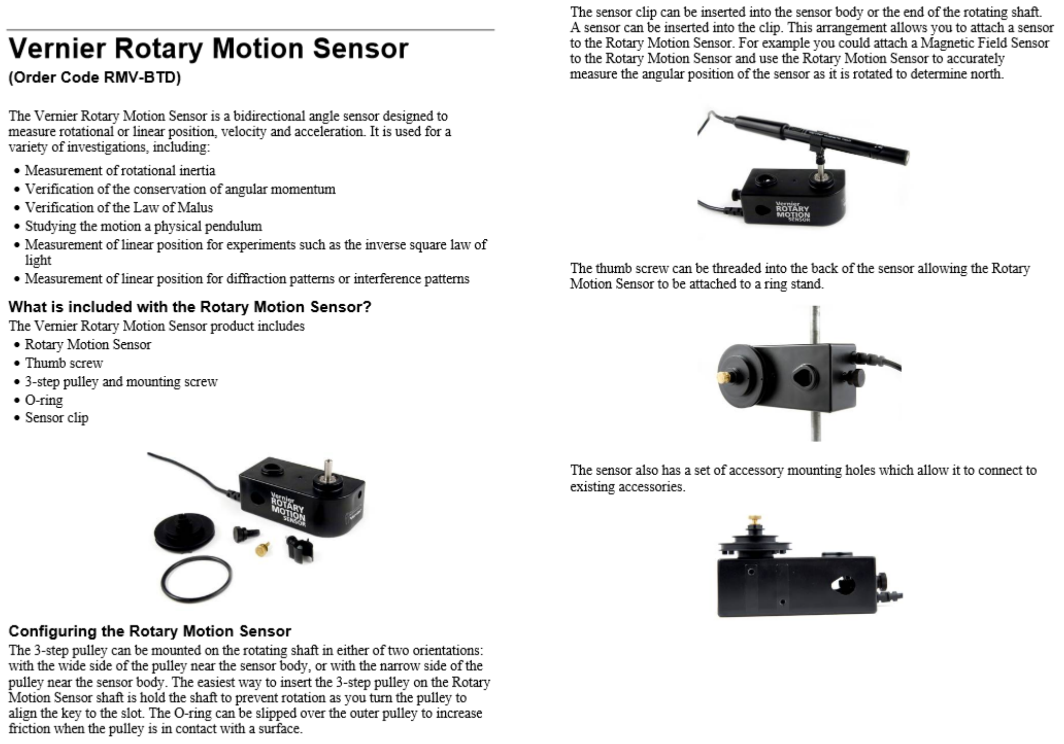
Over Current : 1 RD in 3 seconds.
Over Voltage: 2 RD in 3 seconds.
Under Voltage: 3 RD in 3 seconds.
Motor / Connection Error: 4 RD in 3 seconds.
Over Temperature: 5 RD in 3 seconds.

Microstep Table

Steps/rev.	SW5	SW6	SW7	SW8
Default	on	on	on	on
400	off	on	on	on
800	on	off	on	on
1600	off	off	on	on
3200	on	on	off	on
6400	off	on	off	on
12800	on	off	off	on
25600	off	off	off	on
1000	on	on	on	off
2000	off	on	on	off
4000	on	off	on	off
5000	off	off	on	off
8000	on	on	off	off
10000	off	on	off	off
20000	on	off	off	off
25000	off	off	off	off

Figure 22: Stepper Driver

8.6 Rotary Motion Sensor



Vernier Rotary Motion Sensor

(Order Code RMV-BTD)

The Vernier Rotary Motion Sensor is a bidirectional angle sensor designed to measure rotational or linear position, velocity and acceleration. It is used for a variety of investigations, including:

- Measurement of rotational inertia
- Verification of the conservation of angular momentum
- Verification of the Law of Malus
- Studying the motion a physical pendulum
- Measurement of linear position for experiments such as the inverse square law of light
- Measurement of linear position for diffraction patterns or interference patterns

What is included with the Rotary Motion Sensor?

The Vernier Rotary Motion Sensor product includes

- Rotary Motion Sensor
- Thumb screw
- 3-step pulley and mounting screw
- O-ring
- Sensor clip

Configuring the Rotary Motion Sensor

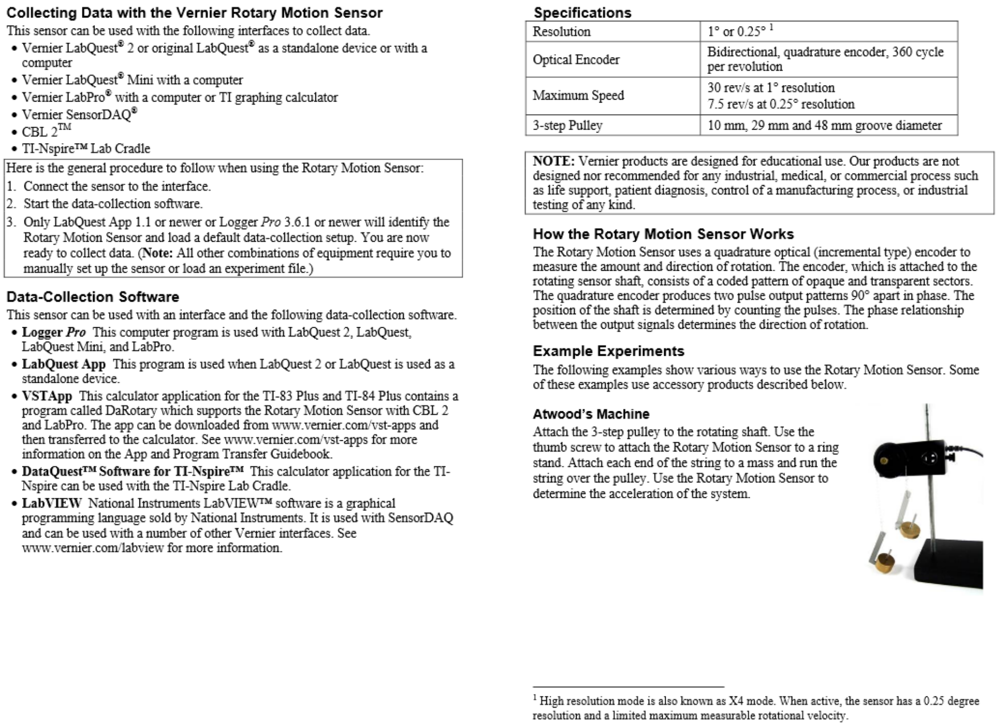
The 3-step pulley can be mounted on the rotating shaft in either of two orientations: with the wide side of the pulley near the sensor body, or with the narrow side of the pulley near the sensor body. The easiest way to insert the 3-step pulley on the Rotary Motion Sensor shaft is hold the shaft to prevent rotation as you turn the pulley to align the key to the slot. The O-ring can be slipped over the outer pulley to increase friction when the pulley is in contact with a surface.

The sensor clip can be inserted into the sensor body or the end of the rotating shaft. A sensor can be inserted into the clip. This arrangement allows you to attach a sensor to the Rotary Motion Sensor. For example you could attach a Magnetic Field Sensor to the Rotary Motion Sensor and use the Rotary Motion Sensor to accurately measure the angular position of the sensor as it is rotated to determine north.

The thumb screw can be threaded into the back of the sensor allowing the Rotary Motion Sensor to be attached to a ring stand.

The sensor also has a set of accessory mounting holes which allow it to connect to existing accessories.

Figure 23: Rotary Motion Sensor Spec. Sheet Part 1



Collecting Data with the Vernier Rotary Motion Sensor

This sensor can be used with the following interfaces to collect data.

- Vernier LabQuest® 2 or original LabQuest® as a standalone device or with a computer
- Vernier LabQuest® Mini with a computer
- Vernier LabPro® with a computer or TI graphing calculator
- Vernier SensorDAQ®
- CBL 2™
- TI-Nspire™ Lab Cradle

Here is the general procedure to follow when using the Rotary Motion Sensor:

1. Connect the sensor to the interface.
2. Start the data-collection software.
3. Only LabQuest App 1.1 or newer or Logger *Pro* 3.6.1 or newer will identify the Rotary Motion Sensor and load a default data-collection setup. You are now ready to collect data. (**Note:** All other combinations of equipment require you to manually set up the sensor or load an experiment file.)

Data-Collection Software

This sensor can be used with an interface and the following data-collection software.

- **Logger *Pro*** This computer program is used with LabQuest 2, LabQuest, LabQuest Mini, and LabPro.
- **LabQuest App** This program is used when LabQuest 2 or LabQuest is used as a standalone device.
- **VSTApp** This calculator application for the TI-83 Plus and TI-84 Plus contains a program called DaRotary which supports the Rotary Motion Sensor with CBL 2 and LabPro. The app can be downloaded from www.vernier.com/vst-apps and then transferred to the calculator. See www.vernier.com/vst-apps for more information on the App and Program Transfer Guidebook.
- **DataQuest™ Software for TI-Nspire™** This calculator application for the TI-Nspire can be used with the TI-Nspire Lab Cradle.
- **LabVIEW** National Instruments LabVIEW™ software is a graphical programming language sold by National Instruments. It is used with SensorDAQ and can be used with a number of other Vernier interfaces. See www.vernier.com/labview for more information.

Specifications

Resolution	1° or 0.25° [1]
Optical Encoder	Bidirectional, quadrature encoder, 360 cycle per revolution
Maximum Speed	30 rev/s at 1° resolution 7.5 rev/s at 0.25° resolution
3-step Pulley	10 mm, 29 mm and 48 mm groove diameter

NOTE: Vernier products are designed for educational use. Our products are not designed nor recommended for any industrial, medical, or commercial process such as life support, patient diagnosis, control of a manufacturing process, or industrial testing of any kind.

How the Rotary Motion Sensor Works

The Rotary Motion Sensor uses a quadrature optical (incremental type) encoder to measure the amount and direction of rotation. The encoder, which is attached to the rotating sensor shaft, consists of a coded pattern of opaque and transparent sectors. The quadrature encoder produces two pulse output patterns 90° apart in phase. The position of the shaft is determined by counting the pulses. The phase relationship between the output signals determines the direction of rotation.

Example Experiments

The following examples show various ways to use the Rotary Motion Sensor. Some of these examples use accessory products described below.

Atwood's Machine

Attach the 3-step pulley to the rotating shaft. Use the thumb screw to attach the Rotary Motion Sensor to a ring stand. Attach each end of the string to a mass and run the string over the pulley. Use the Rotary Motion Sensor to determine the acceleration of the system.

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[1] High resolution mode is also known as X4 mode. When active, the sensor has a 0.25 degree resolution and a limited maximum measurable rotational velocity.

Figure 24: Rotary Motion Sensor Spec. Sheet Part 2

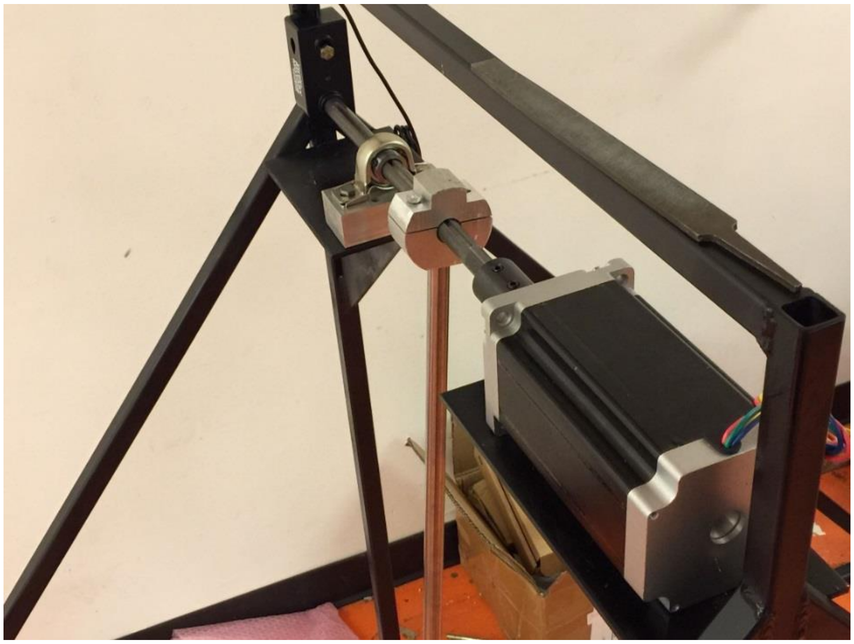


Figure 25 Connecting motor shaft with swing-hammer extension

8.7 DAQ

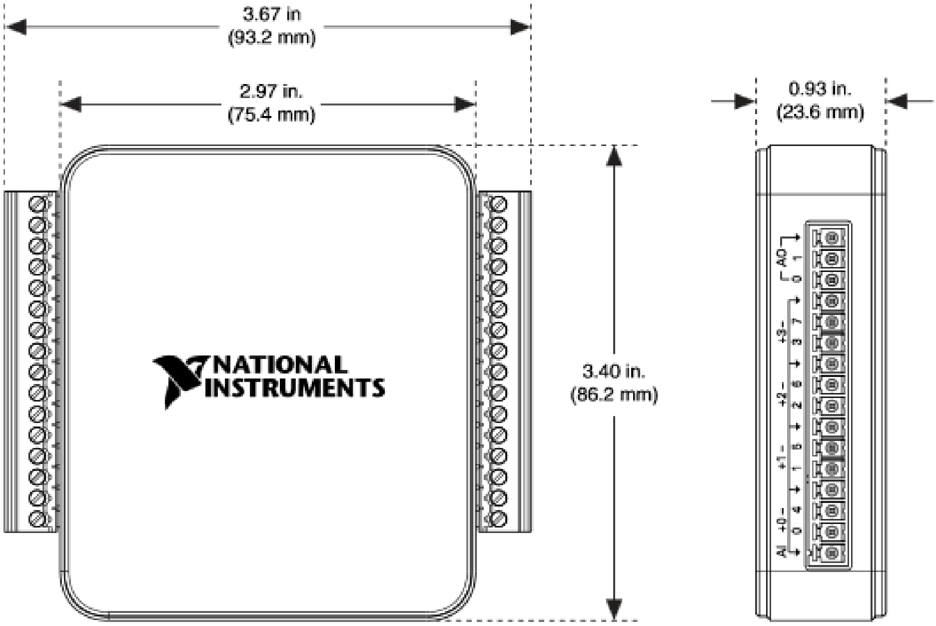


Figure 26: DAQ Device

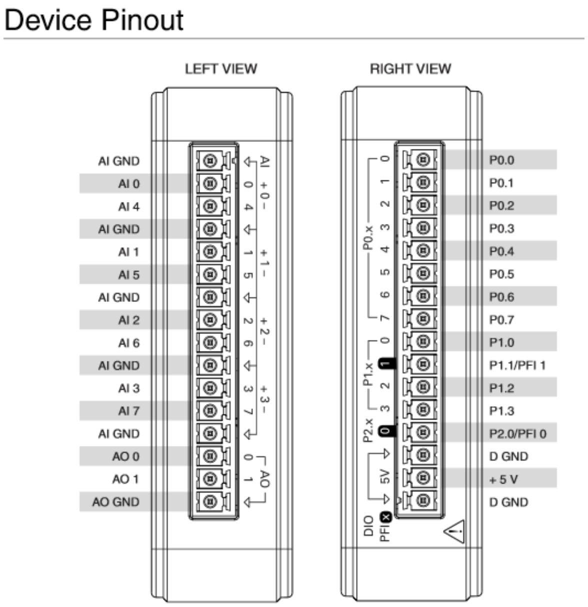


Figure 27: DAQ Pin Layout

8.8 Calculations

Length of swing-hammer= **Lh = 1.07 m**

Mass of swing-hammer + arm= **Mh = 3.64 kg**

Mass of hammer head = 1.23 kg, Distance of hammer head from pivot= 1.04 m

Mass of hammer shaft = 2.41 kg, Distance of shaft center of mass from pivot= 0.53 m

Swing-hammer center of mass distance from pivot= **Cmh = 0.70 m**

$$Cmh = \frac{(1.23\ \times 1.04) + (2.41\ \times 0.53)}{3.64}$$

Hammer torque= $Mh \times g \times center\ of\ mass\ distance = 3.64 \times 9.81 \times 0.7$= **KEh = 25.0 N.m**

If free fall was applied during rotation:

Potential energy lost/kinetic energy gained by hammer during horizontal-to-vertical swing

$Mh \times g \times h = 3.64 \times 9.81 \times 0.7$= **KEh = 25.0 J**

Moment of inertia of swing-hammer = $(\frac{1}{3} \times 2.41 \times 1.07^2) + (1.23 \times 1.04^2) = \boldsymbol{Im} = \boldsymbol{2.25\ kg.m^2}$

Kinetic energy for rotating arm = **KEh** = $\boldsymbol{\frac{1}{2}} \times \boldsymbol{\omega} \times \boldsymbol{Im^2}$

Therefore, during impact, $\boldsymbol{\omega} =$ **9.87** $\boldsymbol{rad/s}$ **= 94.25 RPM**

Linear velocity of hammer-head = $\omega\ \times radius =\ 9.87\ \times 1.07$ = **Vh1 = 10.6 m/s**

Mass of specimen arm= **Ma = 0.46 kg**

Length of specimen arm= **La = 0.22 m**

Initial specimen arm velocity = **Va1= 0**

Assumptions:

During impact, motion of the hammer and specimen arm is linear on the horizontal plane

Energy is conserved

Coefficient of restitution for impact (steel hammer on steel plate) = **e = 0.56**

Linear velocity of specimen arm after impact at impact-point = **Va2 = ?**
Linear velocity of swing-hammer head after impact = **Vh2 = ?**

From Dynamics, we know that:

$$\boldsymbol{e = \frac{Va2-Vh2}{Vh1-Va1} = \frac{Va2-Vh2}{Vh1}} \qquad (\mathbf{1})$$

$$\boldsymbol{e = \sqrt{\frac{KE\ after\ impact}{KE\ before\ impact}} = \sqrt{\frac{\frac{1}{2}Mh\,Vh2^2+\frac{1}{2}Ma\,Va2^2}{\frac{1}{2}Mh\,Vh1^2}} = \sqrt{\frac{Mh\,Vh2^2+Ma\,Va2^2}{Mh\,Vh1^2}}} \qquad (\mathbf{2})$$

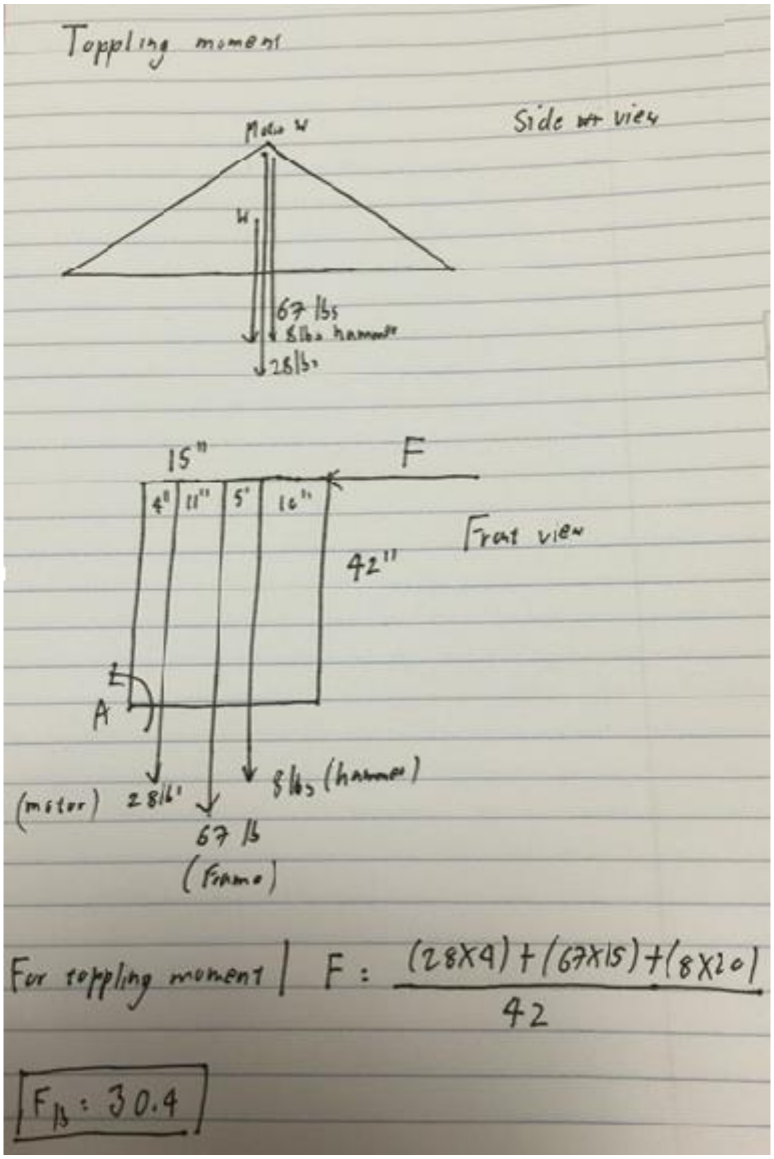
Plugging in known values, and solving equations (1) and (2), we get:
Vh2 = -0.66 m/s (recoil)
Va2 = **5.28 m/s**

Distance of impact-point on specimen hammer from pivot = **Ra = 0.18 m**
Therefore initial angular rotation of Hammer = $\omega a = \frac{Va2}{Ra}$
So $\boldsymbol{\omega a = 29.33\, rad/s}$

Assuming impact happens over the standard time span of 2-3 ms and taking the time at **Ti = 0.003 s**,
Acceleration of the specimen arm = $\boldsymbol{\alpha = {}^{\omega a}/_{Ti} = 9776\, rad/\, s^2}$

Therefore the range of angular accelerations produced by the impact in our system should be in the range of $\boldsymbol{0 - 9776 \frac{rad}{}s^2}$ and the standard range of angular accelerations experienced by the brain during a concussion is $\boldsymbol{2000 - 9000\, rad/\, s^2}$**.**

Theoretically the device meets it purpose. If device was needed to rotate at $9776\, rad/\, s^2$ by a stepper motor, then the applied angular velocity during impact should be $\omega =$ 9.87 rad/s = 94.25 RPM.



For toppling moment | $$F : \frac{(28\times4)+(67\times15)+(8\times20)}{42}$$

$$\boxed{F_{lb} : 30.4}$$

Figure 28 Toppling moment calculation