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Hydrolastic Damping: A Change to the Modern Helmet

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Hydrolastic Damping: A Change to the Modern Helmet

By

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SENIOR THESIS

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Abstract

High rates of concussion in the NFL suggest that helmet technology is not satisfactory for the athletes, and soft foam padding has dominated the helmet industry since its inception. The team proposed that implementing a fluid-based hydrolastic suspension system in the helmet would reduce the risk of concussions at all levels of competition. After using COMSOL to successfully model fluid flow through the dampers and after physical testing on dampers filled with air and water lead to increased "time to stop" of an average of 240% when compared to traditional foam padding, the team concluded that the dampers showed promise and the potential to benefit the padding potential of football helmets and decrease the risk of concussion for football athletes.

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1. Introduction

1.1 Concussion Prevalence in Football

Impacts to the head, which result in a concussion, can occur in a variety of different ways. Motor accidents, falls, and sports-related injuries are some of the most common causes of concussions. In the world of sports and athletics, football is one of the leading causes of concussions [1].

Head-to-head collisions in football are frequent, and one of football's most notable characteristics is its physicality. Teams are aware of the risks that concussions pose to the athletes and try to minimize the occurrence of injuries to the head through the use of football helmets and mouthguards. Though these methods are likely more effective than doing nothing at all, they have not prevented football from being in the spotlight for the highest rates of concussions in sports.

Concussions related to football occur at all (high-school, collegiate, and professional) levels, but much of the attention is on the National Football League (NFL). Athletes frequently incur hard impacts to the head while participating or practicing for the NFL. NFL teams try to prevent concussions by using mouthguards and advanced helmets. Two studies, titled "The Role of Personal Equipment in Preventing Sport-Related Concussions" [2] and "Do mouthguards prevent concussions?" [3] showed that the protective factors for mouthguards were insignificant. The only other method to limit concussions is by improving the helmet. It is therefore imperative to focus on the design of the padding system within the helmet. The padding system within the helmet seeks to increase the duration of an impact and seeks to absorb as much energy as it can from the impact. These two objectives work together to limit the net acceleration of the head and the likelihood of a serious brain injury occurring.

The performance of football helmets has improved consistently throughout the NFL, but even as helmets improve, the rates of concussion are still rising. This is because players are getting stronger faster than helmets are improving. As advances in workout and diet regimes are discovered, players are getting bigger and stronger and the corresponding number of concussions are increasing [4]. This is clear when comparing the size of a lineman from the 1920s and one from today. For example, Wilbur Henry, who was dominant in the league as a lineman during the 1920s at 5’ 11”, 245 lbs, is smaller than the average lineman in 2019 who is now 6’ 3” 330 lbs [5].

Over the years, it is also likely that the frequency of concussions has increased so much because so has the ability to diagnose them. This has allowed statisticians to gather important data regarding the nature of concussions in the NFL. The following are important statistics that highlight concussions in the NFL, and the nature of the injury allows the team to effectively address the issues described [6]:

- More concussions are produced in head-to-full-body contact compared to helmet-to-helmet contact (45% vs 35% respectively)
- Defenders are more likely to get concussions (41% compared to 22% offensive members)
- 19% of all concussions are caused by helmet to ground injury, and in 35% of those instances, the back of helmet hits the ground

Technicians use a variety of methods to diagnose concussions, but it is not a clear science and field diagnosis varies largely based on the player and the situation. Below are some of the symptoms that medical technicians use to diagnose concussions in athletes:

- Loss of consciousness
- Slow recovery (getting back on feet)
- Poor motor control (stumbles, trips/falls, slow/labored movement)
- Blank or vacant expression
- Disorientation (e.g., unsure of where he is on the field or location of the bench)
- Clutching of the head after contact
- Visible facial injury in combination with any of the above [7]

Medical technicians have greatly improved the quality of safety for the athletes and the treatment of concussions, but in an ideal world, concussions would not occur at all. The ideal helmet would be able to prevent them and thereby hold the top spot for “safest football helmet.” Though this has not occurred yet, there are helmet designs that rank higher than others when tested for multiple safety requirements and net head deceleration.

1.2 Extensive Brain Research and Significance

It is important to understand the systems of the brain and what each of these systems is responsible for in order to understand the severity of concussion related injuries. There are four main parts of the brain: the cerebrum, the cerebellum, the limbic system, and the brain stem. The cerebrum is the largest part of the brain, and it was the main focus of the team's study.

The cerebrum is split into four sections, called “lobes”, which are associated with the higher brain function such as thoughts, reasoning, visual processing, memory, and speech. Each lobe is responsible for a different part of human brain function. During a concussion, these lobes are damaged and can lead to changes in not only our motor skills but even our behavior. Frontal impacts will affect the front lobe, and other impacts from different sides of the head will affect those areas of the brain respectively. If a patient is showing a lack of motor skills versus speech skills, this is a potential indicator to medical professionals where the impact could have occurred in the brain.

The frontal lobe is associated with reasoning, planning, emotions, language, and problem-solving. The parietal lobe controls sensory perception including the five senses and includes processing of the various inputs. The occipital lobe processes visual inputs. The temporal lobe is associated with perception and recognition of sound stimuli, memory, and speech.

The cerebellum is associated with coordination of movement, posture, and balance. It receives information from the spinal cord and other areas of the brain and regulates movements. The limbic system deals with emotions, memories, and arousal and is located deep within the cerebrum. The brainstem is responsible for basic vital life functions such as breathing, heartbeat, swallowing, and blood pressure [8].

Concussions can result in swelling of the brain. This swelling contained within a small space (skull) can result in permanent damage to brain cells, which can have untold effects depending on what lobe it is in.

1.3 Motivation and Goal

After extensive research, the primary motivation for the development of better padding was to increase the overall safety of players at all levels. Player safety should be a primary concern at all levels of play and should not only benefit professionals. The final goal of the project was to create and implement a system that improves and replaces current helmet paddings within a standard shell. Other factors that were also considered were pricing, manufacturing, and comfort.

1.4 Current Helmet Designs on the Market

Before attempting to create a completely new design, the team decided to do further research on both basic and high performing helmets that were available to athletes at the professional level to see if any improvements could be made. The ratings for these helmets were provided by the NFL and NFLPA (National Football League Players Association). However, no specific testing procedures were listed. The VICIS ZERO I ranked has the safest helmet in its class according to this study [9].

1.4.1 Standard Helmet Configurations

A standard helmet highlights the basic principles of foam padding behind football helmets. It utilizes a series of foams of different densities to soften impacts to the head. These foams collapse under impact and absorb energy while they deform. Foams in football helmets have varied thickness and density based on location of the head.

1.4.2 VICIS Zero1

The best helmet on the market according to the NFL 2019 study, was the VICIS Zero1 helmet. This helmet utilized a soft external shell to dampen initial impacts. After force was dissipated by the shell, a series of vertical columns were used to disperse the rest of the impact. These unconventional, vertical columns were capable of buckling and deforming to reduce residual impact forces.

1.4.3 Riddell Speedflex

Another effective and popular helmet that was used at the high school, collegiate, and professional level was the Riddell Speedflex. This helmet resembled more of a traditional approach to helmet technology and used standard foam units used to dissipate impact. However, the Speedflex adds an extra layer of protection in the form of inflatable airbag-like units that help dampen impact to a further degree as well as provide users with a snugger fit.

1.5 Background Information on Traditional Padding

The problem with traditional helmets that use foam padding is the manner in which foam pads dissipate impact energy. Foam dampers are not ideal for helmet applications because of their inconsistent damping effects, which is demonstrated well in Figure 1, where the grey curves track foam damper performance.

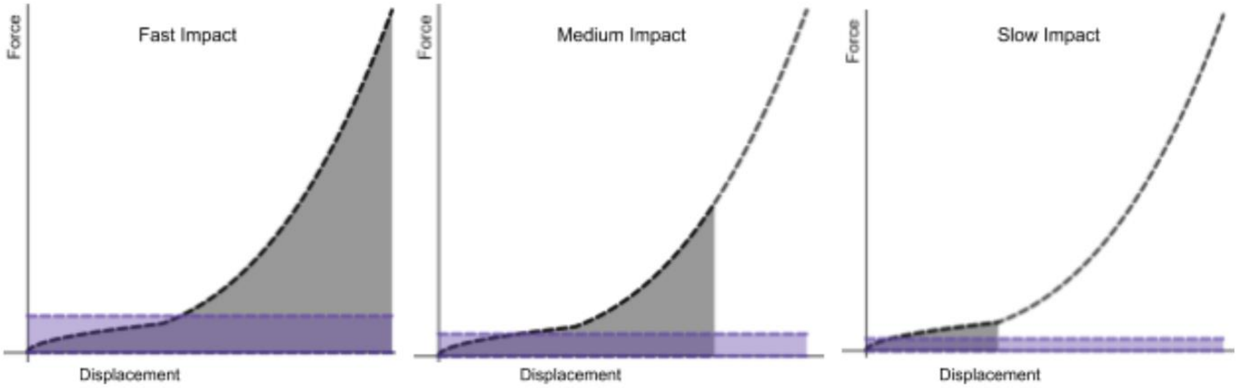


*Figure 1***.** *Force-Displacement plots of dampers at fast, medium and slow impacts, where foam dampers are shown in grey and ideal dampers are shown in purple.*

Force-Displacement plots measure how much force a damper can resist per unit displacement (at a given level of compression) and are a good measure of damper performance. Figure 1 shows that the foam dampers provide very small resistive forces for the first part of their displacement. Additionally, energy must be conserved, so the area under the Force-Displacement curves cannot change. As a result, the foam dampers must spike their resistive forces at the very end to maintain conservation of energy and area. These peak forces or accelerations are what cause concussions [10].

The ideal damper (purple curve) would smooth the grey curve yet maintain the same integral. This is done by providing a resistive force that is constant across all displacements, thus removing any harmful concussion-causing peak accelerations. The team began researching other inspiring dampers that created this effect, as this became the damper design’s driving criteria.

1.6 Proposed Alternative to Traditional Padding

1.6.1 Hydrolastic Suspension and Damping

When researching old damper designs, the team found the hydrolastic suspension most inspiring as it employed several novel and applicable damping techniques.

Hydrolastic suspensions were built in cars like the Austin Maxis (1978) and Leyland Minis (1964-1971) and would vary depending on what fluid was used, but the defining characteristics remained the same [11]. Hydrolastic suspensions used a network of interconnected variable area, “fluid displacer,” units that were fitted to each wheel. Unlike traditional piston-dampers, the individual hydrolastic dampers acted much like a balloon that changes shape under compression. Front and rear displacers were linked via a hose that would route fluid between dampers. This can be seen in Figure 2 below.

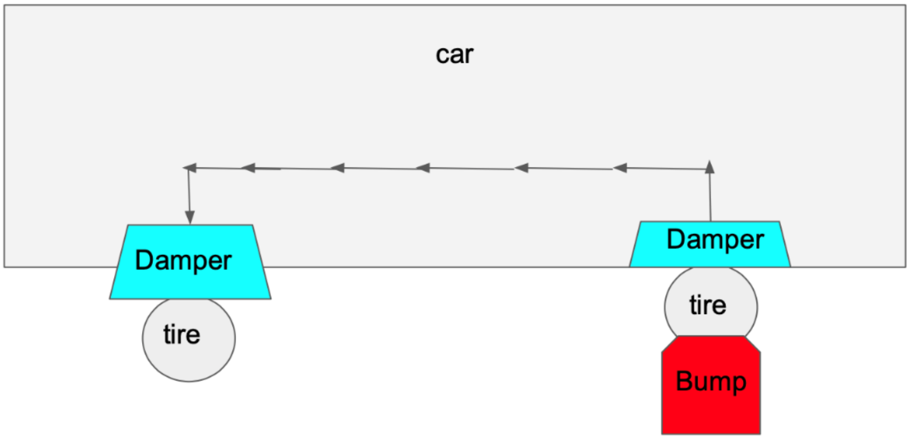


Figure 2. Simple schematic of a hydrolastic system. The damper, in blue, is being compressed by the bump coming in contact with the tire. This damper then sends fluid down a hose, shown through arrows, which then expands the other damper.

Suppose a car hits a road-bump and impacts the front wheels first. The compressed hydrolastic dampers send fluid to their rear-suspension twins, preparing them for the road-bump. It is important to note that during this process, both of the dampers are fixed at a specific height, housed within the vehicle. Also, the area of the damper varies upon impact to utilize hydraulic advantages.

These dampers were slowly phased out of industry use in cars, most likely because it was expensive and there were better and cheaper alternatives available.

1.6.2 Advantages of Fluid Over Foam

The team focused on adopting three key design features of the hydrolastic suspension and transplanting them into the helmet damper design as they showed promise in satisfying the team's criteria:

- A damper whose contact area varies with compression and expansion
- A network of interconnected dampers that work together
- The freedom to choose from several different fluid types

1.6.3 Variable Area

The variable area trait of the suspension's individual dampers seemed to answer the team's goal of smoothing the Force-Displacement curve (Figure 3).

The variable area trait of the suspension's individual dampers allowed it to utilize hydraulic advantage. Hydraulic advantage is most often explained by the example of an automobile jack:

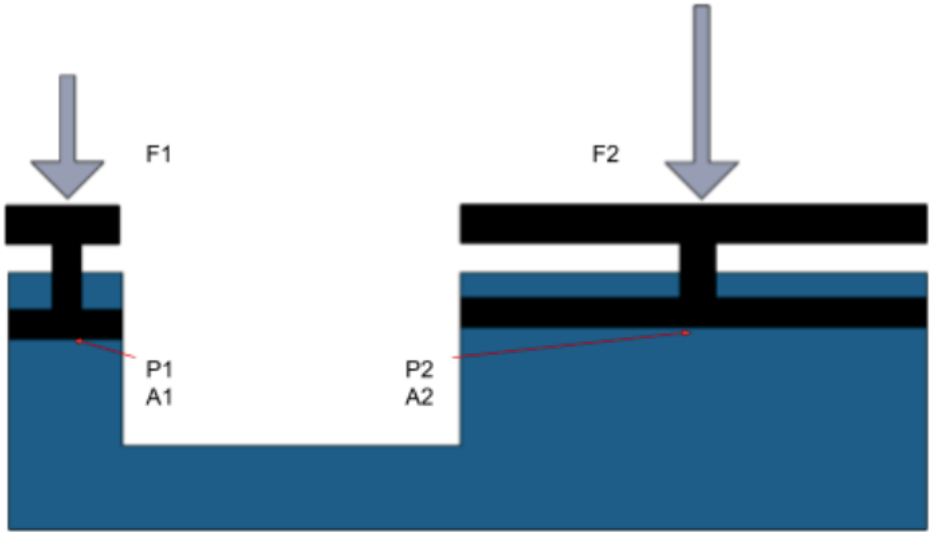


Figure 3. Sketch of a car-jack setup analogy. F_2 *is greater than* F_1 *since* A_2 *is greater than* A_1 *and the pressures are equal* ($P_1 = P_2$) *while the jack is in hydrostatic equilibrium.*

As in Figure 3, the inlet and outlet pressures must be equal for the system to be in hydrostatic equilibrium. Rearranging Equations (1) and (2) for the inlet or applied force, it is clear that the applied force is a function of the ratio of the contact areas, shown in Equation (3).

$$P_1 = P_2 \tag{1}$$

$$P = \frac{F}{A} \tag{2}$$

$$\left[\frac{F_1}{A_1} = \frac{F_2}{A_2}\right] \rightarrow \left[F_1 = F_2\frac{A_1}{A_2}\right] \tag{3}$$

While the suspension dampers are not in hydrostatic equilibrium, the fundamental idea remains and thus gives justification to a variable area damper. Consider the simplified trapezoidal damper in Figure 4 below. The geometry is such that the area of the red side increases as the overall length decreases and increases with compression.

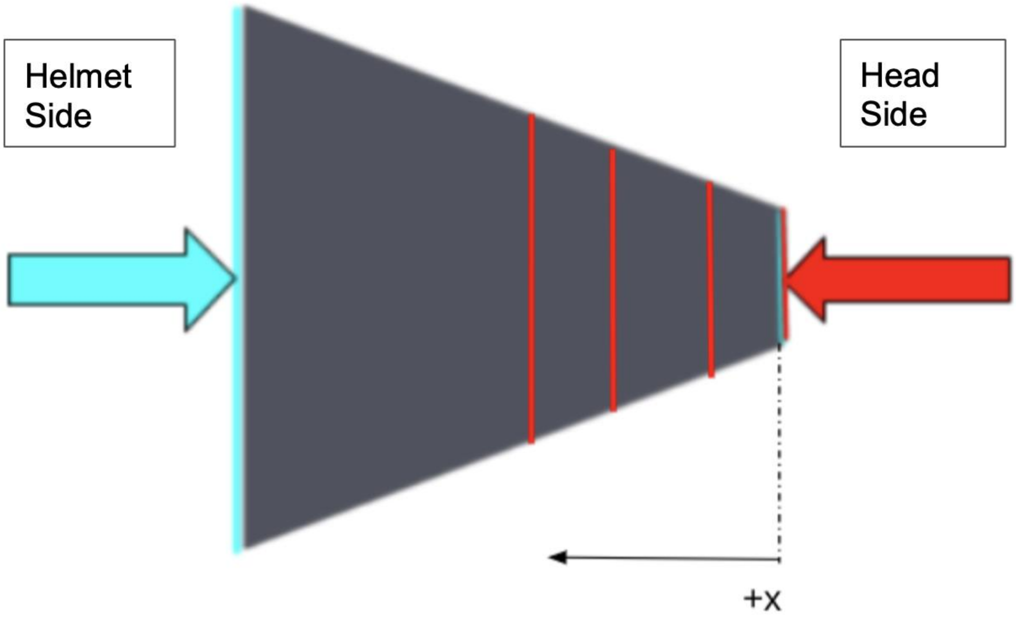


*Figure 4***.** *Image of a trapezoidal damper, demonstrating the increase in contact area with compression.*

Similar to the hydraulic car-jack in Figure 3, an expression for the resistive force (blue) is obtained. The side with the bigger surface area touches the football player’s head, while the side with the smaller surface area interfaces with the helmet shell. Therefore, the red arrow indicates the applied force from impact, and the blue arrow indicates the resistive or reactionary force. The final force on a person’s head can be derived from Equations (4) and (5) and shown in Equation (6).

$$P_{head} = P_{helmet} \tag{4}$$

$$P = \frac{F}{A} \tag{5}$$

$$[\, F_{head} = F_{helmet} \frac{A_{head}}{A_{helmet}} \,] \tag{6}$$

The force felt by the football player’s head (red force) is proportional to the ratio of its area (A_{head}) to the helmet-side area (A_{helmet}), which, as proven above, is a function of damper geometry and compression distance. As a result, F_{head} will always be reduced thanks to hydraulic advantage — the ratio, A_{head}:A_{helmet}, can only be less than or equal to one. Variable area is a greatly valuable trait as it allows the designer to fine-tune damper geometry to achieve constant force (F_{head}) behavior. This avoids the harmful and concussion-causing peak forces to the player’s head (see Figure 6 for more).

Figure 4 was a simplification that was meant to emphasize the increase in contact area with compression; matter can neither be created nor destroyed, so the damper would not simply shorten and change contact area without any other geometric consequences. In reality, the variable area, and therefore constant force, effect would still hold, but the damper would also deform and bulge in the y-axis (whichever axis is perpendicular to the axis of compression) due to Poisson’s ratio and pressure within the damper – unless the fluid outlet orifice is so large that fluid may freely exit the damper without creating a significant outwards radial pressure, the . Figure 5 below demonstrates the variable area and Poisson’s effects for two-time frames: one at the start of compression, and another moments later.

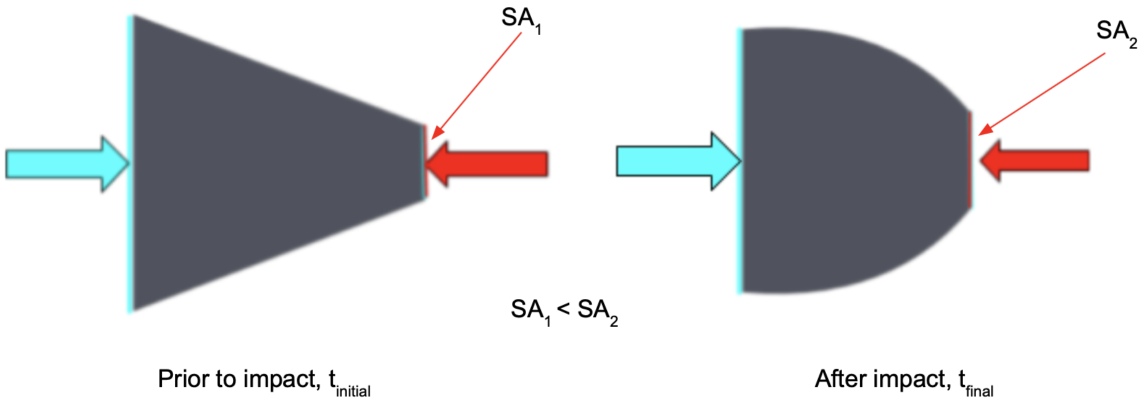


Figure 5. This image shows two time frames of how a deformable fluid damper might compress under impact. The smaller surface area (red) touches the head while the larger surface area (blue) touches the helmet.

1.6.4 Interconnected Dampers

There are three benefits to interconnected dampers. First, interconnected dampers ensure that no damper is working independently. Though only one damper is affected by the applied force at a time, when connected, another damper can help reduce overall impact. The proposed interconnected configuration uses the combined damping effects of dampers to minimize and maximize surface area of the impacted and connected damper respectively. Since space in the helmet is limited, it was crucial to create dampers that were as compact as possible.

Second, in the case of the cars fitted with hydrolastic suspension, this had the benefit of providing a unique and level ride. The team sought to recreate this *leveling* effect to prevent the football player's head from falling off-axis as the neck is bent.

Players who experience a form of whiplash during impact have increased chances of concussion due to the rapid acceleration from the sudden change in direction of travel [12]. Whiplash is caused when the impact force vector is not collinear with the center of mass axis (Figure 6). The team therefore sought to counteract whiplash with the *leveling* effect: a damper on the opposite side of impact would "catch" the head, slowing its speed relative to the helmet.

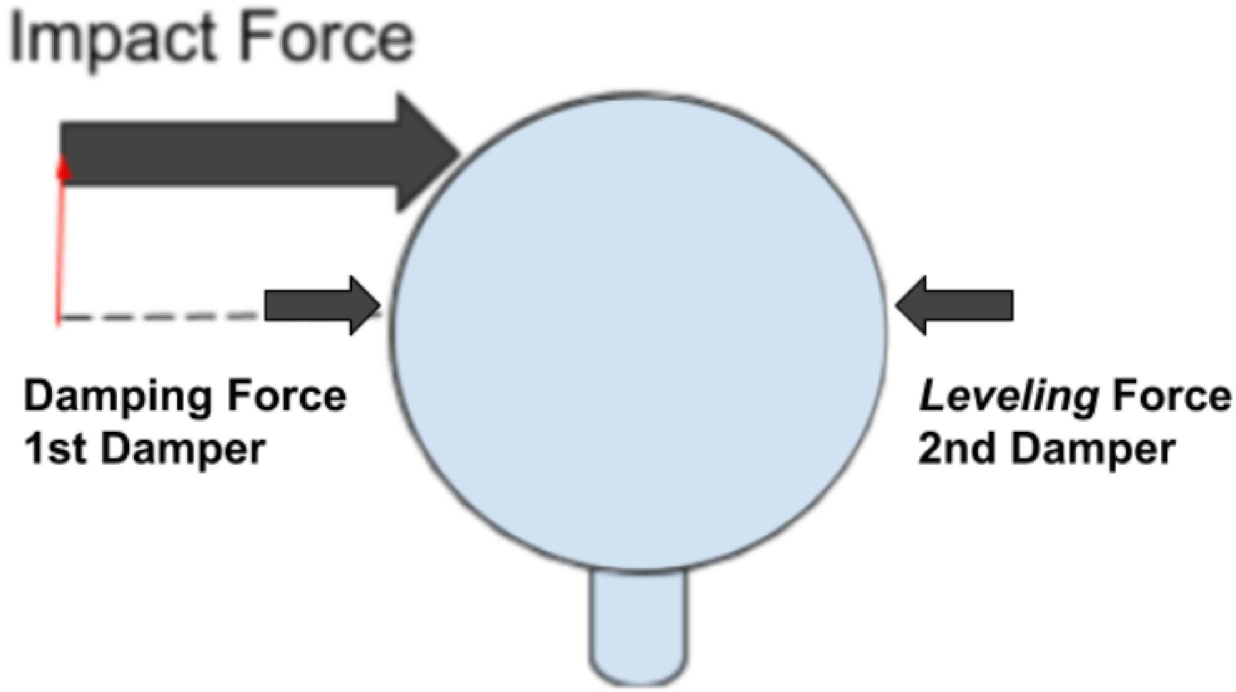


Figure 6. Example of an off-center collision that would cause the whiplash effect — a moment is created about the center of mass, twisting the neck and increasing the chance of concussion.

Third, the fluid line that connected each pair of suspension dampers provided an additional energy dissipation mode in the form of a pressure drop. Pressure drops include pressure losses, head losses, and frictional losses (Equation (7)),

$$\Delta p = (f_D \frac{L}{D_H} + \Sigma K)\frac{\rho V^2}{2} \tag{7}$$

where Δp is the pressure drop, $\boldsymbol{\rho}$ is the fluid density in kg per cubic meter, *L* is the pipe length, D_H is the pipe diameter, *V* is the mean flow velocity, and f_D is the Darcy Friction factor. ΣK is the sum of the minor loss coefficients, which are a result of local flow obstacles, including bends, elbows, and (most importantly) the orifice type and size.

It is clear that the pressure-drop increases with pipe length and decreases with pipe diameter, demonstrating the strong influence of geometric and mechanical design on damping effects. This was ideal because it grants higher variability. The team could easily scale damping effects by simply changing the damper's mechanical design.

This additional mode of energy dissipation would allow the damper geometry to become even more compact, which is another reason the team decided to adopt the interconnected feature into the helmet's damper design.

1.6.5 Several Fluid Choices

It is clear that the team had several fluid choices at their disposal since these suspensions came in the form of hydrolastic and hydrogas suspensions. This is a major benefit of fluid dampers in general: one may vary flow characteristics and damper performance by simply varying the damping fluid and making no changes to the mechanical design.

This ability to easily alter flow characteristics and scale damping effects up or down is another advantage fluid dampers have over foam dampers.

1.7 Customer Needs and Systems Level Requirements

1.7.1 Establishing Needs

Before exploring different methods to improve padding, the team interviewed people of different backgrounds to better understand the areas of improvement for helmets. These people included two football players, one football coach, one EMT, and one neurologist. The data provided from these interviews allowed the team to gain knowledge about the many different factors that go into the sport and its head related injuries and impacts. The EMT and neurologist offered a scientific background to get a better understanding of how and why concussions occur. The football players provided the practical perspective of the problems of wearing a football helmet, both in protection and comfort. The coach provided a useful business perspective, largely because a product needs to satisfy both a practical and financial need, it cannot succeed if it fails to fulfill either one.

1.7.2 Customer Needs

After interviews were conducted, the team charted the most important areas of concern and can be seen in Table 1 below.

Table 1. Organized customer needs from interviews with primary and secondary needs marked then ranked by importance, with a higher number yielding a higher value of importance.

Field of Expertise	Quote Leading to Need	Primary Need & [Secondary Need]	Importance (#/10)
Football Player, Brent Baculi	"He had no information about the type of helmets because they were standardized by his high school"	Personal Player Safety [Increased knowledge of safety and equipment]	8
Football Player, Brent Baculi	"...Greatest head to head contact that he was involved in were head to head clashes at the line of scrimmage. These hits were quick, somewhat like a jab."	Helmet Longevity [Repeated loading and resistance to fracture and leakage]	8
Football Player, Brent Baculi	"...Greatest head to head contact that he was involved in were head to head clashes at the line of scrimmage. These	Helmet Longevity and Durability [Resistance to quick, impactful contact that occurs for short periods of time]	6

	hits were quick, somewhat like a jab."		
Football Player, Brent Baculi	"Many choose to fight through the pain, wanting to avoid meeting with the medical team" - Michael Simeon	Player Safety [Increased knowledge in personal safety and equipment that indicates high hit levels]	8
Football Player, Brent Baculi	"He found that a lighter helmet would be beneficial for his own position"	Change in helmet design [Decrease in overall weight on head]	10
Football Player, Brent Baculi	"These helmets tended to get really stuffy due to the nature of the game"	Change in helmet design [Increase in ventilation]	10
Football Player/Coach	“they are not that bad, measuring about 5 lbs.”	Retain helmet design [Keep weight somewhere near 5 lbs]	7
Football Player/Coach	Current helmets are so good that he could “take a nap in one.”	Retain helmet design [Keep similar headspace within helmet]	7
Football Player/Coach	Vince introduced Xenith’s fitment concept.	Needs fitment adjustability	3

		[Helmet should be form fitting, not just size]	
Football Player, Kaleb Pattawi	Issued a Riddell Speedflex helmet that was issued by the school. He had no choices when choosing a helmet, as the helmets that were provided only fit certain head types	Needs fitment adjustability [Helmets should be easily adjustable to account for how much space that one needs within the helmet]	7
EMT, Kennedy Sundberg	"a magnitude of G's would be helpful to set an index of suspicion following the impact"	Accurate force magnitude readings [Accelerometers must provide accurate force magnitude readings]	10
EMT, Kennedy Sundberg	"way easier to take the front off completely"	Needs fitment adjustability [Helmet can be disassembled]	7
EMT, Kennedy Sundberg	"the back part, where the brain stem meets the skull, is a super important area"	Must protect the lower-back of the head [Requires fluid dampers at the lower back of the head]	10
EMT, Kennedy Sundberg	"evenly spaced along the temples, and with special attention to	Dampers must at least protect all surfaces of the skull	9

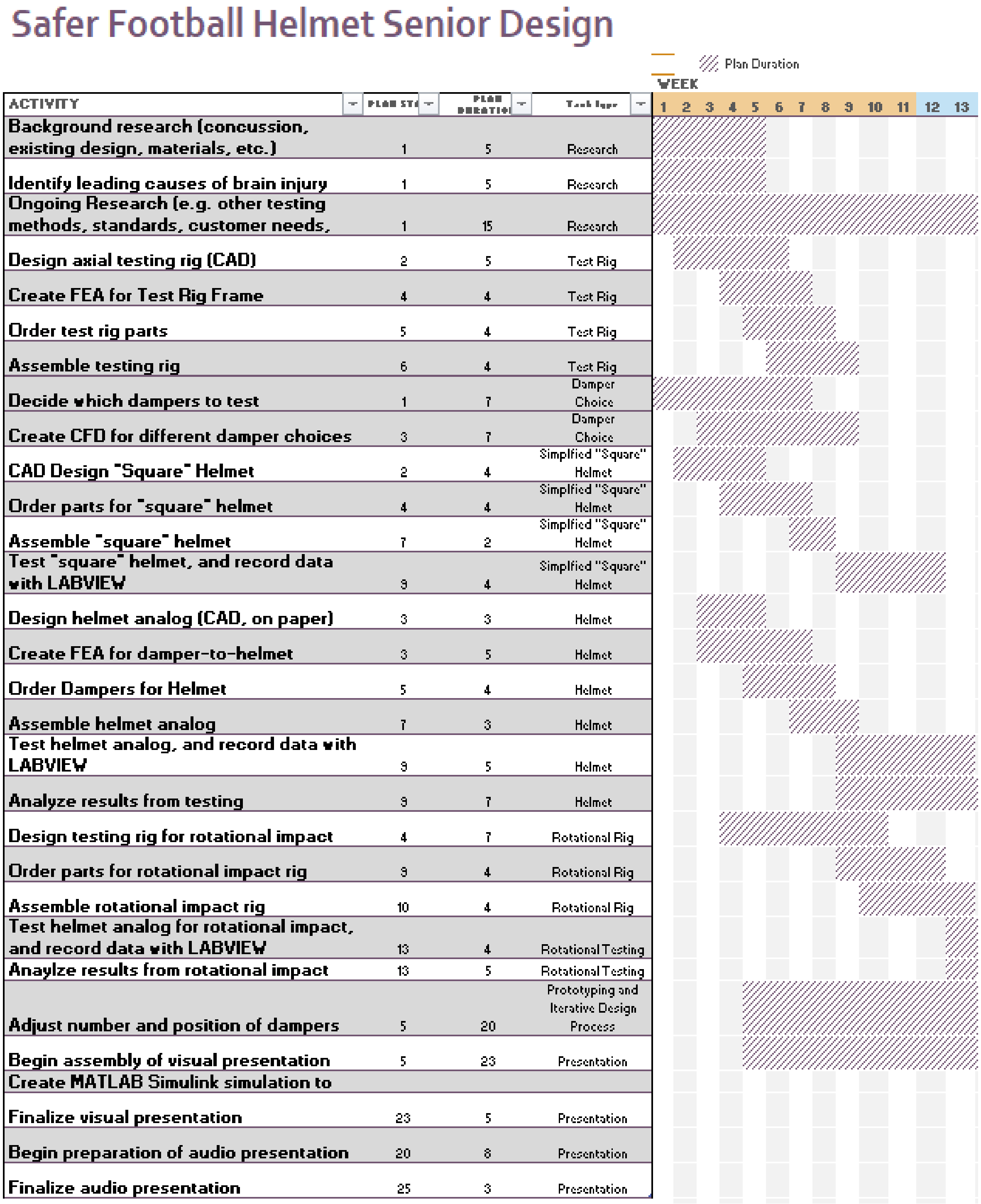
	the cracks in the skull that connect it together."	[Damper location coincides with biomechanics of the skull]	
Neurologist, Dr. James Kelly	countercoup and coup impacts are equally common and equally dangerous	Helmet must protect against both types of impacts [Test helmet for satisfaction of both impact types]	10

See Appendix A1 For Raw Transcripts and Information for Interviews.

1.8 Scheduling and Planning for the Project

1.8.1 Fall Quarter Schedule

The fall quarter schedule, seen in Figure 7, was focused on project planning for the rest of the year and laying the foundations for testing in the future. This schedule predicted that the testing apparatus would be designed and parts for it would be purchased within the quarter. The schedule also predicted that testing of the linear impact would be completed and that the FEA (Finite Element Analysis) models for the impact would be completed.



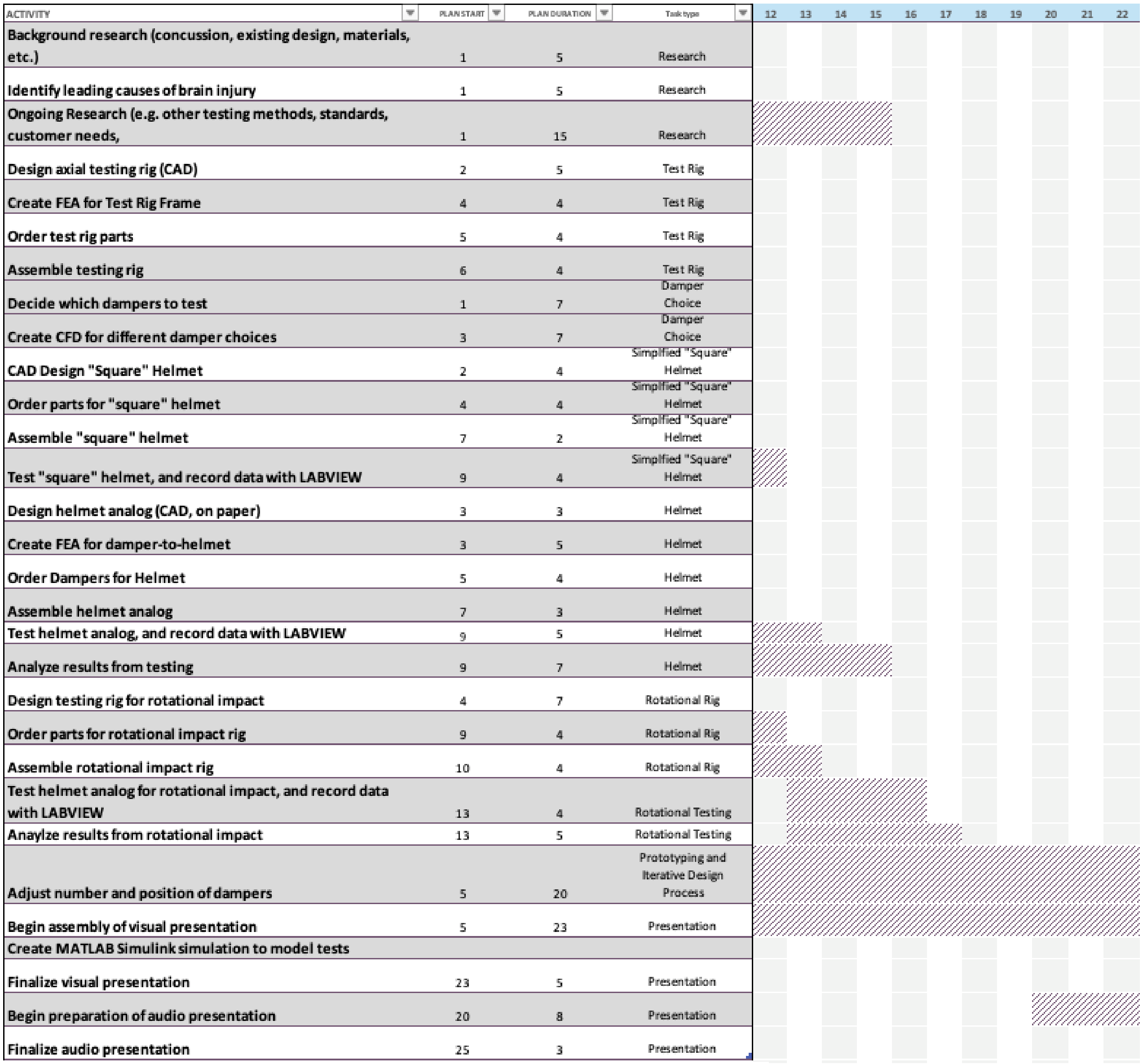
Safer Football Helmet Senior Design

ACTIVITY	PLAN STA	PLAN DURATIO	Task Type
Background research (concussion, existing design, materials, etc.)	1	5	Research
Identify leading causes of brain injury	1	5	Research
Ongoing Research (e.g. other testing methods, standards, customer needs,	1	15	Research
Design axial testing rig (CAD)	2	5	Test Rig
Create FEA for Test Rig Frame	4	4	Test Rig
Order test rig parts	5	4	Test Rig
Assemble testing rig	6	4	Test Rig
Decide which dampers to test	1	7	Damper Choice
Create CFD for different damper choices	3	7	Damper Choice
CAD Design "Square" Helmet	2	4	Simplfied "Square" Helmet
Order parts for "square" helmet	4	4	Simplfied "Square" Helmet
Assemble "square" helmet	7	2	Simplfied "Square" Helmet
Test "square" helmet, and record data with LABVIEW	9	4	Simplfied "Square" Helmet
Design helmet analog (CAD, on paper)	3	3	Helmet
Create FEA for damper-to-helmet	3	5	Helmet
Order Dampers for Helmet	5	4	Helmet
Assemble helmet analog	7	3	Helmet
Test helmet analog, and record data with LABVIEW	9	5	Helmet
Analyze results from testing	9	7	Helmet
Design testing rig for rotational impact	4	7	Rotational Rig
Order parts for rotational impact rig	9	4	Rotational Rig
Assemble rotational impact rig	10	4	Rotational Rig
Test helmet analog for rotational impact, and record data with LABVIEW	13	4	Rotational Testing
Anaylze results from rotational impact	13	5	Rotational Testing
Adjust number and position of dampers	5	20	Prototyping and Iterative Design Process
Begin assembly of visual presentation	5	23	Presentation
Create MATLAB Simulink simulation to			
Finalize visual presentation	23	5	Presentation
Begin preparation of audio presentation	20	8	Presentation
Finalize audio presentation	25	3	Presentation

Figure 7. Gantt chart of Fall Quarter Schedule.

1.8.2 Winter Quarter Schedule

The winter quarter schedule focused on completing many of the tasks that were not completed during the fall quarter. These tasks included building the testing apparatus, finding suitable dampers and putting together a testable helmet. Also, the winter quarter further developed the FEA models that were developed during the previous quarter. This schedule can be seen in Figure 8 below.



ACTIVITY	PLAN START	PLAN DURATION	Task type	12	13	14	15	16	17	18	19	20	21	22
Background research (concussion, existing design, materials, etc.)	1	5	Research											
Identify leading causes of brain injury	1	5	Research											
Ongoing Research (e.g. other testing methods, standards, customer needs,	1	15	Research	▨	▨	▨	▨							
Design axial testing rig (CAD)	2	5	Test Rig											
Create FEA for Test Rig Frame	4	4	Test Rig											
Order test rig parts	5	4	Test Rig											
Assemble testing rig	6	4	Test Rig											
Decide which dampers to test	1	7	Damper Choice											
Create CFD for different damper choices	3	7	Damper Choice											
CAD Design "Square" Helmet	2	4	Simplified "Square" Helmet											
Order parts for "square" helmet	4	4	Simplified "Square" Helmet											
Assemble "square" helmet	7	2	Simplified "Square" Helmet											
Test "square" helmet, and record data with LABVIEW	9	4	Simplified "Square" Helmet	▨										
Design helmet analog (CAD, on paper)	3	3	Helmet											
Create FEA for damper-to-helmet	3	5	Helmet											
Order Dampers for Helmet	5	4	Helmet											
Assemble helmet analog	7	3	Helmet											
Test helmet analog, and record data with LABVIEW	9	5	Helmet	▨	▨									
Analyze results from testing	9	7	Helmet	▨	▨	▨	▨							
Design testing rig for rotational impact	4	7	Rotational Rig											
Order parts for rotational impact rig	9	4	Rotational Rig	▨										
Assemble rotational impact rig	10	4	Rotational Rig	▨	▨									
Test helmet analog for rotational impact, and record data with LABVIEW	13	4	Rotational Testing		▨	▨	▨	▨						
Anaylze results from rotational impact	13	5	Rotational Testing		▨	▨	▨	▨	▨					
Adjust number and position of dampers	5	20	Prototyping and Iterative Design Process	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Begin assembly of visual presentation	5	23	Presentation	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Create MATLAB Simulink simulation to model tests														
Finalize visual presentation	23	5	Presentation											
Begin preparation of audio presentation	20	8	Presentation									▨	▨	▨
Finalize audio presentation	25	3	Presentation											

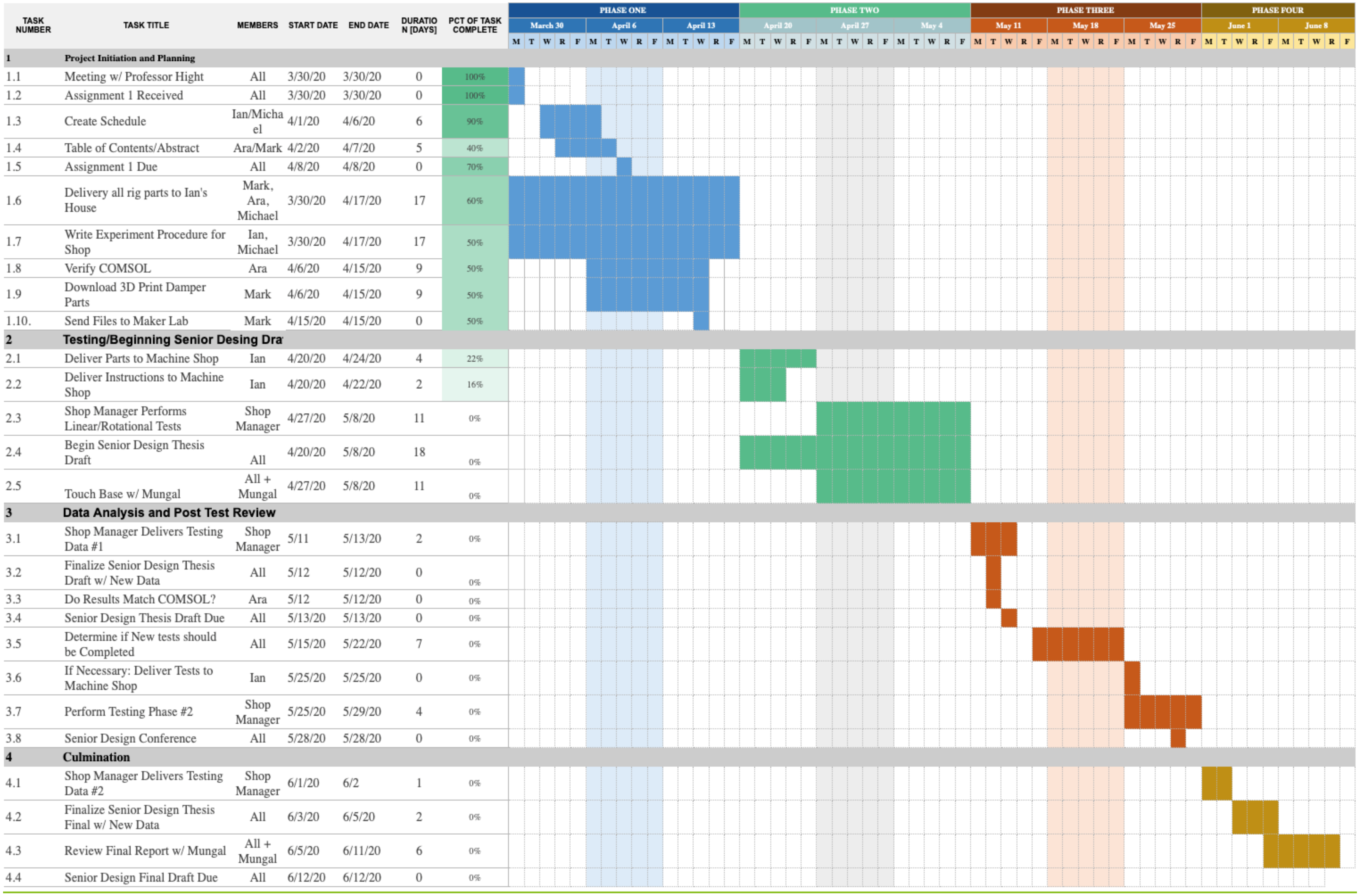
Figure 8. Gantt chart of Winter Quarter Schedule.

1.8.3 Spring Quarter Schedule

For the spring quarter, the team made both a "best-case" and a "worst-case" schedule depending on the severity of the COVID-19 pandemic (see Figures 9 and 10 respectively for each scenario). COVID-19 would greatly affect the availability of the Machine Shop. The "best-case" schedule predicted that the Machine Shop would reopen during the third week of classes, and the "worst-case" schedule predicted that the Machine Shop would not open throughout the remainder of the year. Unfortunately, the Machine Shop stayed closed throughout the rest of the year.

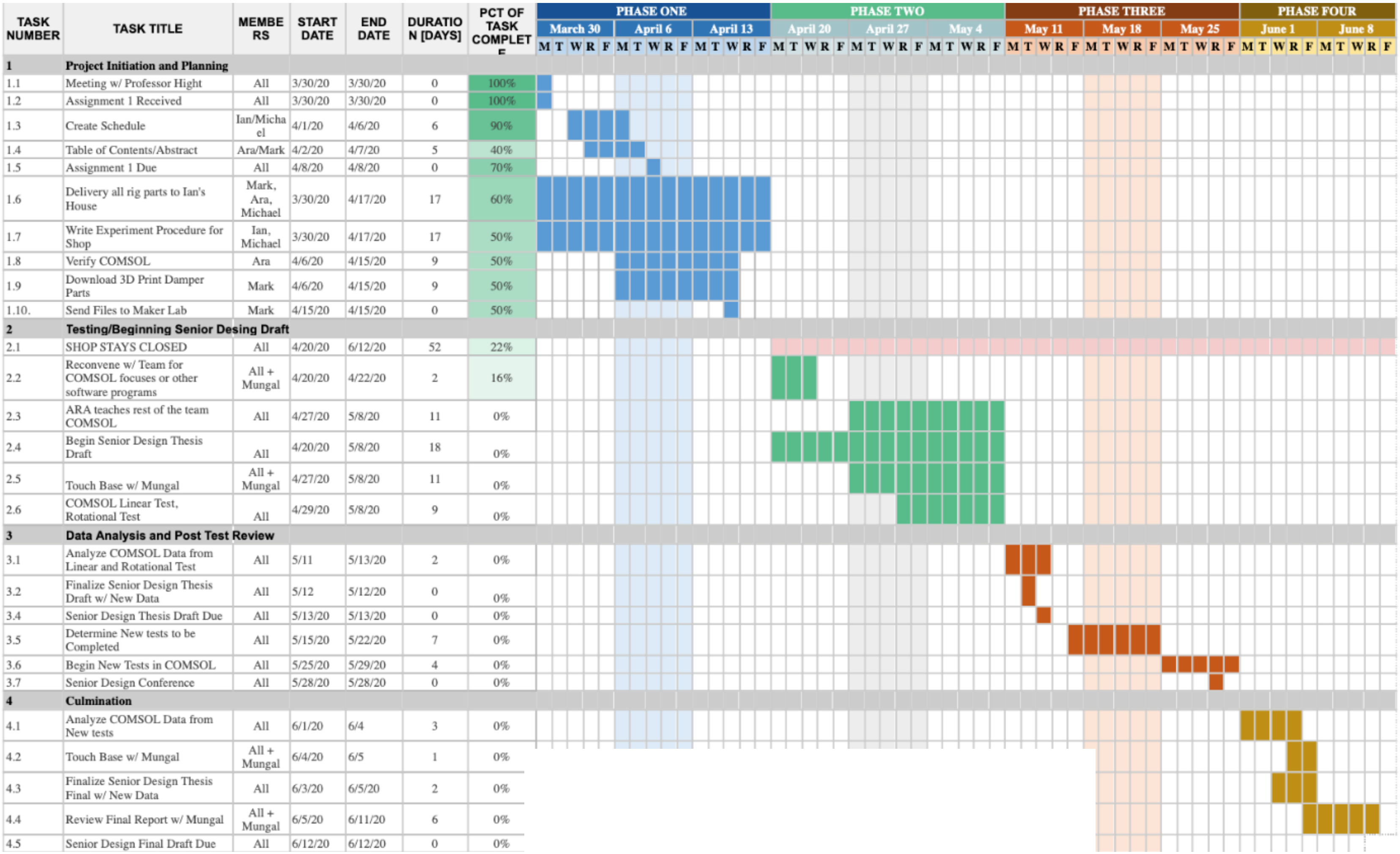
The spring quarter "best-case" schedule focused on preparations for when the Machine Shop would open. If allowed, the team would have finalized the testing apparatus and finalized the assembly of the helmet and put them together in the Machine Shop to complete impact testing. Another main focus of this quarter was to prepare for the senior design conference.

The “worst-case” schedule shifted focus away from the use of the Machine Shop. The team planned to focus more efforts into FEA modeling in Solidworks and COMSOL as well as exploring other impact simulations for the best possible results. This schedule also prepared the team for the senior design conference.



TASK NUMBER	TASK TITLE	MEMBERS	START DATE	END DATE	DURATION [DAYS]	PCT OF TASK COMPLETE
1	**Project Initiation and Planning**					
1.1	Meeting w/ Professor Hight	All	3/30/20	3/30/20	0	100%
1.2	Assignment 1 Received	All	3/30/20	3/30/20	0	100%
1.3	Create Schedule	Ian/Michael	4/1/20	4/6/20	6	90%
1.4	Table of Contents/Abstract	Ara/Mark	4/2/20	4/7/20	5	40%
1.5	Assignment 1 Due	All	4/8/20	4/8/20	0	70%
1.6	Delivery all rig parts to Ian's House	Mark, Ara, Michael	3/30/20	4/17/20	17	60%
1.7	Write Experiment Procedure for Shop	Ian, Michael	3/30/20	4/17/20	17	50%
1.8	Verify COMSOL	Ara	4/6/20	4/15/20	9	50%
1.9	Download 3D Print Damper Parts	Mark	4/6/20	4/15/20	9	50%
1.10.	Send Files to Maker Lab	Mark	4/15/20	4/15/20	0	50%
2	**Testing/Beginning Senior Desing Dra**					
2.1	Deliver Parts to Machine Shop	Ian	4/20/20	4/24/20	4	22%
2.2	Deliver Instructions to Machine Shop	Ian	4/20/20	4/22/20	2	16%
2.3	Shop Manager Performs Linear/Rotational Tests	Shop Manager	4/27/20	5/8/20	11	0%
2.4	Begin Senior Design Thesis Draft	All	4/20/20	5/8/20	18	0%
2.5	Touch Base w/ Mungal	All + Mungal	4/27/20	5/8/20	11	0%
3	**Data Analysis and Post Test Review**					
3.1	Shop Manager Delivers Testing Data #1	Shop Manager	5/11	5/13/20	2	0%
3.2	Finalize Senior Design Thesis Draft w/ New Data	All	5/12	5/12/20	0	0%
3.3	Do Results Match COMSOL?	Ara	5/12	5/12/20	0	0%
3.4	Senior Design Thesis Draft Due	All	5/13/20	5/13/20	0	0%
3.5	Determine if New tests should be Completed	All	5/15/20	5/22/20	7	0%
3.6	If Necessary: Deliver Tests to Machine Shop	Ian	5/25/20	5/25/20	0	0%
3.7	Perform Testing Phase #2	Shop Manager	5/25/20	5/29/20	4	0%
3.8	Senior Design Conference	All	5/28/20	5/28/20	0	0%
4	**Culmination**					
4.1	Shop Manager Delivers Testing Data #2	Shop Manager	6/1/20	6/2	1	0%
4.2	Finalize Senior Design Thesis Final w/ New Data	All	6/3/20	6/5/20	2	0%
4.3	Review Final Report w/ Mungal	All + Mungal	6/5/20	6/11/20	6	0%
4.4	Senior Design Final Draft Due	All	6/12/20	6/12/20	0	0%

Figure 9. The Spring Quarter "best case" Schedule.



TASK NUMBER	TASK TITLE	MEMBERS	START DATE	END DATE	DURATION [DAYS]	PCT OF TASK COMPLETE
1	**Project Initiation and Planning**					
1.1	Meeting w/ Professor Hight	All	3/30/20	3/30/20	0	100%
1.2	Assignment 1 Received	All	3/30/20	3/30/20	0	100%
1.3	Create Schedule	Ian/Michael	4/1/20	4/6/20	6	90%
1.4	Table of Contents/Abstract	Ara/Mark	4/2/20	4/7/20	5	40%
1.5	Assignment 1 Due	All	4/8/20	4/8/20	0	70%
1.6	Delivery all rig parts to Ian's House	Mark, Ara, Michael	3/30/20	4/17/20	17	60%
1.7	Write Experiment Procedure for Shop	Ian, Michael	3/30/20	4/17/20	17	50%
1.8	Verify COMSOL	Ara	4/6/20	4/15/20	9	50%
1.9	Download 3D Print Damper Parts	Mark	4/6/20	4/15/20	9	50%
1.10.	Send Files to Maker Lab	Mark	4/15/20	4/15/20	0	50%
2	**Testing/Beginning Senior Desing Draft**					
2.1	SHOP STAYS CLOSED	All	4/20/20	6/12/20	52	22%
2.2	Reconvene w/ Team for COMSOL focuses or other software programs	All + Mungal	4/20/20	4/22/20	2	16%
2.3	ARA teaches rest of the team COMSOL	All	4/27/20	5/8/20	11	0%
2.4	Begin Senior Design Thesis Draft	All	4/20/20	5/8/20	18	0%
2.5	Touch Base w/ Mungal	All + Mungal	4/27/20	5/8/20	11	0%
2.6	COMSOL Linear Test, Rotational Test	All	4/29/20	5/8/20	9	0%
3	**Data Analysis and Post Test Review**					
3.1	Analyze COMSOL Data from Linear and Rotational Test	All	5/11	5/13/20	2	0%
3.2	Finalize Senior Design Thesis Draft w/ New Data	All	5/12	5/12/20	0	0%
3.4	Senior Design Thesis Draft Due	All	5/13/20	5/13/20	0	0%
3.5	Determine New tests to be Completed	All	5/15/20	5/22/20	7	0%
3.6	Begin New Tests in COMSOL	All	5/25/20	5/29/20	4	0%
3.7	Senior Design Conference	All	5/28/20	5/28/20	0	0%
4	**Culmination**					
4.1	Analyze COMSOL Data from New tests	All	6/1/20	6/4	3	0%
4.2	Touch Base w/ Mungal	All + Mungal	6/4/20	6/5	1	0%
4.3	Finalize Senior Design Thesis Final w/ New Data	All	6/3/20	6/5/20	2	0%
4.4	Review Final Report w/ Mungal	All + Mungal	6/5/20	6/11/20	6	0%
4.5	Senior Design Final Draft Due	All	6/12/20	6/12/20	0	0%

Figure 10. Spring Quarter "worst case" Schedule.

1.9 Teamwork and Task Management

The team employed a democratic style of leadership throughout the entirety of the year, and this allowed members to break off into areas of expertise. In general, two members oversaw most of the design and building of the testing apparatus, one member focused mostly on COMSOL simulations to provide baseline numbers, and the last member focused on damper design and fabrication once the specific damper was chosen. Additionally, every member showed leadership, keeping others accountable for deadlines and other necessary requirements. Moreover, in terms of logistics, two members took more control of ensuring that every assignment and deadline was met well before the due date, but all four members worked on assignments when necessary.

From the early stages of the project, one person was designated the primary contact between different faculty members and staff. This member was held responsible for contacting advisors, shop managers, and other faculty members. However, as the project began to expand and ramp up, other team members took control and contacted appropriate faculty when needed.

In terms of team management, each team member held each other accountable to ensure that progress was being made on both the hardware and software side of the overall project. All members were responsible for different areas.

2. Product Development

2.1 Product Goal and First Sketch

To develop and test a novel football helmet padding system which utilized hydrolastic damping, the team would need to develop a testing apparatus for the helmet, design the helmet, and incorporate instrumentation devices to measure the helmet's performance compared to other helmets on the market. As this was an entirely new product, the team needed to create each of these three components in order to have a successful product. Below, in Figure 11 was one of the team's first ideas for a hydrolastic football helmet.

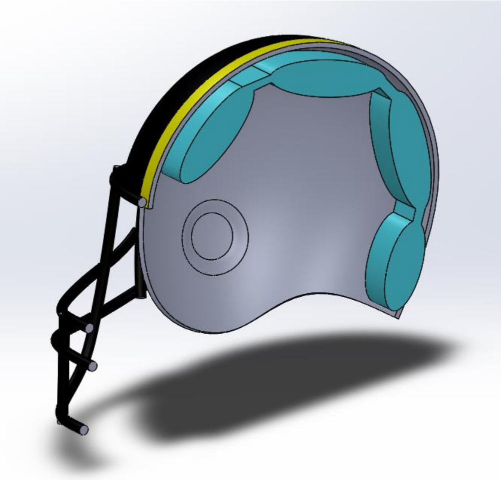


Figure 11. This was one of the team's first design ideas for a novel padding system for the football helmet. It would use connected fluid dampers (as seen in blue) and it would be able to fit within the prescribed geometries of a traditional football helmet.

2.2 Developing a Testing Apparatus

2.2.1 Brainstorming

Prior to refining a design for a testing apparatus, a number of different options were considered and scored accordingly. The first idea chosen was an air compressor driven system that would send a weighted mass down a secure track. This method was considered due to its repeatability and its overall likeness to realistic scenarios. A weighted mass being launched down a track would allow for an instantaneous impact that was desired for this testing procedure. However, the team felt as if this method of testing would be deemed unsafe due to the necessity of pressurized air. This method of testing would require the design of an intricate safety shield and rail based system that would detract from the original goal of the project.

A safer method of testing that was also considered was a standard drop test mechanism. This mechanism would allow for the team to hoist and drop an object to a specific height using a remote pulley system. Though this system was safer and just as repeatable as the compressed air idea, this system provided the team with only one testing form. It would only simulate head to ground impact, which was not enough to justify a creation of an entire testing apparatus.

The third and most realistic testing idea was a simplified version of a Charpy testing apparatus. This pendulum based design theoretically provided the team with all of the strengths of both the compressed air and drop test ideas. It was just as safe as the drop test mechanism because all of the stored energy was accounted for from the height of the pendulum. Also, it was just as repeatable as both of the prior testing mechanisms because the pendulum arm could be raised to a specific height at relative ease. Moreover, this testing design would prove to be just as multi-dimensional as the compressed air idea as this design could simulate both head to head and head to ground impacts.

2.2.2 Final Selection Parameters

2.2.2.1 Frame

The pendulum design was created primarily of standard 10’ sections of 1½” ABS (which were cut to size) in order to reduce overall weight and cost of the testing frame. ABS was the preferred material of choice due to its high strength to weight ratio and its ease of assembly. The frame was assembled using stock ABS joining-pieces, such as 1½” elbows, wyes, and double wyes. Also, 1½” PVC table cap fittings were used as well. The assembly of the frame was completed quickly due to the usage of quick-drying ABS and PVC adhesives as well as the ease of cutting ABS pieces to length with a standard hand saw. The final height of the frame stood at 5’ tall.

2.2.2.2 Railing

A 5’ x 1⅝” aluminum Unistrut railing and 1⅝” channel wheels allowed for testing to simulate both a free impact and impact against a hard surface, both of which are very common methods of impact within the sport of football. This railing was mounted onto the base of the apparatus using ⅝” sheet screws at both ends of the rail. The Unistrut channel chosen was durable and compatible with the 1⅝” wheels used during testing.

2.2.2.3 Base

A ¾” thick 4’ x 8’ birch plywood board was chosen for the base. First, the standard 4’ x 8’ board could be resized to 2.5’ x 8’ in order to account for storage restraints. The overall dimensions of the base were very flexible, and a plywood board was the best available material due to its low cost as well as its ease of customization. Moreover, this material was selected because of its ease of assembly. The ABS frame could be easily mounted onto the base using ⅝” sheet screws and 1½” pipe clamps. These pipe clamps held the ABS frame in place and were installed by hand using a screwdriver and the ⅝” sheet screws.

2.2.2.4 Pendulum System

The initial pendulum used acrylic bearings that were attached to the top of the frame and oak arms that extended to the acrylic-encased brick that was chosen as the impact mass. This encasing was created by laser cutting a ¼” thick sheet of acrylic (Figure 12). The mass encasing would also feature a foam pad on the face of impact to simulate a more realistic method of impact, as well as protecting the encasing from shattering. However, after careful consideration, this design was changed because the acrylic was too brittle and could have fractured during impact.

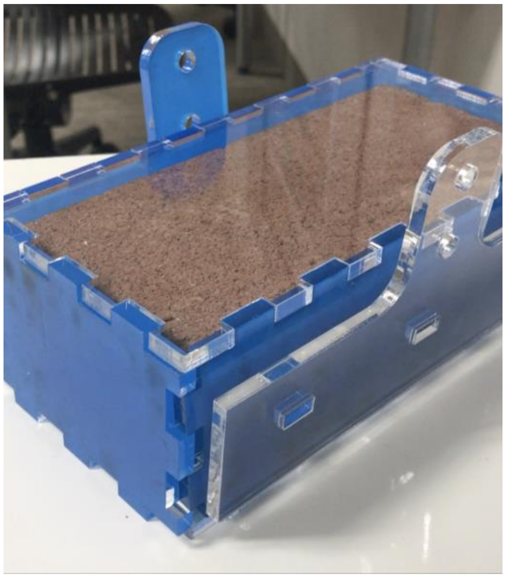


Figure 12. Image of the first impact mass (a brick encased in an acrylic enclosure). This design was deemed unsafe because it was too brittle and could have shattered during impact testing.

2.2.2.5 Changing Materials

The acrylic bearings and the acrylic impact mass encasing were changed due to safety concerns. Though acrylic was highly customizable, cheap to purchase, and easy to handle, it suffered from immediate and catastrophic failure when broken.

To replace the acrylic bearings, the team laser cut 3-layer ¼" plywood in the same shape that was used for the acrylic. For the swinging mass, the brick encased in acrylic was replaced with an aluminum block. Wood and aluminum do not chip and fracture as easily as acrylic, and the brick was essential for testing, so a solid aluminum impact mass would be sufficient for testing. The team then set out for custom machining of an aluminum block to be used as the impact mass.

2.2.2.6 Modifying the Frame

The frame also raised some safety concerns when considering tensile stresses and beam bending. Before constructing the testing apparatus, the team needed to ensure that the horizontal beam would not fracture under load. The tensile strength of ABS was approximately 3210 psi, and after using a Solidworks FEA model for both a 30” beam and a 16” beam, as seen in Figures 13 (30” beam) and 14 (16” beam) below, the estimated max stress that the beam would feel while carrying a load of roughly 16 pounds would be approximately 196 psi and 98 psi for the 30” and

16” beams respectively. Both of these values provided reassurance and the common understanding that the beam would not fracture.

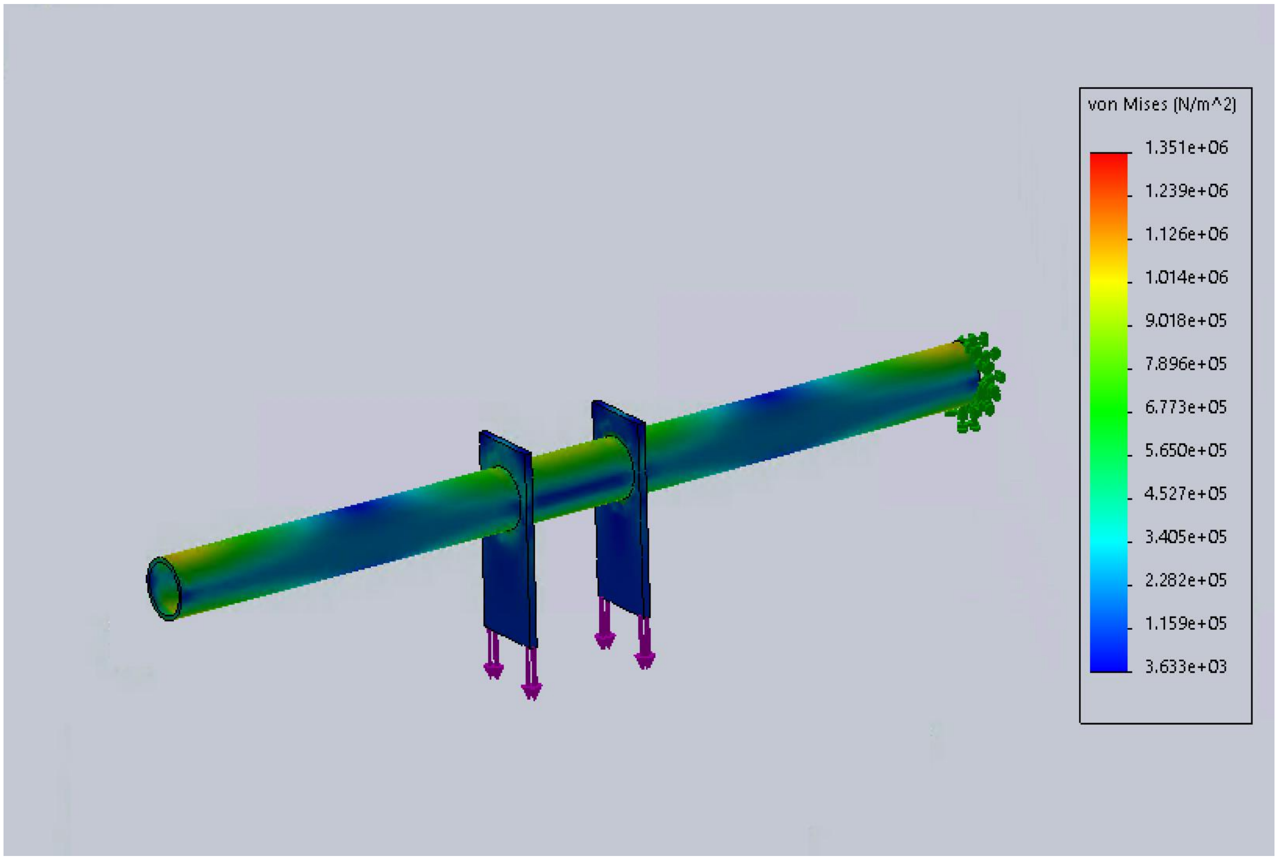


Figure 13. *Simple FEA of the 30” horizontal beam supported at its ends and holding the weight of the impact mass via two bearings. The stress concentration can be visibly seen toward the ends of the beam, noted in red.*

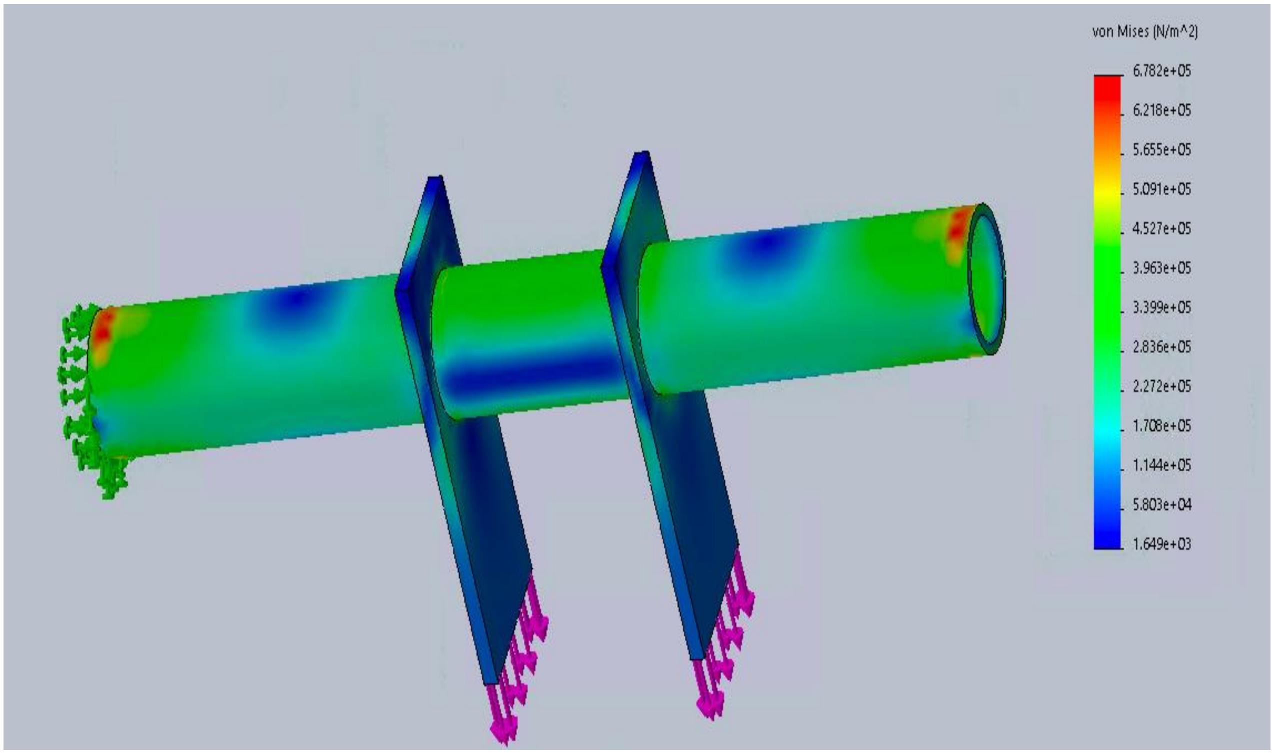


Figure 14. Simple FEA of the 16" horizontal beam supported at its ends and holding the weight of the impact mass via two bearings. The stress concentration can be visibly seen toward the ends of the beam, noted in red.

After ensuring the beam would not suddenly fracture, it was important to address beam bending and overall deflection. The deflection equation that the team used can be highlighted in Equation (8) below.

$$\delta = \frac{PL^3}{48EI} \tag{8}$$

Where the load (P) was 16 lbs, the Modulus of Elasticity (E) was 145,000 psi, the Moment of Inertia (I) was 37.766 in^4, and the length of the beam (L) was 30". The moment of inertia was calculated with the assumption of using a 4" inner diameter piece of ABS and a 0.14" thickness.

After inputting values in Equation (8), the calculated deflection for the 30" beam was predicted to be 0.0016 in. Though this value seemed realistic and no cause for initial concern, the horizontal beam of the testing apparatus deflected visibly when applied to the final design. As a result, the team decided to decrease the length of this beam to 16” to reduce deflection. Moreover, cutting the horizontal beam did not impact the testing area because the helmet would have still had more than enough space on the railing system on the plywood floor.

2.2.2.7 Final Features and Interlocks

To finalize the testing apparatus, the team needed to implement a safety interlock and a safety shield. The safety interlock would ensure that the release of the pendulum arm could be done remotely, and the safety shield would protect team members in case of sudden fracture of any material. The safety shield was to be added to the end of the plywood base, on the side that the pendulum mass was to be swung from, as seen in Figure 15 below.

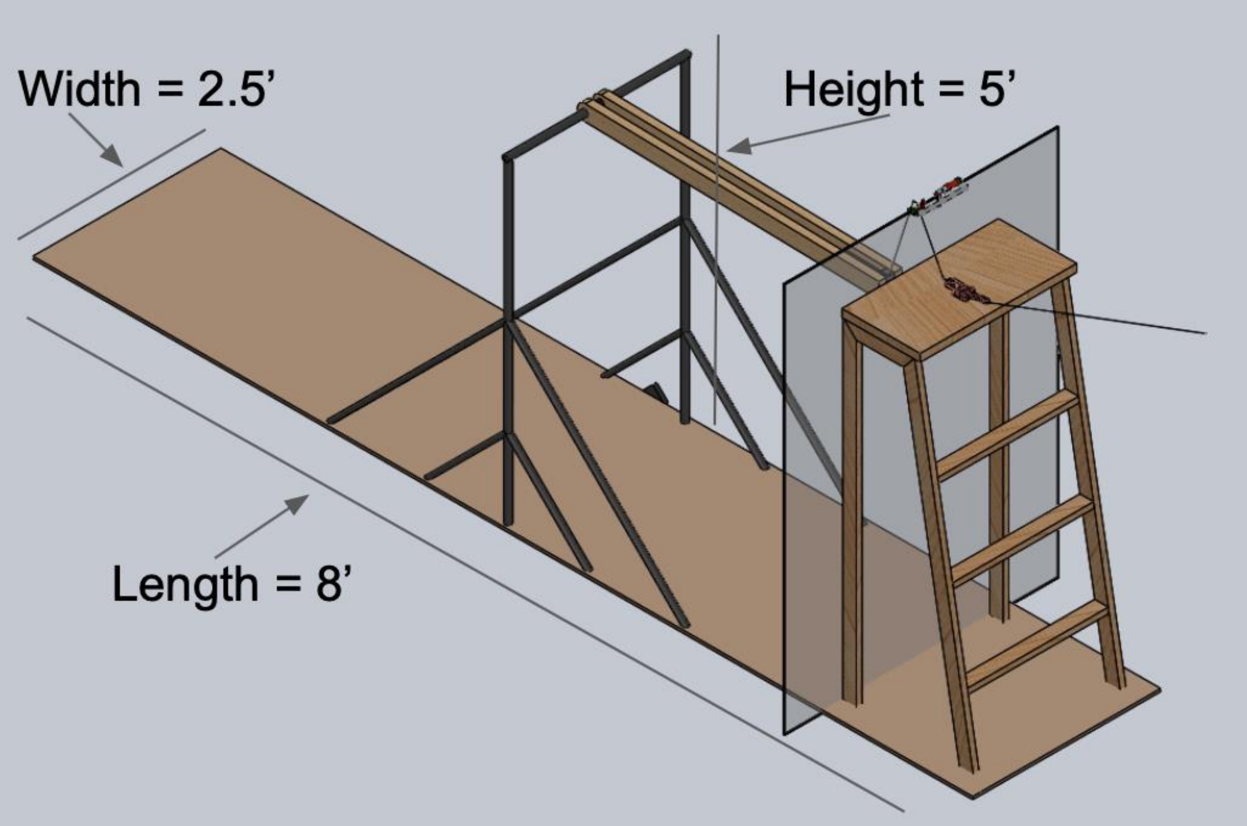


Figure 15. Solidworks model of the completed testing apparatus as well as a safety interlock and a safety shield. The height of the rig of is 5' tall.

The safety shield was to be supported by screws placed at the bottom of the plywood base as well as supported by a standard stepping stool. Ideally, this would have kept the safety shield in place throughout the duration of the testing process.

The safety interlock would allow the pendulum arm to be cranked and fed through a latch, and the interlock latch would then have another piece of rope attached to it. Finally, the second piece of rope could then be pulled from a safe distance away from the apparatus to release the primary rope of the pendulum arm. The safety interlock is highlighted in Figure 16.

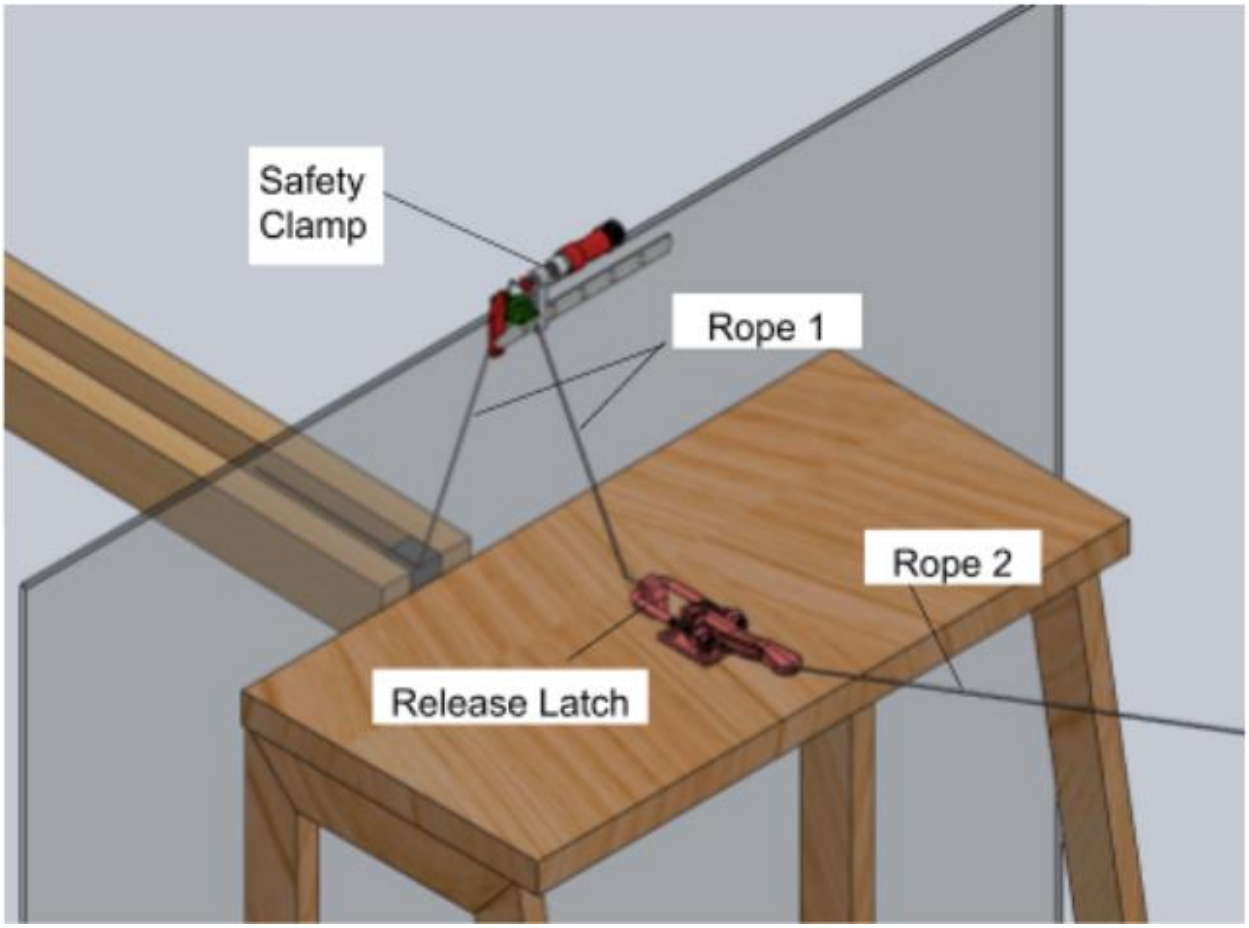


Figure 16. Closer view of the two clamp system that allows the release mechanism to be completely remote.

2.2.2.8 Current State

At its current state, the testing apparatus was not fully completed due to COVID-19 restrictions. The team created manuals explaining how to finish the construction of the testing apparatus, including safety interlocks and mechanisms.

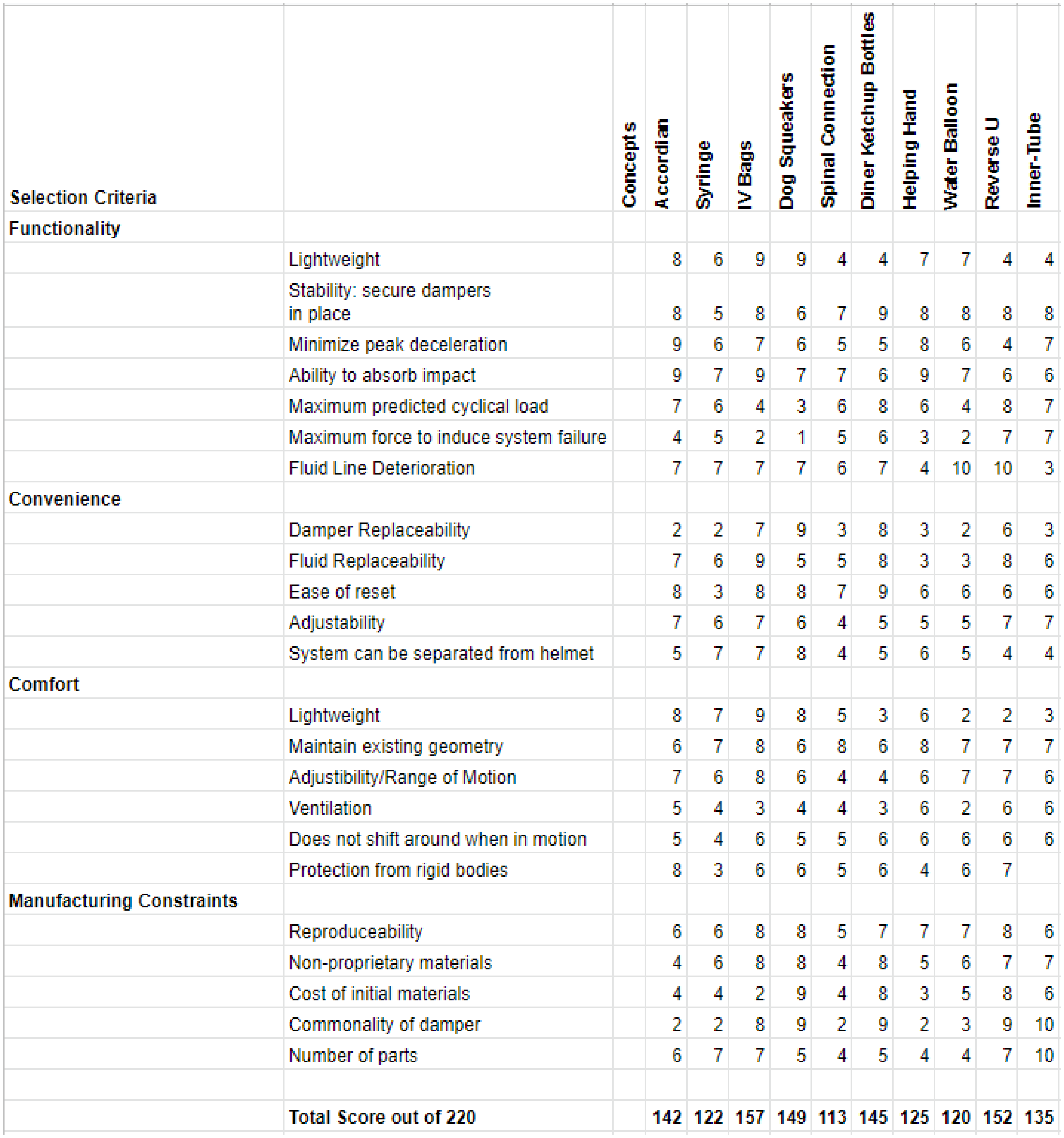
Manuals for finishing safety apparatus can be found in Appendix A2.

2.3 Developing a Fluid Damper

2.3.1 Brainstorming

To begin the process of selecting a damper, the team created a scoring matrix that predicted the effectiveness of different damper solutions based on set parameters in terms of functionality, convenience, comfort, and manufacturing constraints. The best score was 10, and the worst score was 1. All values were properly scored in Table 2.

Table 2. This table shows the different damper designs graded based on different factors that the team was considering, such as functionality, convenience, comfort, and manufacturing restraints.



Selection Criteria		Concepts	Accordian	Syringe	IV Bags	Dog Squeakers	Spinal Connection	Diner Ketchup Bottles	Helping Hand	Water Balloon	Reverse U	Inner-Tube
Functionality												
	Lightweight		8	6	9	9	4	4	7	7	4	4
	Stability: secure dampers in place		8	5	8	6	7	9	8	8	8	8
	Minimize peak deceleration		9	6	7	6	5	5	8	6	4	7
	Ability to absorb impact		9	7	9	7	7	6	9	7	6	6
	Maximum predicted cyclical load		7	6	4	3	6	8	6	4	8	7
	Maximum force to induce system failure		4	5	2	1	5	6	3	2	7	7
	Fluid Line Deterioration		7	7	7	7	6	7	4	10	10	3
Convenience												
	Damper Replaceability		2	2	7	9	3	8	3	2	6	3
	Fluid Replaceability		7	6	9	5	5	8	3	3	8	6
	Ease of reset		8	3	8	8	7	9	6	6	6	6
	Adjustability		7	6	7	6	4	5	5	5	7	7
	System can be separated from helmet		5	7	7	8	4	5	6	5	4	4
Comfort												
	Lightweight		8	7	9	8	5	3	6	2	2	3
	Maintain existing geometry		6	7	8	6	8	6	8	7	7	7
	Adjustibility/Range of Motion		7	6	8	6	4	4	6	7	7	6
	Ventilation		5	4	3	4	4	3	6	2	6	6
	Does not shift around when in motion		5	4	6	5	5	6	6	6	6	6
	Protection from rigid bodies		8	3	6	6	5	6	4	6	7	
Manufacturing Constraints												
	Reproduceability		6	6	8	8	5	7	7	7	8	6
	Non-proprietary materials		4	6	8	8	4	8	5	6	7	7
	Cost of initial materials		4	4	2	9	4	8	3	5	8	6
	Commonality of damper		2	2	8	9	2	9	2	3	9	10
	Number of parts		6	7	7	5	4	5	4	4	7	10
	Total Score out of 220		**142**	**122**	**157**	**149**	**113**	**145**	**125**	**120**	**152**	**135**

More detailed description on each preliminary damper design is included in Appendix A3.

From this matrix, the team decided to further develop the “Reverse U,” Dog squeakers, and IV bag designs due to their successes in all aspects of the scoring matrix.

2.3.2 Primary Sketches

The Reverse U design was highlighted because of its ease of construction. It was a simplistic design that would be easily implemented and tested. Similar to the IV bag design, the reverse U will have large dampers which are connected through a series of fluid lines. The main advantage of the reverse U is that it can be wrapped around the entirety of the helmet and helps disperse the energy of the impact across a greater area. Preliminary designs can be seen in Figure 17 below.

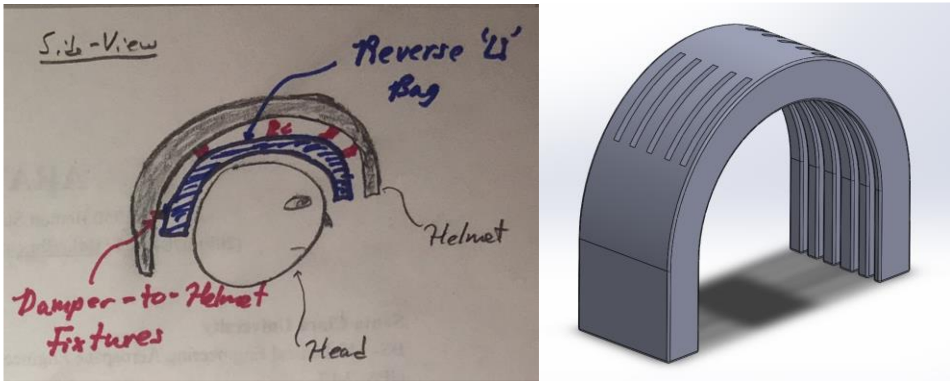


Figure 17. *The image on the left shows a side view sketch of the “Reverse U” damping system. The image on the left shows the Solidworks model of the "Reverse U" damping system.*

The dog squeaker design was chosen for its ease of construction and pairing abilities. Dog squeakers had an air outlet that was perfect for tube fittings and were small enough to implement multiple units in one area. Initial designs can be seen in Figure 18 below.

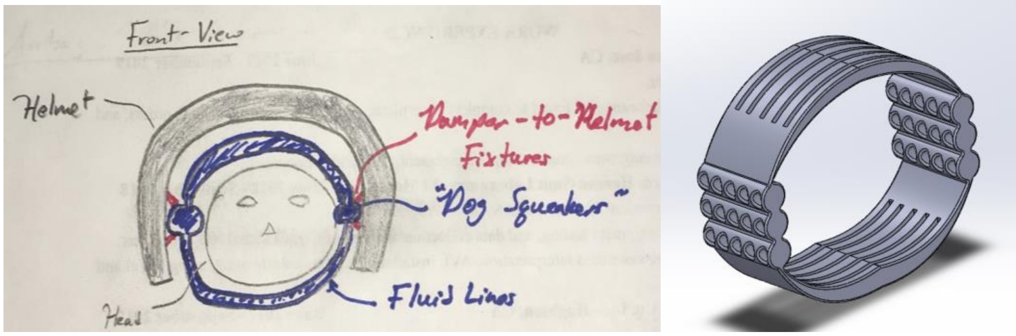


Figure 18. *The image on the left represents the front view sketch of the "Dog Squeaker" damping system. The image on the right represents the Solidworks model of the "Dog Squeaker" damping system.*

IV bags were chosen to test for an overall proof of concept. They provided the team with enough volume to prove the positive impacts of fluid damping. Moreover, IV bags were already configured to be attached, so linking the bags together was relatively easy. The system utilizes two large dampers located on the sides to absorb impacts then transfer fluid expanding the bags on the opposing side of the helmet. In Figure 19 below, the primary sketches of IV bag dampers can be seen.

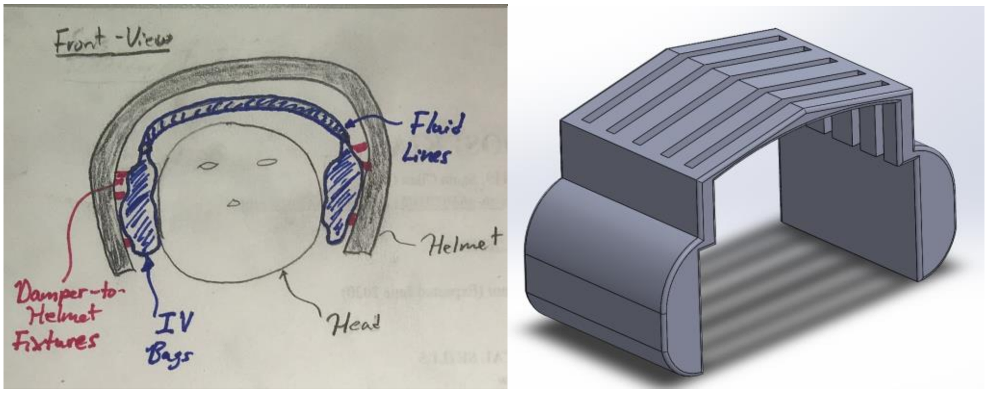


Figure 19. *The image on the left represents the front view sketch of "IV Bags" damping system. The image on the right represents the Solidworks model of the "IV Bags" damping system.*

2.3.3 Store Bought Dampers

Because IV bags and dog squeakers were relatively cheap and theoretically effective, both of these options were pursued. However, the team discovered a reusable water balloon, a silicone-based membrane, that could be a sufficient damping material. Because of its predicted effectiveness, this solution was also purchased.

When conducting primary testing on the team's three damper solutions, noticeable issues were discovered. First, the rigidity of the IV bags proved to be disadvantageous. When an instantaneous impact struck the water filled bag, no water was displaced. Moreover, when testing the water wubble, the membrane displaced too greatly in all directions. The water wubble disbursed the impact and flattened completely. The dog squeakers did not store enough volume to be tested further.

To combat issues of rigidity and flexibility, the team decided to use an IV bag to encase the water wubble, so that the rigid shell would force water into the fluid tube and into the other water wubble. This configuration can be seen in Figure 20 below.

*Figure 20**.** The two water wubbles were connected together with a ¼" inner diameter plastic tube and the tubes and water wubbles were connected with zip ties.*

Though this worked to a certain extent, this solution was not optimal because this configuration did not take advantage of the benefits of hydrolastics. One of the main functions of hydrolastics involved a damper with a varying area in order to smoothen the impulsive forces into more constant forces spread over a longer impact duration. This design featured a uniform surface area membrane that could be improved greatly.

2.3.4 Custom Solutions to Store Bought Dampers

To implement a variable area system, the team first looked to create a 3-D printed model to encase the water wubble. This encasing included a bulge toward the bottom of the structure to allow for water to be forced up from the water wubble into the tube, and into the other damper. It would have expanded both vertically and horizontally within the casing to allow for max coverage. The issue with this design was trying to find a material that was rigid enough to encase the free-forming water wubble but also malleable enough to not take away from the mechanical advantages of hydrolastics. This initial design can be seen in Figure 21 below.

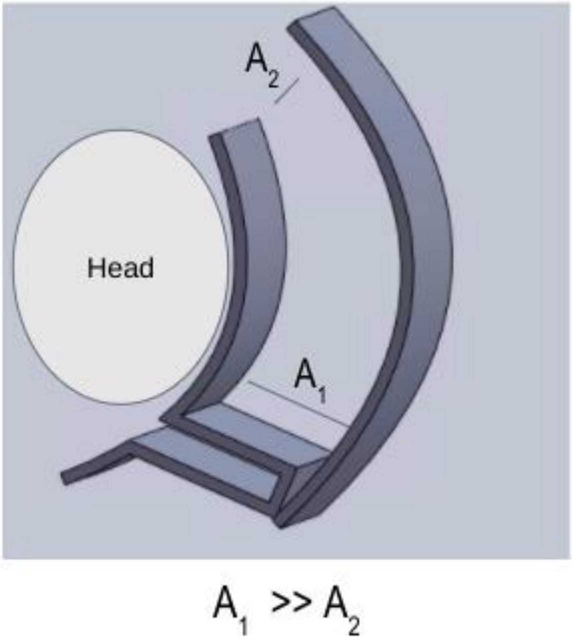


*Figure 21**.** Encasing of the water wubble to provide rigidity and a varying area. The piece on the left would slide upward, reducing the overall area of the enclosure, forcing fluid from one damper to the other.*

2.3.5 Designing a Custom Damper

Because of challenges with store bought dampers and encasings, the team looked into custom dampers, of which 3D-printed TPU (thermoplastic polyurethane) was the best solution. TPU has similar properties to rubber but can be 3D printed or injection molded, making it ideal for rapid prototyping and mass production. 3D printing gives the flexibility to rapidly and cheaply prototype designs to get instant feedback.

The difficulty with 3D printing lies in the variability that results from which specific material, print settings, and printer is being used. The primary printer being used was a Prusa MK3 with the default configuration of a AA 0.4mm brass nozzle and single extruder. The three 1.75mm TPUs used were manufactured by Sainsmart (blue), NinjaTek (black), and Ultimaker (black). Each of the three manufacturers only had one type of TPU available for purchase.

Using these materials, a number of different print settings were tested to identify the one that worked best for the materials being used. The final print settings were a variation of the native TPU print settings in the 2020 PrusaSlicr software, the native software provided by Prusa printers to convert 3D files into a printable format. The infill was changed to 90% to prevent ghosting of the damper wall - where an inner layer and outer wall would form with some degree of space in between the two - and to limit the likelihood of leaking (print failure). An infill pattern of gyroid was used since it maximized the strength and flexibility profile of the print in all 3 directions (X, Y, and Z). Cubic was also used with success. Print bed temperature was originally set at room temperature (non-heated), but it resulted in a high print failure rate as the print in its early stages would get caught on the extruder. The resulting print bed temperature of 100 C with a layer of glue (from an off-the-shelf glue stick) led to more reliable prints without getting stuck to the print bed. Each damper was also printed one-by-one, since multiple damper prints resulted in stringiness and gaps in the layers as the extruder rapidly changed direction to move from one damper to another. Other print settings such as print speed, layer thickness, and extruder temperature were unchanged from the native settings in PrusaSlicr.

The initial damper design had a conical shape which provided a variable damping effect where the farther the damper is compressed, the larger the contact area is. It also utilized a side-facing connection port to allow the dampers to be interconnected while minimizing the size. However, the pointed end of the conical damper resulted in instability so that the damper wouldn't compress vertically but lean to one side or another.

2.3.6 Final Design

Figure 22 below shows the cross-sectional view of the final design. The pointed top was changed for a flat one to ensure vertical stability. The wall thickness also increased from an original 1mm all around to 1mm at the top and 1.5mm at the bottom. The increasing thickness added more structural stability the further the damper was compressed to reduce the risk of blow-out.

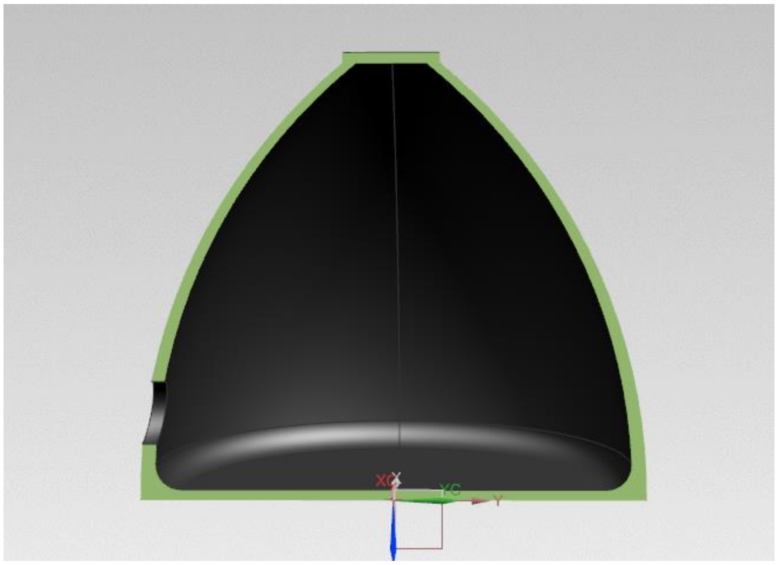


*Figure 22***.** *Cross section of final design. The final damper had a base with a diameter of 2" and a height of 1.75". A fillet of .25" was internally to decrease the stress concentration.*

FEA was also conducted on the final design to determine the areas of greatest elongation or stress. FEA was conducted using SolidWorks Education 2020 for static modeling. Each of the following models was conducted using the 3D design in CAD (Computer-Aided Design) with the bottom of the damper fixed and a total load of 50N being exerted on the top surface of the damper. The mesh created for the analysis was extremely fine and the analysis replicated to ensure accurate results. The elongation FEA (denoted in blue of Figure 23) showed that the critical area was a band around the lower midsection, roughly .45" from the bottom of the damper. This was a positive result since that section was also where the thickness of the damper was the greatest and therefore the strongest. The stress concentration showed bending around the same area as well pictured as a green band in Figure 2.13. The finished dampers and some of the variations can be seen in Figure 24. The black dampers were printed with Ninjatek TPU and the blue dampers were printed with Sainsmart 95A TPU.

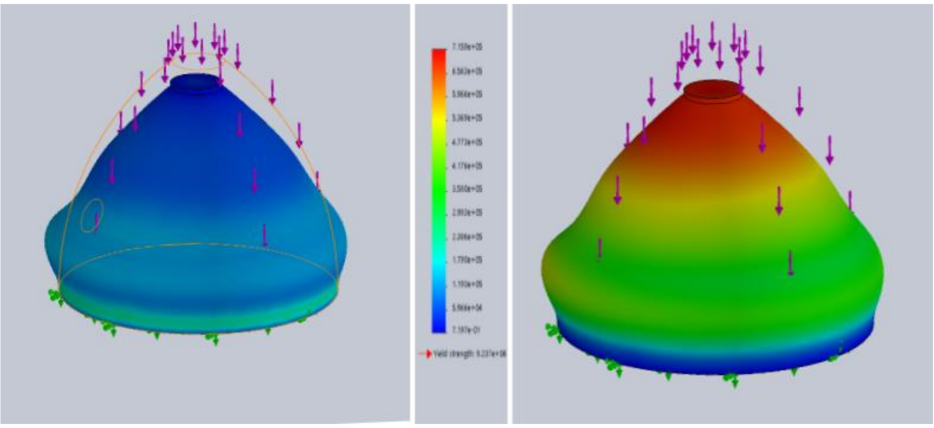


Figure 23. FEA of the damper. Elongation FEA on the left and stress FEA on the right. Both FEAs proved to be positive responses as the areas that showed increased risk were also reinforced.

Figure 24. 3D samples of the initial design in the background with the pointed tip and final design with the flat top. The black TPU was made using Ninjatek but proved to be too flexible whereas the blue TPU was made using Sainsmart 95A TPU which proved to have the best balance of flexibility and strength.

2.3.7 Fluid Choices

Many different fluid options were considered for this project because the team wanted to consider viscosity as a beneficial or disadvantageous factor within the damper as well. However, because the fluid of choice was designed to come in close contact with people, it was important for the fluid of choice to be nontoxic. Syrup, water, and air were chosen as fluids of choice due to their wide range of viscosities, seen in Table 3 below, as well as their accessibility and overall safety.

*Table 3***.** *The dynamic viscosities of water and air were found at 20 °C, while the dynamic viscosity of syrup was found at 21 °C due to the lack of charted data at a consistent interval.*

Fluid Type	Dynamic Viscosity [Pa*s]
Water [13]	$1.002 * 10^{-3}$
Air [14]	$18.13 * 10^{-6}$
Syrup [15]	$15 * 10^{-2}$

2.4 Developing a Model Head

To test the dampers, the team needed a head to put them on as well as a body to attach instrumentation devices, such as accelerometers, too. It was important the head could survive multiple impacts from the testing apparatus, and it was important that the head would be rigid enough as to not take away potential force damping results from the dampers.

2.4.1 Brainstorming

The team decided between a traditional round head and a block head. A round head, as pictured on the left in the Figure 25 below, would have been effective, but its high price point led the team to search for other options for testing. When looking for other ways to mount and test the dampers, the team considered using a block head. A block head would provide customizable geometry and have flat surfaces which would make the attachment of dampers to the sides of the head easier.

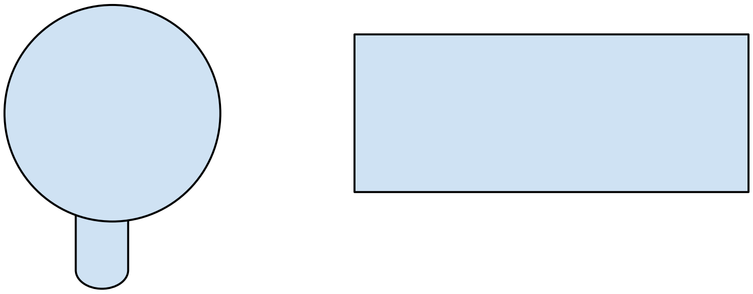


Figure 25. (Pictured Left) A round head would be more similar to a human head, but its high price point was a limited factor for the team. (Pictured Right) The block head was simpler to design and more customizable for the team, and ultimately was the final choice testing.

Each helmet design had pros and cons. For the round head, it's geometry would be most similar to that of a football athlete, but it was too expensive. The block head on the other hand was a cheaper alternative and was easier for the team to use during testing because of its flat surfaces. The team ultimately decided to use a block head instead of a round head. The block head would simplify the fabrication of the head, and it would provide the team with flat surfaces to attach dampers and instrumentation devices to.

2.4.2 Developing a Block Head

The final design of the block head included dampers on both sides, an accelerometer, Unistrut wheels, and a hard, outer shell. The blue dampers (as seen in the Figure 26 below) were connected by a blue fluid line. The accelerometer was placed on the side of the helmet and out of the way of the dampers.

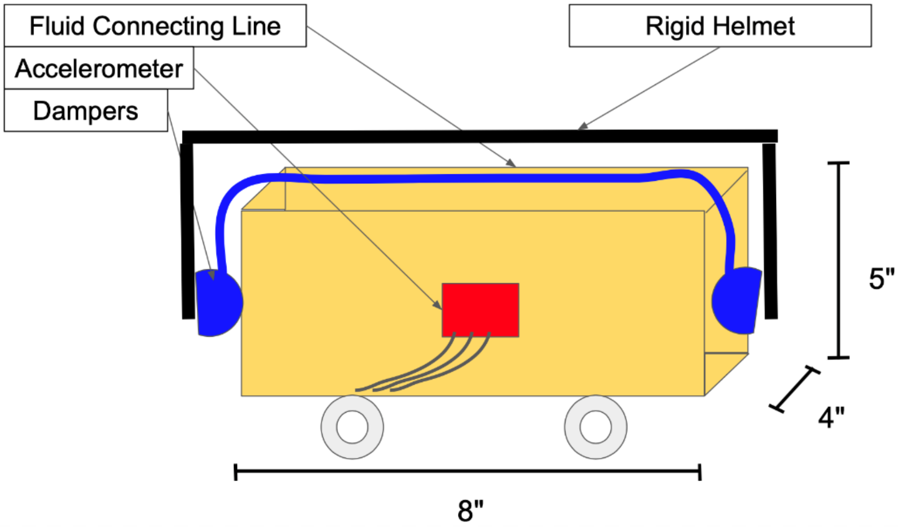


*Figure 26***.** *Shows the block head and its instrumentation attachments. The dimensions of the block head were 8" x 4" x 5".*

The main features of the block head were the dampers and the connective fluid line, the accelerometer, the Unistrut wheels, and the rigid helmet. The dampers were mounted on either side of the helmet at a distance of 8" to replicate the average width of a football helmet (as was measured with a Riddell helmet which was donated to the team by St. Ignatius College Preparatory). The fluid line was to be attached to each of the dampers and mounted to the top of the block head. The inner diameter of the fluid line was not set at the time of design for the block head, and it was to be varied throughout the testing process.

Another important feature of the block head was the accelerometer location. The accelerometer was placed on the side of the helmet so that it was out of the way of the damper fluid lines and so it could capture any rotational accelerations that could have occurred during the impact on top of the expected axial accelerations. Next, Unistrut wheels were attached to the bottom of the helmet to allow the helmet to roll away after impact. This movement would give the helmet dynamic movement and be more similar to the movement that a player may exhibit after a large contact to the head.

Finally, a polycarbonate shell was to be attached to the outside of the block head which could encase the dampers and block head. This would replicate the hard shell of conventional helmets, and it was important to the team that this shell was as rigid as possible to ensure that the shell did not absorb energy from the impact that otherwise would have gone to the dampers.

2.4.3 FEA

The purpose of this study was to learn whether or not the original square helmet design would deflect enough to render the rigid body assumption invalid. It was important to measure the square helmet's rigidity for the purpose of future data validation. If the square helmet was too flexible, the rigid body assumption could not be made, and the accelerometer data would account for the combined damping effects of the dampers and square helmet. Such a result was undesirable as the team needed to measure the damping performance of only the dampers.

Solidworks was used to create a CAD model and time-dependent FEA study of the block head and square helmet (Figure 27). The bottom face (Unistrut track side) of the block head was given a fixed boundary condition, and the left face of the square helmet was given an impact force.

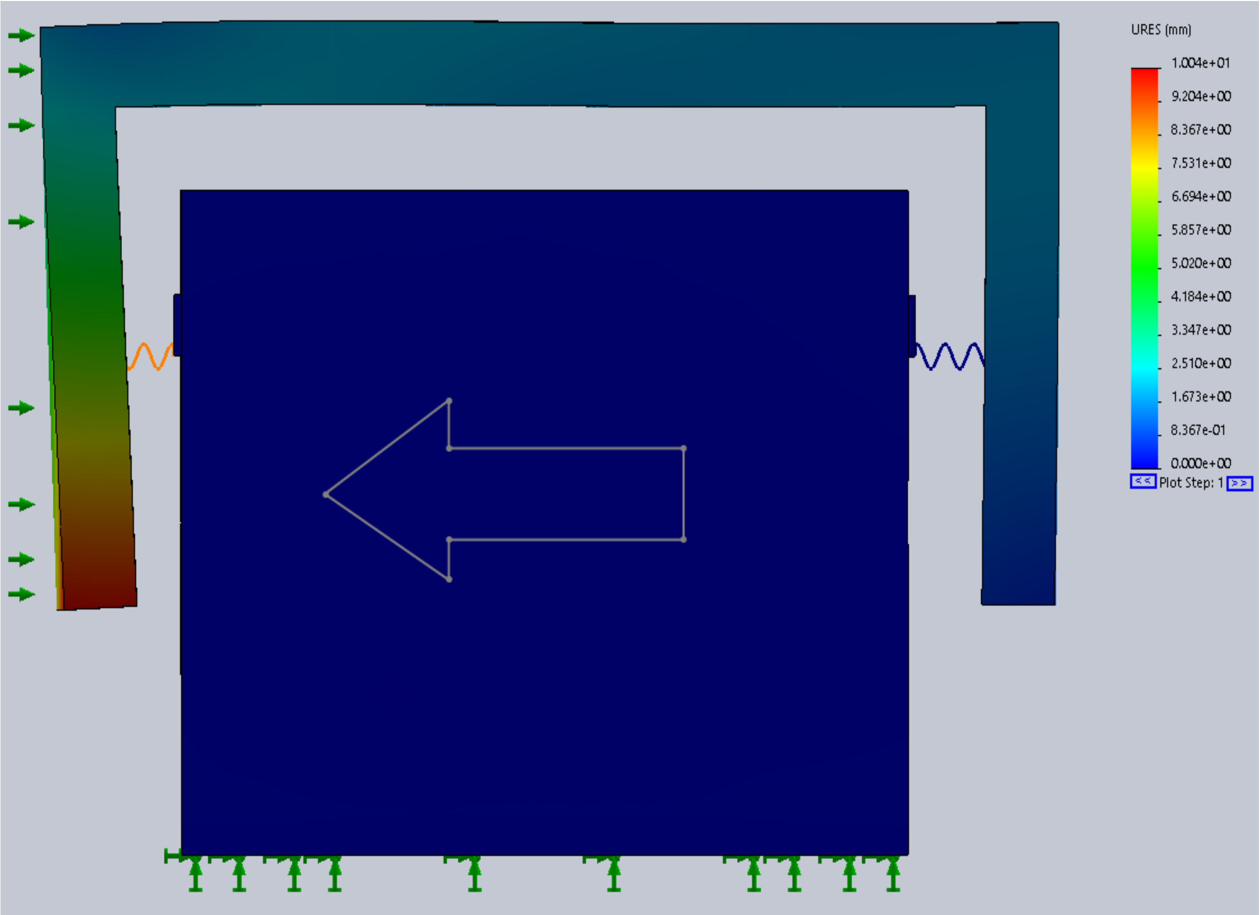


Figure 27. Snapshot of the dynamic FEA study at the time-frame when square helmet deformation is greatest. Color gradient is representative of the displacement gradient.

Unfortunately, the team found that the deformation was not negligible at a maximum displacement of 10.5 mm, as in Figure 27. As a result, the team redesigned the square helmet's geometry to be completely covered except for the bottom face where the block head would fit through (Figure 28).

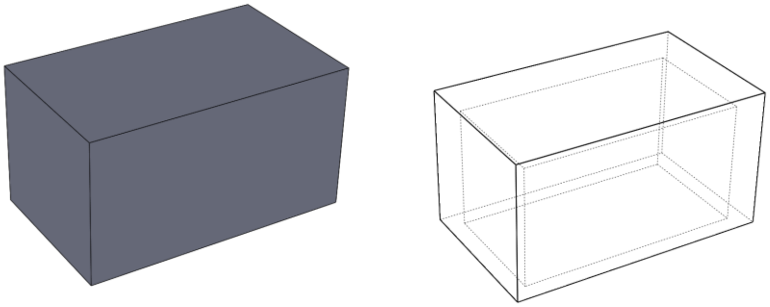


Figure 28. Image of second square helmet design iteration (left). The same part is on the right, but with hidden geometries shown to indicate the inner cavity.

This iteration to the mechanical and geometric design of the square helmet increased its rigidity, thus reducing the maximum at the edge displacement to 3.2 mm (Figure 29) from 10.5 mm (Figure 27).

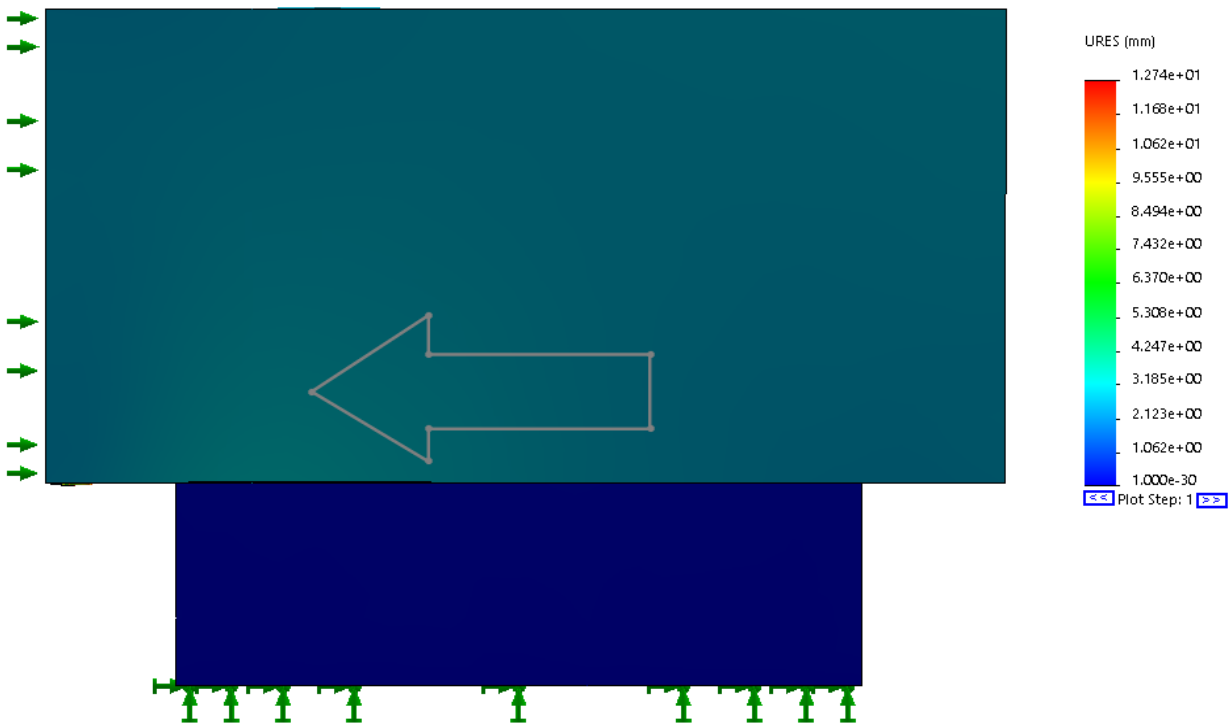


Figure 29. Snapshot of the dynamic FEA study at the time-frame when square helmet deformation is greatest. Color gradient is representative of the displacement gradient.

2.4.4 Instrumentation

The most important instrumentation device for this project was the accelerometer. The accelerometer would measure the peak acceleration of the block head following the impact and give the team a better understanding of the forces felt by the block head during impact. The results from instrumentation tests are shown below in Figure 30.

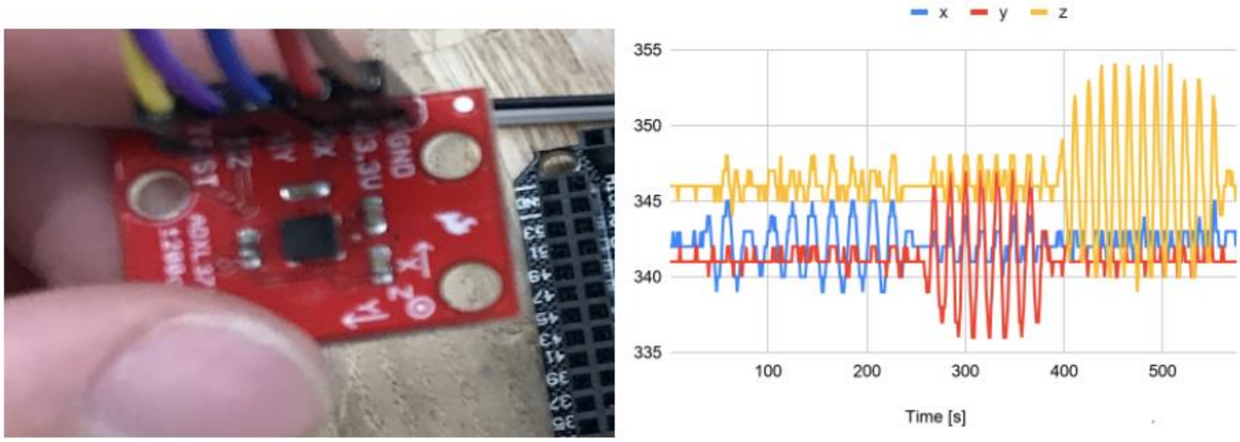


Figure 30. The triple-axis accelerometer was calibrated through an Arduino and the plot on the right shows the output of the accelerometer after it was shaken by hand in the x, y, and z directions. The accelerometer functioned properly and showed peaks in the x, y, and z directions.

A Sparkfun 3-axis Accelerometer ADXL377 breakout (part number: SEN-12803) was used in this experiment. The accelerometer had an operating voltage of 1.8V - 3.6V with a typical current of 300 µA. It had a range of ±200g with 3-axis sensing, and it was compatible with an Arduino UNO R3 [A000066]. Because of the success of the accelerometer during hand testing, both in terms of magnitude capture and precision, the team was confident with attaching the accelerometer to the side of the block head and trusted that it would record reliable data during the experiments.

3. Budget

Over the course of the calendar year, the majority of the costs that accumulated can be traced back to the raw materials needed for the testing apparatus. Though some funding was required for testing and creating different dampers and other costs were allotted toward instrumentation, the testing apparatus required the most funding. Below in Table 4 is a small summary of the team's costs.

A more detailed list of purchases can be found in Appendix A4.

Table 4. Summary of the team's costs sorted by subsystem category and primary vendor.

Subsystem	Primary Vendor	Combined Costs
Testing Rig	Home Depot	$371.61
Testing Rig/Dampers	Amazon/Ebay	$264.32
Instrumentation/ 3D Print Filament	Quartzy	$107.23
Block Head	Maker Lab	$14.00
	Total	$757.16

As a whole, the project was geared toward optimizing spending. For example, the team chose ABS over other materials for the testing frame because it was cheaper than metal alternatives but still fulfilled the design requirements. Figures 31 and 32 below show physical representations of most of the cost involved with this project.

To make this project cheaper, the team could have replaced the metal Unistrut wheels and track components for cheaper alternatives because those two items together were $190. Plastic wheels and a plastic track could have been used as an alternative to the metal parts.

Figure 31. The completed testing apparatus ($600).

Figure 32. The completed dampers ($40).

The team's project totaled to be $757.16, and this total was greatly under the $2,000 allotment that the team was awarded at the beginning of the year. The most expensive component of the project, the testing apparatus, totaled around $600. The damper filaments to 3D print the dampers were $40 and other components that were bought for this project, but were never used, totaled to be around $120.

4. Effects of COVID-19

The COVID-19 pandemic restricted the team's access to school facilities and it changed the team's plans for physical testing. As the impact of the virus unfolded, it was realized by the team that the combination of the testing apparatus and the testing head would not be able to be combined together and tested to achieve results. COVID-19 limited access to the machine shop and limited the team's interactions with each other. However, the situation did not stop the team from performing some forms of physical testing. Instead, it inspired the team to think of new ways to test the dampers.

4.1 Designing a New Testing Apparatus

The team's new testing apparatus was a simplified form of the drop test apparatus. This apparatus was designed to drop a 10-pound weight from a distance of 0.9” away from the top of the damper. The team felt as if this height was sufficient enough to provide adequate data as well as maintain a level of safety. The weight was held up by bricks, and these bricks could be pulled away quickly to allow the weight to fall on top of the damper consistently. To capture the behavior of the damper, an iPhone was used to videotape the behavior on slow motion capture. The two constants in this experiment were to be the weight of the impact mass (which was held constant at 10 pounds) and the distance from the bottom of the weight to the top of the damper (which was held constant at 0.9”). When the padding was to be tested, these parameters would not change. The Figure 33 below represents the basic design of the apparatus.

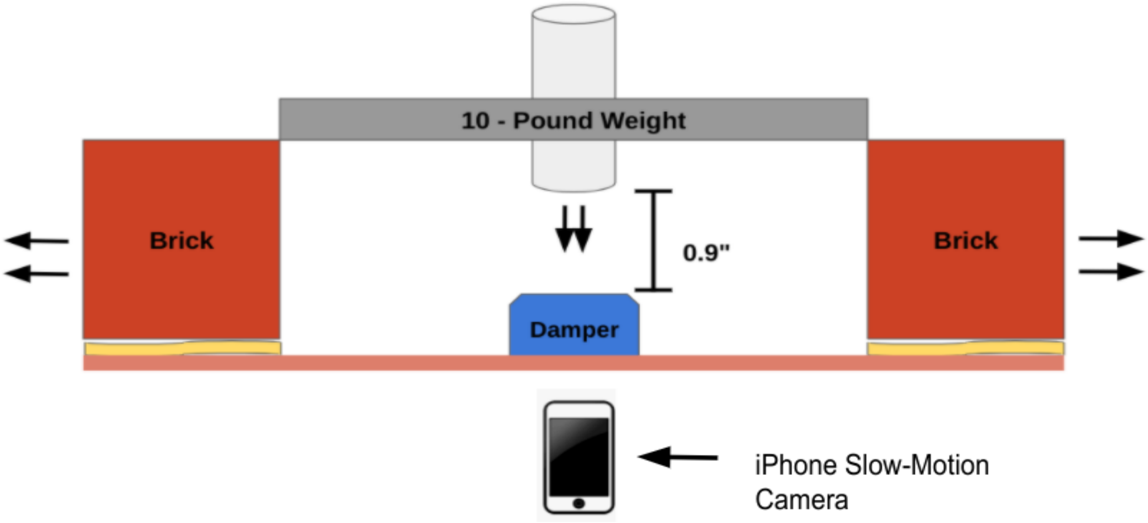


Figure 33. Schematic of the second testing apparatus.

This apparatus cost $0 to make by using easy-to-access parts that could be found around a home and backyard. Though this apparatus was not exactly similar to a traditional drop test, the team was confident that the consistency of the weight and the consistency of the distance between the weight and the damper would provide reliable results for the team to analyze later.

4.2 Completed New Testing Apparatus

Below, in Figure 34, is the completed testing apparatus. This apparatus took approximately one hour to assemble, and as expected, the cost of this apparatus was $0. Lighting was provided behind the iPhone to give better visual results to the videos. As well, a ruler was added behind the damper to see how far the damper would compress before the weight would come to a complete stop. Towels were added under each of the bricks to limit scratches on the table as well as make the bricks slide away more easily and quickly.

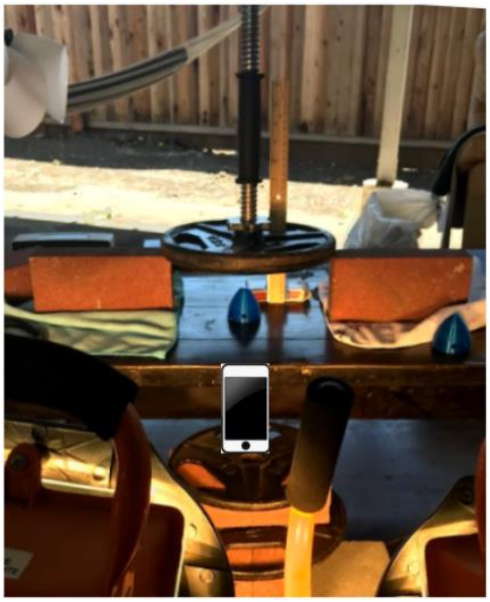


Figure 34. Image of the completed second iteration of the testing rig.

5. Experimental Procedures

5.1 COMSOL Setup Procedure and Boundary Conditions

The CFD (Computational Fluid Dynamics) studies in COMSOL served as a prototyping ground for fundamentals, which helped the team to better understand which input parameters would change the output and how. The team chose to model in COMSOL because of its FSI (Fluid-Structure Interaction) option, which provided a two-way coupled simulation study. This type of study was necessary since the damper subsystem exhibits flow acting on the damper structure as well as the damper structure acting on the flow.

5.1.1 Model Setup

The team created a simulation in which the flow would interact with a body (the damper) by pushing on and bending the damper (Figure 35).

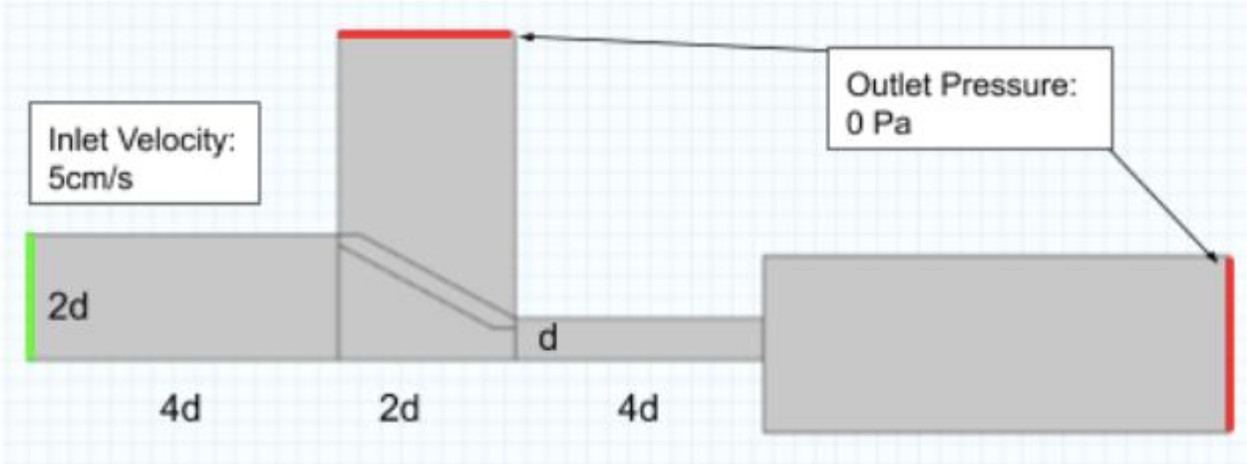


Figure 35. Screenshot of the COMSOL model setup, with key parameters shown, such as geometric properties, and inlet and outlet conditions. For this scenario, the lengths of different sections were defined and compared to one another using diameter "d," which was 30 cm. The model's large scale (d=30cm) was chosen to avoid computational difficulties – the scale was increased to 30 cm to mitigate the effects of unwanted flexibility within the walls of the proposed damper, which would otherwise prevent convergence of the solution.

However, the model was not simply composed of a structural damper region that would be impacted by a fluid region. Multiple regions were needed to help lessen the computational load, as well as enable COMSOL to more easily satisfy the user-defined boundary conditions. By trial and error, the team found that a total of six regions were necessary — one solid region and five fluid regions.

5.1.1.1 Boundary Conditions

The first fluid region served as the fluid inlet. This region needed to be wide enough to provide user-variability in the model, and long enough to allow the flow to fully develop.

Similarly, the two outlet or relief regions needed to be long enough to have a fully developed flow and wide enough to be able constrain a uniform pressure outlet boundary condition. Were the outlet regions too short or too narrow, the flow would still be influenced by structural deformations, and thus local pressure gradients would be enough to make such a boundary condition impossible to satisfy. For example, if the uniform pressure boundary condition was constrained too close (Figure 36), the eddies caused by fluid exiting the smaller pipe diameter region would cause a non-uniform pressure gradient, causing the boundary conditions to be unsatisfied and the simulation to fail. Thus, the outlet boundary conditions were placed much further away to avoid this issue.

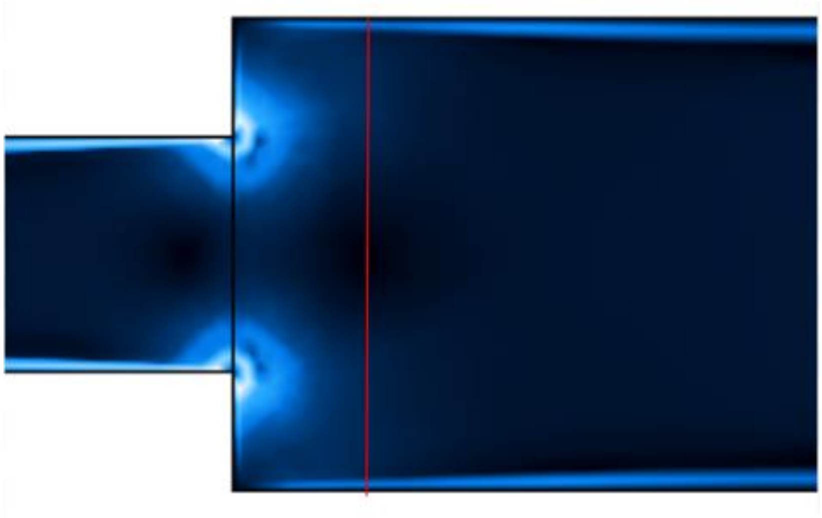


Figure 36. Screenshot of the simulation, zoomed-in to display the eddies between the inner-pipe region and outlet region. The redline indicates an outlet-pressure boundary condition that would cause the simulation to fail as it is too close to a varying pressure gradient.

There will always be some variability of pressure of inner-pipe flows due to the no-slip boundary condition, but the model can more easily force this uniform outlet pressure when the flow has more time to naturally approach that condition anyway. This method became standard practice in creating models in order to ensure all boundary conditions were at the same time satisfied and did not force the simulation to quit due to an error. Additionally, these outlet regions allowed the model to accept an incompressible flow. While this is not exactly the geometry of the actual model, these relief valves would not allow the team to study damper compression under a simplified model that assumes a familiar incompressible flow.

5.1.1.2 Domain Definitions

The damper domain (green and angled shape in the center of the model) was assigned to be the structural domain and was given acrylic plastic material properties. All domains but the central green and angled one were defined as fluid domains, and given the material properties of water (Figure 37)

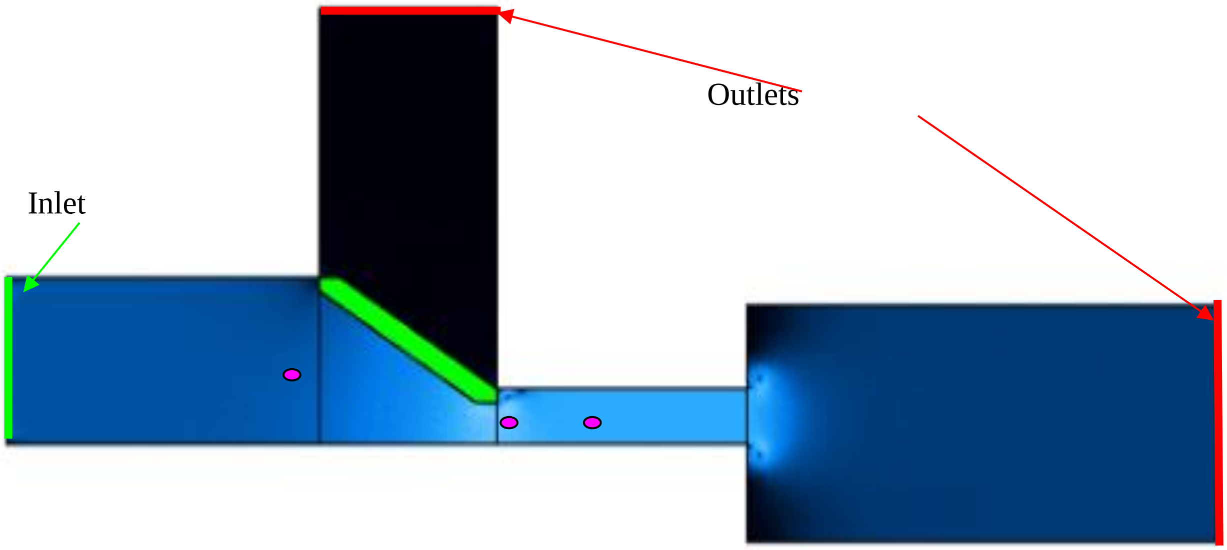


Figure 37. Image indicating the domain definitions (structural and fluid).

Additionally, because the fluid is pushing on the structural domain, the mesh of the structural domain and the fluid domain around the structure must be able to deform as the structure deforms. For example, if the damper were to stretch because of a high internal pressure, the internal fluid cavity naturally grows in real-life. The function of the "deforming domain" setting is to mimic fluid's ability to naturally adapt to its container's geometry as its container deforms.

5.1.1.3 Evaluating Pressure Drop

Damping effects were measured by considering the pressure drop between measurement nodes in the CFD model. These points were defined in the model and then evaluated for each test. For example, Figure 38 below graphs the Pressure-Time plots from data at the measurement nodes.

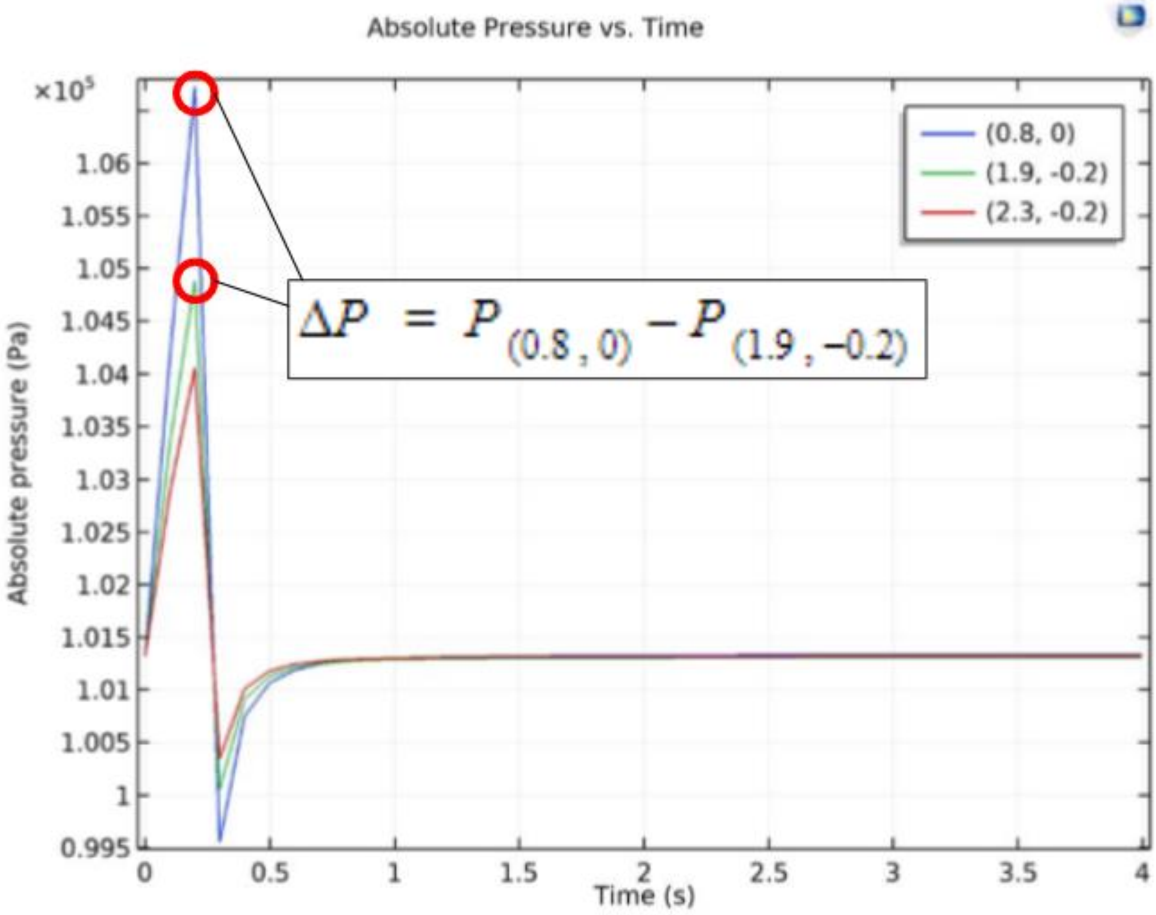


*Figure 38***.** *Pressure-Time plots for the three measurement nodes. The Legend indicates the location, in Cartesian coordinates, of each measurement node.*

Pressure-Time data was then exported into an Excel spreadsheet for post-processing. This procedure was repeated for each test, and results were recorded in the following section.

While pressure drop itself is not a metric for damping effects, a greater pressure drop indicates a greater loss of energy or force dissipation, since the rate of energy dissipation is equal to the pressure drop times the volumetric flow rate. The pressure drop equation for flow through a pipe points to this (Equation 7). Pressure drop is directly proportional the frictional losses (Darcy Friction Factor) and kinetic energy change — kinetic energy is, which lies within the density and velocity terms $\frac{\rho V^2}{2}$. This assumed relationship between pressure drop and energy loss is being made for two reasons. First, the damper model was a simplified one that intentionally bears much resemblance to inner-pipe flow to enable such fundamental connections and assumptions. Moreover, the results were intended to be judged loosely, rather than scrutinized by their precise values. For example, the team was interested in whether or not increasing the pipe diameter increases or decreases the pressure drop and by what order of magnitude rather than a precise value.

5.2 Physical Testing Procedure for Testing Apparatus 2.0

The team's experimental procedure needed to change to fit the new testing apparatus, and the team would measure how long it would take for the damper to come to a complete stop. Multiple tests were performed on the dampers with different fluids of different viscosities to see the effect of each of them compared to traditional padding.

As shown in Equation (9) below, the acceleration of the mass would be directly related to length of time for the velocity of the weight to come to zero. Increasing that time would theoretically lower the acceleration felt by the user, so the team wanted to know the length of time for the damper to come to a complete stop. Testing the time for the weight to come to a complete stop, where velocity of the weight equaled zero, for each of the dampers with different fluids in them would consist of the first phase of testing.

$$F = ma = m\left(\frac{\Delta v}{\Delta t}\right) \tag{9}$$

The second phase of testing would explore the performance of the dampers when they were connected to each other through a metal straw. The goal of this test was to determine if the pressure force from the first damper would be enough to affect the shape of the second damper. The initial conditions for the second round of testing can be seen in Figure 39 below.

Figure 39. Both of these dampers were to be filled with water or syrup (depending on the test) and one of the dampers would start as partially compressed whereas the other damper would be full. In this image, the closer damper is partially compressed and the farther one is full, and both of these dampers are filled with water.

If the force of the water rushing out from the compressed damper was enough to affect the shape of the other damper, causing it to expand, then the team would conclude that the dampers were capable of communicating with each other.

The new physical testing procedure for testing apparatus 2.0 was summarized below in Tables 5 and 6.

Table 5. Experimental procedure for Experiment 1. The purpose of Experiment 1 was to evaluate the performance of the individual dampers.

Experiment 1			
Evaluating the Performance of Individual Dampers			
Damper Filling	Trials	Drop Weight [lbs]	Drop Height [in]
Air	10	10	0.9
Water	5		
Syrup	2		
Padding	10		

*Table 6**.** Experimental procedure for Experiment 2. The purpose of Experiment 2 was to evaluate the performance of the connected dampers.*

Experiment 2				
Evaluating the Performance of Connected Dampers				
Damper Filling	Trials	Drop Weight [lbs]	Drop Height [in]	Impact Duration
Water	1	10	0.9	1 < second
Water	1			Sustained
Maple Syrup	1			1 < second
Maple Syrup	1			Sustained

Because these tests were repeated for a small number of trials (<30), the team acknowledged that these tests were not statistically significant. However, the team was confident that the small number of trials would give at least a general idea of if the dampers could perform better than traditional foam padding.

To accurately collect data for these experiments, the team used a slow-motion camera on an iPhone 7, which uses 240fps (1:8 time), to capture the total compression of the damper. To more precisely gather results, the team then used a computer to slow down the slow-motion video to a 1:4 speed to better estimate the total time of compression. Once the slow-motion video was slowed down on the computer, the team again took another slow-motion video of the computer to slow down the video again by 1:8 again. The team was able to slow the motion of the experiment by a factor of 1:256. This meant that something that took 1 second in the real world would take 256 seconds on the team's data, and that something that would take 10 seconds as data would take 0.04 seconds in real time. Below in the Figure 40 is a visual aid for the data acquisition process and ratio achieved.

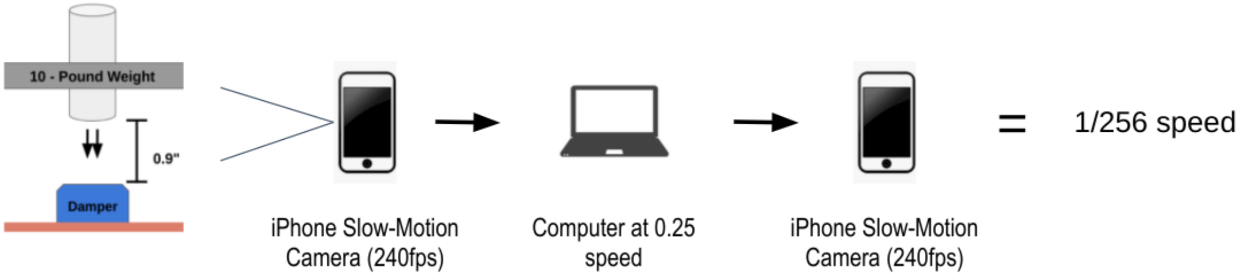


Figure 40. Process of achieving a slow-motion factor of 1:256.

The team slowed down the impact so the team would have more accurate measurements of the time it would take for the impact to occur. The team hoped to limit the error by a factor of 256.

6. Results and Discussion

6.1 Simulation Results and Discussion Through COMSOL

Aside from the variable input parameters, all other model definitions remained constant throughout tests and were thus the controlled variables. The variable input parameters, labeled in Figure 41, were the pipe diameter, the damper angle of attack, and the damper elasticity.

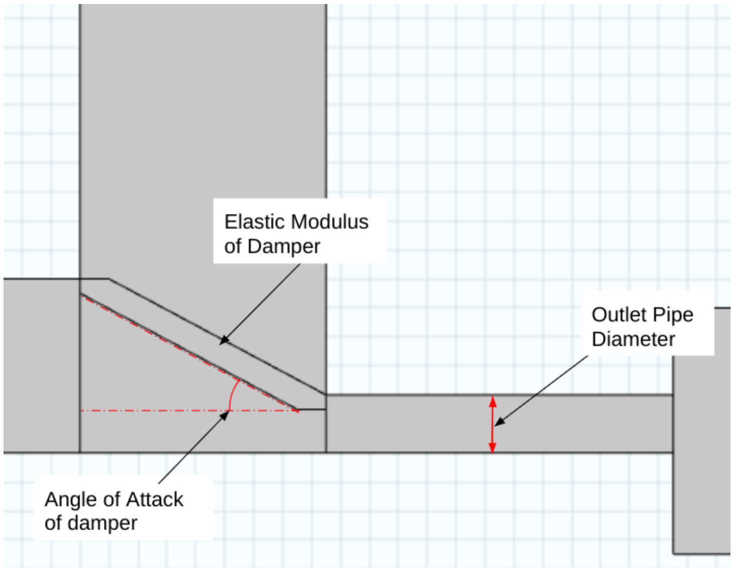


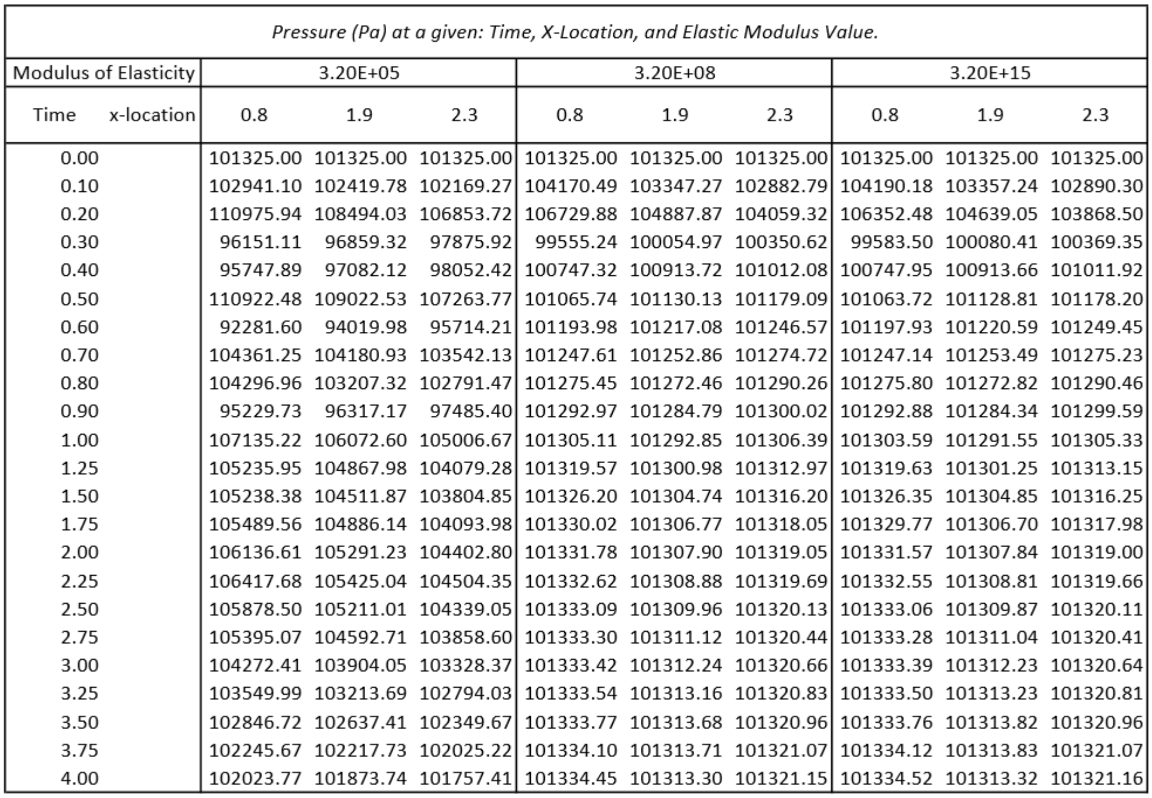
*Figure 41***.** *Zoomed-in section of the three parameters that were varied in the COMSOL model, with labels.*

6.1.1 Experiment 1: Varying Damper Elasticity

6.1.1.1 Raw Data

As stated in *Evaluating Pressure Drop* (Section 5.1.1.3), the change in pressure drop was measured by exporting Pressure-Time data from each pair of comparable tests, and comparing their pressure drops. For example, Table 7 shows the raw Pressure-Time data for three tests of different damper elastic moduli.

Table 7. *Raw Pressure-Time data for three tests of different damper elastic moduli (Pa). Each test records Pressure-Time data at three different x-locations inside the pipe flow model: 1. One before the damping region (x=0.8), 2. One after the damming region (x=1.9) and 3. One further still past the damping region (x=2.3).*



Pressure (Pa) at a given: Time, X-Location, and Elastic Modulus Value.									
Modulus of Elasticity	3.20E+05			3.20E+08			3.20E+15		
Time x-location	0.8	1.9	2.3	0.8	1.9	2.3	0.8	1.9	2.3
0.00	101325.00	101325.00	101325.00	101325.00	101325.00	101325.00	101325.00	101325.00	101325.00
0.10	102941.10	102419.78	102169.27	104170.49	103347.27	102882.79	104190.18	103357.24	102890.30
0.20	110975.94	108494.03	106853.72	106729.88	104887.87	104059.32	106352.48	104639.05	103868.50
0.30	96151.11	96859.32	97875.92	99555.24	100054.97	100350.62	99583.50	100080.41	100369.35
0.40	95747.89	97082.12	98052.42	100747.32	100913.72	101012.08	100747.95	100913.66	101011.92
0.50	110922.48	109022.53	107263.77	101065.74	101130.13	101179.09	101063.72	101128.81	101178.20
0.60	92281.60	94019.98	95714.21	101193.98	101217.08	101246.57	101197.93	101220.59	101249.45
0.70	104361.25	104180.93	103542.13	101247.61	101252.86	101274.72	101247.14	101253.49	101275.23
0.80	104296.96	103207.32	102791.47	101275.45	101272.46	101290.26	101275.80	101272.82	101290.46
0.90	95229.73	96317.17	97485.40	101292.97	101284.79	101300.02	101292.88	101284.34	101299.59
1.00	107135.22	106072.60	105006.67	101305.11	101292.85	101306.39	101303.59	101291.55	101305.33
1.25	105235.95	104867.98	104079.28	101319.57	101300.98	101312.97	101319.63	101301.25	101313.15
1.50	105238.38	104511.87	103804.85	101326.20	101304.74	101316.20	101326.35	101304.85	101316.25
1.75	105489.56	104886.14	104093.98	101330.02	101306.77	101318.05	101329.77	101306.70	101317.98
2.00	106136.61	105291.23	104402.80	101331.78	101307.90	101319.05	101331.57	101307.84	101319.00
2.25	106417.68	105425.04	104504.35	101332.62	101308.88	101319.69	101332.55	101308.81	101319.66
2.50	105878.50	105211.01	104339.05	101333.09	101309.96	101320.13	101333.06	101309.87	101320.11
2.75	105395.07	104592.71	103858.60	101333.30	101311.12	101320.44	101333.28	101311.04	101320.41
3.00	104272.41	103904.05	103328.37	101333.42	101312.24	101320.66	101333.39	101312.23	101320.64
3.25	103549.99	103213.69	102794.03	101333.54	101313.16	101320.83	101333.50	101313.23	101320.81
3.50	102846.72	102637.41	102349.67	101333.77	101313.68	101320.96	101333.76	101313.82	101320.96
3.75	102245.67	102217.73	102025.22	101334.10	101313.71	101321.07	101334.12	101313.83	101321.07
4.00	102023.77	101873.74	101757.41	101334.45	101313.30	101321.15	101334.52	101313.32	101321.16

The data of Table 7 was plotted in Figures 42 and 43 to show the pressure drop between the points of interest (before and after the damping region).

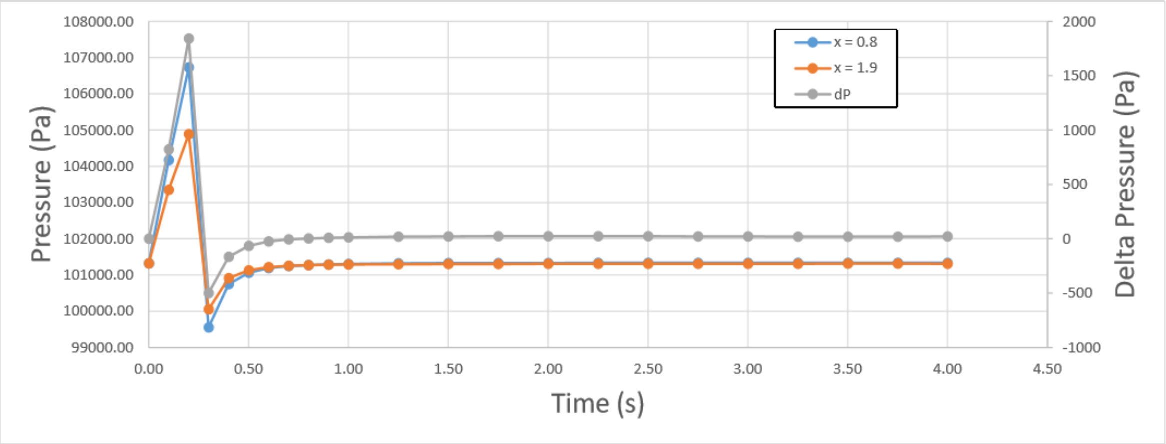


Figure 42. Pressure-Time data at the x-locations, x=0.8 and x=1.9, for the test where the damper's elastic modulus was 3.2e8 Pa.

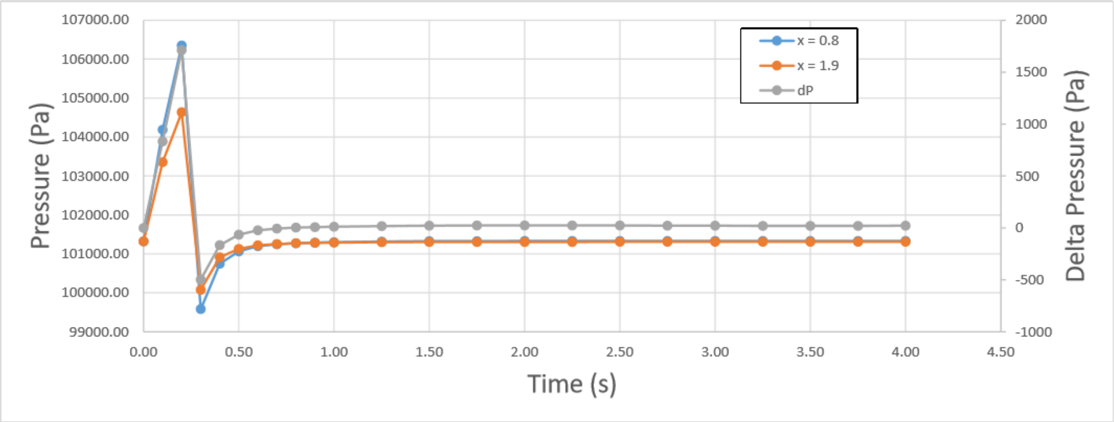


*Figure 43**.** Pressure-Time data at the x-locations, x=0.8 and x=1.9, for the test where the damper's elastic modulus was 3.2e15 Pa.*

Again, the data from Table 7 was post-processed to evaluate the pressure drop between two points of interest (x=0.8 and x=1.9), and then compare the pressure drop from each test of different elastic moduli (E_{Damper} = 3.2e8 Pa and E_{Damper} = 3.2e15 Pa). The comparison, plotted in Figure 44, is expressed by the following Equation (10).

$$\Delta p \;=\; \Delta p_{E_1} - \Delta p_{E_2} \;=\; p_{x=1.9_{E_1}} - p_{x=0.8_{E_1}} \;+\; p_{x=1.9_{E_2}} - p_{x=0.8_{E_2}} \tag{10}$$

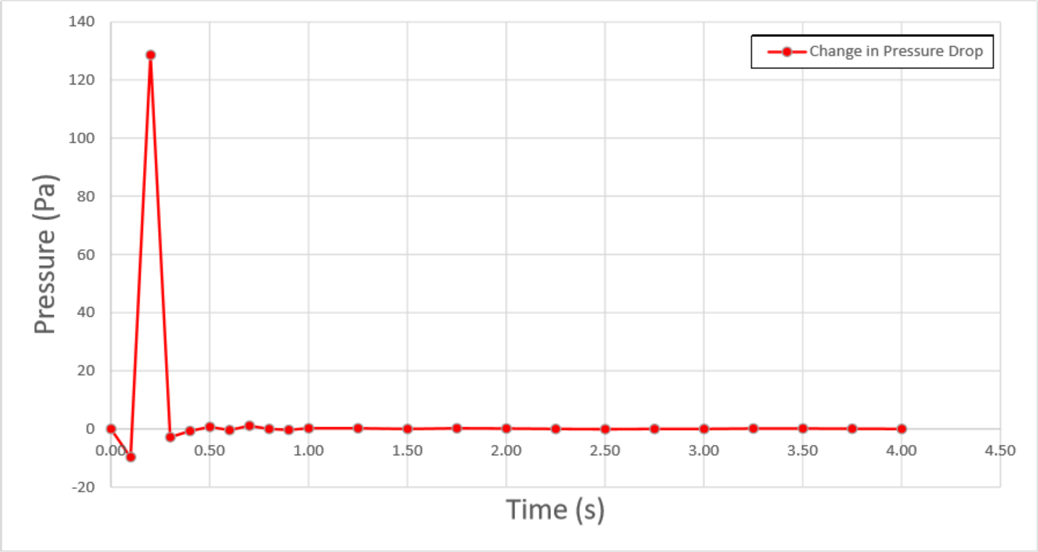


Figure 44. Change in pressure drop from two tests or different elastic moduli (E_{Damper} = 3.2e8 Pa and E_{Damper} = 3.2e15 Pa).

6.1.2.2 Discussion

The Pressure-Time plots for both the variable elasticity tests (Figures 42 and 43) and variable geometric obstructions tests shared the same overall behavior. The pressure drop had an initial peak and trough of high magnitude, before resolving to a steady state region.

The relative maxima of both test pairs indicate the initial flexing of the damper that is large compared to the rest of the test. The damper acts much like a spring in oscillation: it is first pushed by the flow and bent in the positive x-direction, then, since the damper is a material with some stiffness, it pushes back on the fluid. In the Pressure-Time data, this manifests as a peak (damper bent by the fluid) and a trough (damper pushed back on the fluid). This makes sense given that the flow must lose energy in order to cause structural deformation.

This is crucial to understanding the result of using a more flexible damper. Because a more flexible damper was used, only the first section of the curve (the transient peak and trough region) showed a change in pressure drop. In other words, the more flexible damper had a greater pressure drop peak because more energy was lost to more deformation.

Once deformation was complete, the damper found a new equilibrium at steady state, and thus generated no change in pressure drop compared to the more rigid damper (see Figure 44). Therefore, changing elasticity only changes the pressure drop peak, not the steady-state pressure drop. It is therefore dangerous to decrease the damper's stiffness too much because it creates peaks in energy dissipation, yet has no effect on the steady-state region. This peaking behavior is dangerously close to the undesirable plot behavior in Figure 6.

6.1.2 Experiment 2: Varying Geometric Obstructions - Angle of Attack and Outlet Diameter

6.1.2.1 Raw Data

The same method of measuring, acquiring, and post-processing Pressure-Time data was used to compare the pressure drops between models of different damper geometries. In this test, the geometric obstructions to the flow were increased: the damper's angle of attack, Θ, increased and the outlet pipe diameter, D_{Outlet}, decreased. Figure 45 is the final Pressure-Time plot that compares the two tests (1. Small angle of attack and large pipe diameter and 2. Large angle of attack and small pipe diameter.)

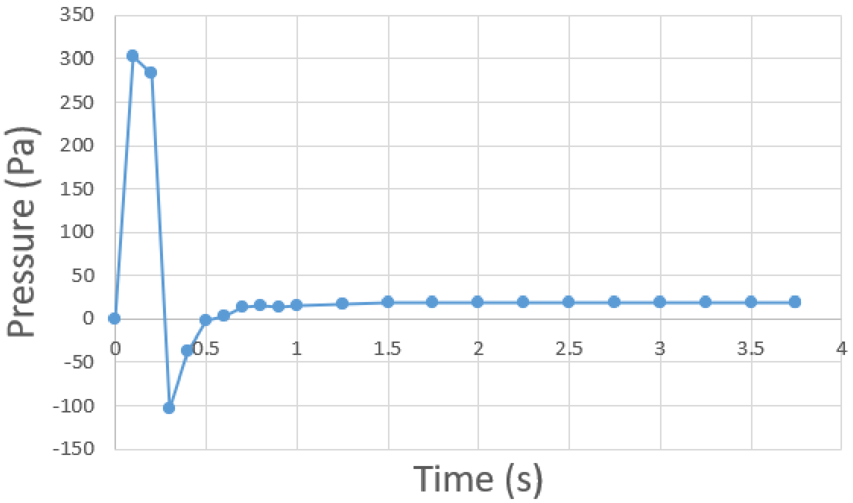


Figure 45. Change in pressure drop from two tests (1. Θ = 28° and D_{Outlet} = 15cm, and 2. Θ= 18° and D_{Outlet} = 30cm).

6.1.2.2 Discussion

Unlike the elasticity test pair, the geometric obstruction test pair showed a change in pressure drop in both the transient and steady state regions (see Figure 45). The change in pressure drop was steady at about 20 Pa more for the more obstructive test (when the angle of attack and pipe diameter decreased). This makes sense because the overall model geometry was much more obstructive.

Decreasing the outlet diameter increased the pressure drop because it is a type of flow obstruction. Flow obstructions will dissipate flow energy much like how discontinuities in structural design that cause stress concentrations. They can be thought of as taking away the flow's momentum. The team was also confident with this result as it is consistent with the flow through a venturi: as the flow enters the venturi's tighter geometry domain, it speeds up and pressure decreases.

6.1.3 Application Conclusions and Simulation Limitations

Both tests were able to increase the pressure drop and therefore damping effects of the simplified damper. Decreasing outlet diameter and increasing the angle of attack are flow obstructions that dissipated flow energy by decreasing the flow's momentum. Decreasing the damper's elastic modulus also increased dissipation effects as it ensured additional flow energy was spent on deforming the damper structure.

However, it was important to know the limitations of one's model. These simulations were not meant to be a conclusive test for all dampers. These tests were simplified in order to achieve a working COMSOL model. Therefore, these results should not be extrapolated by their precise nominal values, but rather by their overall trend. Nonetheless, the team still learned of these modes of energy dissipation, and thus intended to apply them to the final damper design.

6.2 Physical Testing Results and Discussion

6.2.1 Experiment 1: Performance of Individual Dampers

6.2.1.1 Raw Data

Within Figure 46 below, results from the physical testing using the drop test 2.0 were shown.

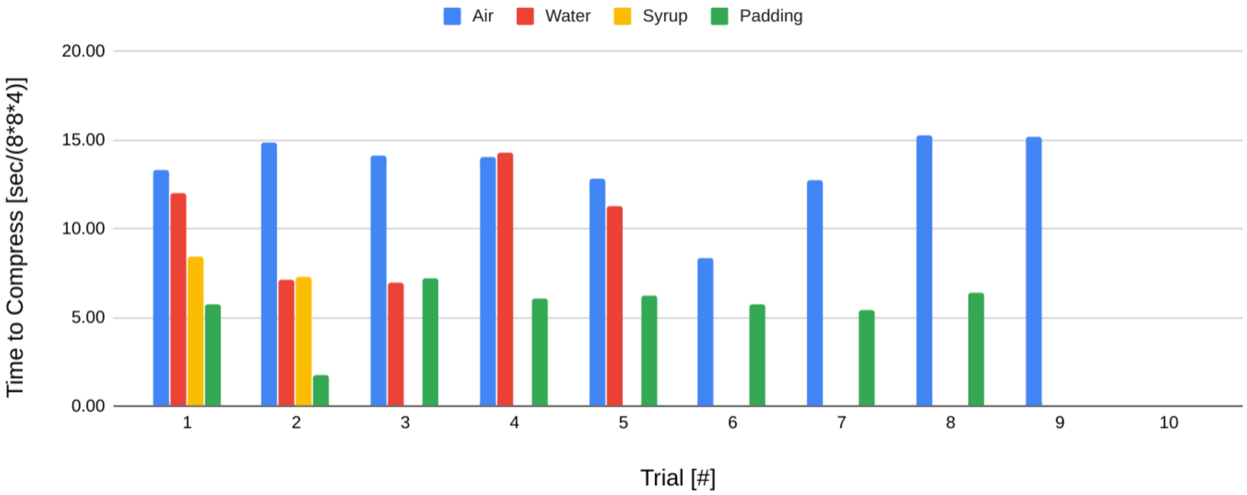


Figure 46. Results from physical testing using the drop test 2.0. Air is the blue line; water is the red line; maple syrup is the yellow line; and padding is the green line.

Air had the highest times for "time to stop" whereas traditional helmet padding had the lowest times for "time to stop". Water stood in the middle of the air and padding. Because syrup had only two data entries, it was difficult to reach conclusions from syrup testing. Figure 47 below shows the summarized results from the physical testing using the drop test 2.0.

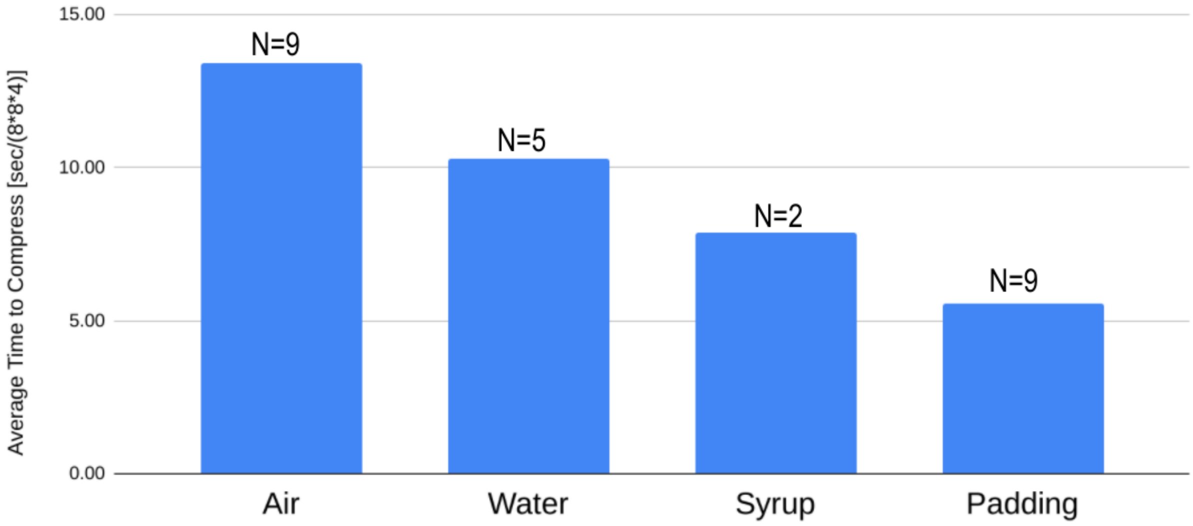


*Figure 47***.** *Average "time to stop" times of the fluid dampers tested and the foam padding which was tested.*

Air had the highest average "time to stop" at 13.40 seconds, followed by water with an average time of 10.31 seconds, then syrup with 7.87 seconds, and lastly padding with an average "time to stop" at 5.57 seconds. With a slowest time to stop, air took 240% longer than the baseline (padding).

6.2.1.2 Discussion

The results from the performance of the individual dampers suggest that the air-filled damper was the best material for lowering the peak acceleration of the weight during the test. Also, the higher number of tests performed on this type of damper gave the team confidence that the damper would behave similarly if future tests were to be done.

The results also suggest that the foam padding from the traditional football helmet was the worst material for lowering the peak acceleration of the weight during the test. This test also had nine trials and gave the team confidence in the testing process.

The team expected the water-filled damper to be the best performing damper. However, it was discovered that the water-filled damper performed worse than the air-filled damper in terms of increasing the "time to stop." It was difficult for the team to come to concrete conclusions about the syrup-filled damper because only two tests were completed.

The downward trend of the "time to stop" related to the viscosity of the damper, as seen in Figure 47, (air having the lowest viscosity, followed by water, then syrup, and lastly the football helmet padding with an assumed highest viscosity because it is solid), shows that less viscous the working fluid, the longer it would take for the damper to compress.

This trend suggests that there exists an ideal damping constant (which can be achieved by modifying the stiffness of the damper combined with the viscosity properties of the working fluid) that would allow the weight to come to a complete stop in the longest amount of time without hitting the base of the table.

It was also important to note that though trends in data showed that air would be the best fluid for an individual damper, air still may not be the desired fluid when connected to another damper. The team's testing called for the stoppage of time as soon as the weight came to its first full stop without accounting for the recoiling force of the fluid contained. This phenomenon can be explained to a further degree in Figure 48 below. Unlike air, the viscosities of both water and syrup forced the fluid to experience a recoiling effect when a weight was dropped onto the damper, which negatively impacted the weight's time to stop.

When the damper filled with air was impacted, it compressed in a single motion. However, Figure 48 below shows how the damper filled with water compressed once before pausing and compressing even further. This results in two stopping times, the initial stopping time was used as the official result. However, the presence of these two stopping times might need to be further researched to determine its impact on the practical damping effect.

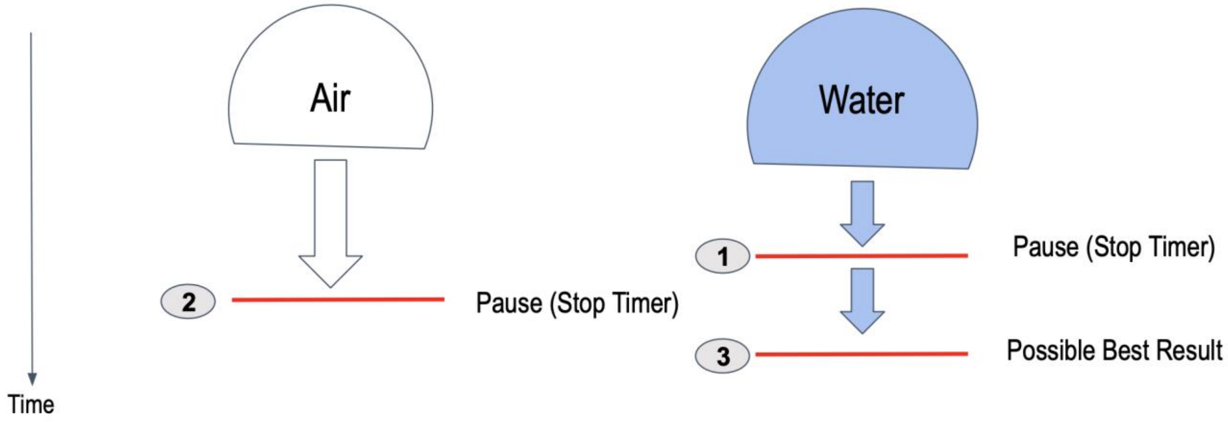


Figure 48. *Proposed behavior of the fluid recoil effect on the measured "time to stop."*

6.2.1.3 Error Analysis

There were a few sources of error that could have affected the results of the physical testing. First, the weight could have contacted the damper in different areas of the damper and slid off to the sides of the damper. Inconsistent impact locations would have led to inconsistent damper deformation behaviors. To minimize this error however the team attempted to have the weight strike the top of the damper consistently.

Also, the method of recording the length of time for the weight to come to a full stop by hand and eye introduced human error into the results. This error however was minimized by slowing down the videos multiple times and having the same group member analyze all of the videos. Having one person analyze all of the videos limited other biases of what the definition of "time to stop" could have been.

6.3 Experiment 2: Performance of Connected Dampers

6.3.1 Raw Data

Due to COVID-19 restrictions and limitations on budgeting, a standard metal straw (.315" diameter and 8.5" long) was used to connect dampers together. When connected, both the water and syrup-filled dampers did not immediately refill the other damper after impact. "Immediately" was defined as "within the duration of the impact."

However, during a sustained force of 10 pounds, during which the weight was held steady on top of the damper, the syrup damper filled its counterpart damper in 5.1 seconds real-time. The water-filled damper still did not fill its counterpart damper with the sustained force of the 10-pound weight. Below in Figure 49 are the testing results of the sustained force of 10 pounds.

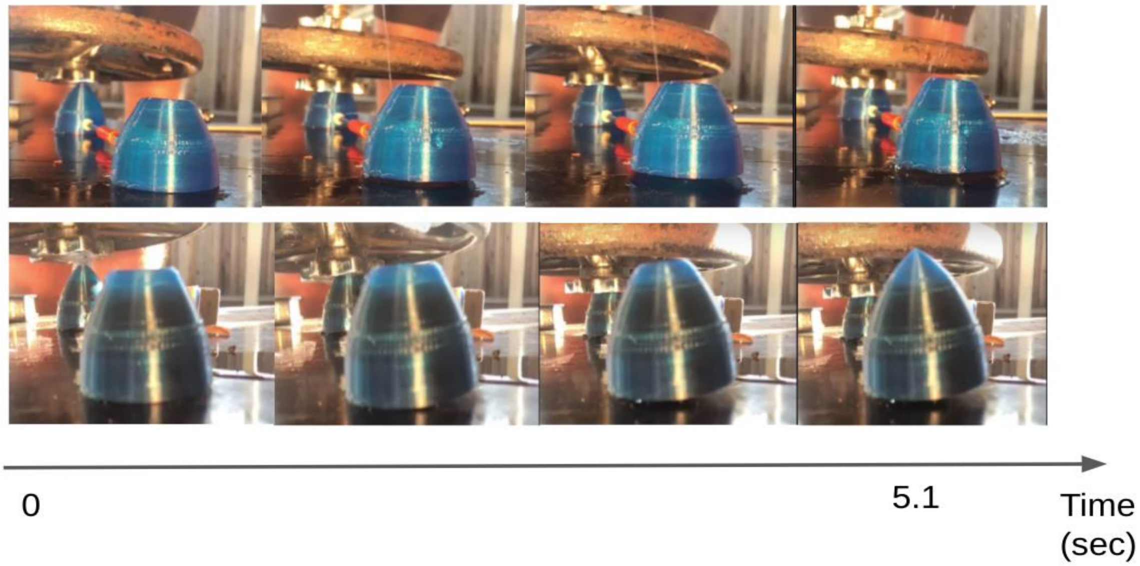


*Figure 49***.** *These are sequential photos from the sustained impact testing. The top row shows the water-filled damper results. It can be seen in the second image that there was a stream of water (a leak) from the water-filled damper. This leak likely led to pressure losses and inefficient communication between the two dampers. In the second row are the results from the syrup-filled damper sustained impact testing. At 5.1 seconds the syrup-filled damper fully expands to its original shape.*

6.3.2 Discussion

During the interconnected test for the water-filled damper, it was noticed that water was spraying out of the inlet where the straw connected to the other damper. It was likely that these leaks were causing the pressure differential between the two dampers to be less than what it could have been had the dampers been sealed properly. If the leaks were patched, this would allow for a greater pressure differential and hopefully allow the water-filled damper to fill its damper counterpart. It was important to note that due to time and resource restraints, a properly sealed connection could not be tested.

The syrup on the other hand, because it was more viscous than the water did not leak as much as water and was able to have a pressure differential high enough to fully expand the other damper. This proved that for this test, the dampers were able to communicate with each other through the metal straw.

6.3.3 Error Analysis

The leaks in the rubber seals between the dampers and the metal straw introduced error into measuring the effect of pressure differential on the deformation of the dampers. Because of leaking, pressure could not be effectively used and even led to the experiments with water-filled dampers to fail completely. Because of these errors, the team could not say for certain whether the water-filled damper could not fill its counterpart damper because the leaks were too detrimental to the test or if the damper would have failed to inflate each other even with water-tight sealing. It is also likely that some leaking increased the amount of time for the syrup damper to fill. The team would have liked to refine the attachments between the two dampers to stop leaking completely.

7. Business Plan

7.1 Introduction

One of the problems athletes today face are concussions. Especially in younger athletes who have a developing brain, that damage can be more harmful in ways we are still understanding. Football is a sport that’s both very popular but also well known for its high rate of concussions. Unlike other sports, football relies heavily on protective gear, but the rate of injury shows that there is still a large degree of improvement that can be made.

The way a football helmet works can largely be broken down into a few systems. A hard-exterior shell helps disperse the energy from impact over a larger area. This allows the padding to cushion the blow and decrease the rapid movement of the head. Other peripheries are designed to ensure the helmet is secured to the player and provides a comfortable fit. Focusing on the padding, a number of modern helmets use foam. Foam is a cheap and good way to cushion impacts, however they also suffer from something called a densification zone. What that means is that foam can cushion movement up to a point where the foam is too dense to compress easily. In this densification zone, the amount of energy absorbed decreases significantly.

The product designed by the team was a damper system replacing foam padding in helmets which would utilize hydrolastic damping to eliminate the densification zone and reduce the rate of concussion in football players.

Since the damper system would effectively increase the effectiveness of helmets but at a fraction of the cost of newer or extremely advanced helmets, the primary market of the product would be football programs at the high school and younger categories since they generally have constrained budgets. The secondary market would be for collegiate and professional players who want to supplement their personal safety in addition to the professional grade equipment their programs can generally afford.

The organization necessary to make this product succeed would include a customer service team, mechanical design team, a quality team, and a manufacturing team. This organizational structure would help ensure that a quality product is being delivered efficiently across large markets.

The competition currently on the market uses OEM products or generic foam replacement pads. In general, the competition focuses on improved helmets in their entirety rather than focusing specifically on the padding.

7.2 Goals and Objectives

The goal of the company would be to create a functional product which can be tested at scale and prove that better protection doesn’t have to come at a high cost. Some level of certification or use by some football league or athletic body would give the product and idea the recognition to achieve national reach and give the company brand recognition within the industry.

7.3 Description of Product

The product is an advanced damping system which utilizes interconnected dampers and hydrolastic damping technology to decrease the acceleration felt by the player during impacts. This decrease in acceleration would reduce the risk of concussions or decrease their severity when they occur.

Since the product would replace the normal foam padding in helmets, it would utilize a plug-and-play type model so the player can easily and quickly remove the old padding to install the new system. In order to do this, the damper system would have OEM support across the brands and models common in the primary or secondary market. This would allow each player to install a damper system that is optimized for their helmet, both in protection and comfortability.

7.4 Potential Markets

The product fills a niche in the football helmet market as a cheap upgrade, which can make a cheaper helmet perform like a better helmet but at a cheaper price. The North American sports industry is worth more than $83 million today [16]. In 2018 alone, there were over 5.5 million touch football players estimated across the United States [17]. When the number of players is compared to the average cost of a football helmet ($200-$300) which is recommended to be replaced every 5-10 years, then the touch football market alone is worth approximately $220 million a year.

If the proposed damper is designed to be replaced every 2 years, at 3% market penetration, and the selling price of $25, the target market is approximately $2 million annually. In order to achieve this market, the product would have a focused release beginning in the West Coast moving eastward. This would simplify distribution while hitting one of the largest markets, since California generally experiences weather conducive to outdoor sports almost year-round.

7.5 Competition

The primary competition are OEM products that are specifically and originally engineered for specific helmets. Since they are OEM products, they are tailor-made to each existing product and the cost of manufacturing is lower since they're designed and produced in bulk. However, OEM products from the two main helmet manufactures - Riddell and VICIS - are expensive.

Generic foam pads are cheaper, easier to access, but don't have the level of protection or ease of replacement as OEM products. Other products such as D3O through Schutt Sports, an experimental padding technology, has relatively weak market penetration and leans towards the upper end of the market due to its cost.

7.6 Sales Strategy

The primary sales strategy for the product is hitting the middle market, balancing between cost and protection. By taking the middle market, the product would appeal to a wider range of programs since it would be attainable for programs that struggle financially and still be attractive for programs who can afford to pay more for better products.

The marketing strategy in order to hit that market would include targeted advertisements to gain the support of key schools - such as De La Salle - which are well known and have a following in order to reach the upper end of the market. Student athlete sponsorships and give-back programs would help improve brand recognition amongst lower income schools and programs towards the lower end of the market.

By initially focusing on middle and high school sports, the product would have time to earn the brand recognition which would allow it to be more successful in reaching the high end of the market such as collegiate and professional programs. Additional marketing strategies such as wider OEM support, detailed installation videos, and selling through Amazon could help the brand be easier to access and utilize.

7.7 Manufacturing Plans

The damper system can be broken down into the dampers themselves, interconnected tubing, and a damping fluid. The dampers themselves could be made from injection molded TPU which allows for scalable production at cheaper cost after the initial tooling. Since injection molded factories are common, the dampers could be produced cheaply abroad and then assembled within the United States for packaging and distribution. The interconnected tubing could be made from off-the-shelf parts with little to no modifications. This would allow the damper system to be constructed cheaply and easily from alternative suppliers if necessary. The damping fluid could also be an off-the-shelf part or made in bulk in a factory.

The price of the damper system will likely be within $20-30 in order to reach the middle market. The exact cost however will depend on the vendor - Amazon for examples takes significantly more as a fee compared to other online vendors - and how cheap tooling and production costs can be.

7.8 Service and Warranties

Since the designed lifespan of the product is about 2 years, then it would be reasonable for each system to have a warranty for six months after purchase for manufacturing defects, subject to review by the company. A service line could also be established by chat or email to help players who are having trouble installing their product or otherwise unsatisfied with their purchase.

7.9 Financial Plan

The financial plan for the first phase of company development would focus on product design and operational expenses. Roughly $15k could be allotted for research and finalizing the design. Initial tooling could run between $10-20k, assuming that only the damper would need to be injection molded. Other costs such as advertisements and customer support are allotted $75k to focus on positive brand recognition. Operational expenses relating to storage, inventory, and office space would have a budget of $250k a year. Salary for a small design and office team could collectively run about $750k a year. Altogether, the annual expenses before product cost is roughly $1.1 million per year for the first phase. With $2 million projected in annual sales after a 2-year ramp time, the ROI after 5 years would net $500k. However, ROI after five years significantly drops since market share should be increasing and both operational and design costs should drop after focused cost-down efforts.

The key markets would be high school and below football programs. Since these programs are generally more cash-strapped than collegiate and protection is especially important, then these programs are more likely to be early adopters. The business plan would focus on two key selling points: a product that offers a competitive level of protection (a significant improvement over existing foam padding) and at a low cost. This would help the product gain the recognition needed as a proven product to penetrate the collegiate and professional markets. A summary of key financial planning flow is described in Figure 50 below.

Figure 50. The team's business plan outline.

8. Impact of Solution

8.1 Economic and Ethical Advantages

8.1.1 Background Information

In terms of the economics of designing a novel football helmet, the team expected that the product would be received well. The current market of football helmets was widely expanding, and industry competition has led companies to constantly push to have the best performing helmets on the market [18]. There were helmets on the market that ranged anywhere from $200-$1500, and this was due to varying degrees of complexity within the helmets. Most helmets were made and designed to look similarly aesthetically, but differences came from changes within the padding, inner-lining, and other components of the helmet.

This product would also fill the niche of a maintainable and therefore durable football helmet. As helmets wear, their foam padding becomes less compressible and therefore less effective, and replacing the padding on traditional helmets can be difficult, often needing to be sent back to the manufacturer [19]. Also, the team did not see helmets on the market which boast replaceable parts. Opposite to what was currently on the market, the damper system could be replaced whenever needed without the need to purchase a new outer shell and other parts of the helmet. This would dramatically lower costs over the life of the football helmet and provide much needed relief to low-budget programs. The need to buy new helmets and equipment for a team could range anywhere from yearly to every 10 years depending on the program: assuming that richer professional programs bought new gear more frequently whereas lower-tier high school teams went years without buying new equipment. Many professional athletes preferred to use the more expensive helmets because they were generally safer and more reliable [20].

The team proposed that, with the proper development and testing, a new damping system could be used to replace the traditional inner padding of helmets and provide the same force dampening effects for just a fraction of the price of other helmets on the market. Most collegiate and high school athletes usually did not have access to such funding, especially for the abundance of players around the nation. Therefore, a more affordable, but just as effective, solution would be beneficial for athletes below the professional level [21].

Also, because of budgeting concerns, many athletes at the high school level were not being protected as well as they should be. Athletic directors needed to make an ethical choice based on budgeting, choosing whether or not to provide better protection or paying a higher premium.

Designing and implementing a novel football helmet padding system also posed ethical improvements. As noted above, professional athletes preferred to use the higher end helmets because they were safer and more reliable, but for the average player, this was not a luxury he or she had. Leveling the cost of helmets would open doors for everyone, not only those who could afford it.

8.1.2 Potential Impact

In terms of an economic impact, this helmet's lower base price would allow many athletes who do not have the means to afford the best product on the market to have the safest gear. The Vicis Zero I helmet, for example, had a higher end retail price of $950 [22]. When one considered football programs under the collegiate and professional level, budgets were usually constrained, and not only can the initial cost of good helmets be high, but they also required maintenance and replacement as they are used over time. For programs where funding is scarce, players are forced to choose between cheaper helmets or reusing older ones.

According to the CDC, the lifespan of a helmet should be up to 10 years after the manufacturing date [23]. One high school in Texas for example, faced an annual budget of $7500 [24], which would only cover the cost of 7 fully-priced VICIS helmets (which provide the best level of protection on the market [25]). The reality was that when it came down to football as a sport, economics was a significant factor in terms of what players and teams could afford.

This had an unintentional social consequence as well as those in areas unable to afford proper equipment were left with higher likelihoods of permanent brain injury, which was significantly worse if they were incurred at a younger age.

8.2 Environmental and Sustainability

8.2.1 Background Information

In terms of sustainability, traditional pads were made of foam. These foams, usually EVA, take an estimated "hundreds of years" to degrade and can compound problems with trash collecting in landfills. Despite this, these helmets were still produced since foam is a relatively cheap and effective damper. Though the helmet's lifespan could range for up to 10 years [24], their environmental impact and time to degrade was significantly longer. Specifically, an EVA midsole, which was made of the same EVA used for football helmets, showed very low amounts of degradation after 12 years [26]. In comparison, the TPU dampers that were developed for this project could decompose in 3-5 years in soil [27].

8.2.2 Potential Impact

In terms of long-lasting impacts on the environment, it was no secret that plastics and similar materials take hundreds of years to decompose. As they do break down, they can result in microplastics which can be hard to detect and easy to contaminate water systems. While foam is not like traditional hard plastics, it’s still possible for them to cause damage to marine life if the waste can get into the ocean.

The TPU material of choice, that made up the material for the 3-D printed damper, was a step in the direction toward sustainability and reducing overall waste since it has shown signs of decomposing faster than traditional foams, and companies were trying to improve this even more. The ability to decompose and breakdown easily also reduces the risk of microplastics.

Specifically, the company API has been developing a more sustainable TPU material that is bio-based. Moreover, it required less energy to develop this type of TPU when compared to EVA (60%) [28]. Less energy required would also mean less pollution involved and a smaller carbon footprint in the production of TPU compared for EVA foam. Therefore, with more development and breakthroughs, TPU dampers would realistically reshape into a better alternative not only just for users, but for the environment, too.

Developing a solution which was both economically-friendly and safe would positively impact programs across the board. The damping system that the team manufactured was far more cost efficient, even if multiple systems were to be utilized within a helmet. Moreover, this economic impact would result in an ethical reaction as parents, athletic directors, and others who were purchasing helmets can do so without having to sacrifice safety for cost.

8.3 Health and Safety

8.3.1 Background Information

Due to numerous safety concerns and controversies on the professional level, for example the targeting scandals as well as high number of head-to-head collisions throughout the league, the number of athletes participating in tackle football has been on a steady decline over the years [29]. As evidenced in the team's personal interviews and statistical data, some parents did not feel comfortable allowing their children, who represented the majority of football athletes across the nation, to participate in such activities like football. Moreover, high school athletes who did participate frequently do not know what type of helmet they are receiving. This was both due to there being many different types of helmets that look similar externally and poor information from the high school level [30]. Some players' helmets may be less safe than others due to differences within the helmet that are not immediately noticeable from the outside such as padding wear-and-tear or different inner paddings all together. A liquid-damping helmet would eliminate this mystery and ensure that people know what they were using from the start. On top of that, the liquids within the helmet and its other components could be swapped out cheaply year by year to ensure that wear and tear was not an issue for coaches and players.

8.3.2 Potential Impact

A better damping system would invariably improve the safety of football helmets. Since TPU dampers did not experience the same densification zone, it limited the jarring effect. The linked dampers allowed the helmet to keep a better fit on the player's head, reducing the likelihood of the helmet coming off during an impact. This enabled players to be safer during the sport, reducing the likelihood of permanent brain damage. This improvement in personal safety was even more important for players that are still young since their brains were still developing.

A statistical survey comparing high school football player reactions to being slapped on the head with a helmet on were somewhat alarming. Over 30% of the participants of the survey stated that they felt some sort of pain just from being slapped on the head with a helmet, with another 8% saying that they felt a headache afterwards. This level of protection was inadequate when considering the high levels of energy that occurs in a sport like football. Safety of players should not be jeopardized from a simple slap to the helmet. This study from 2017 in Hawaii showed that football athletes were sacrificing safety for cost at levels under the professional scale [31].

8.3.3 Notable assumptions

Several assumptions were made for the project. The primary assumption was that implementing a liquid damping system instead of traditional EVA foam would still satisfy the design requirements for a football helmet (size, weight, and comfort constraints). The team designed a 3-D printed damper with volume restrictions within a 2x2x2” cube, which was the same space that traditional padding requires. However, because the system was never actually tested, it was difficult to confirm the accuracy of this sizing. Other assumptions, such as assuming a reduction of peak acceleration of the damper would result in less concussions and that the model used in FEA and CFD were accurate enough that the results of the simulations would be applicable to the physical dampers. Similarly, due to the limits placed upon the team due to COVID-19, this theory was never fully confirmed because no testing took place. Lastly, the scope of the project assumed that testing would be sufficient for a proof-of-concept build, which could then be used to narrow down the functional design for a real football helmet.

9. Conclusion

Though the results of this project could not be fully explored, preliminary research and testing were important building blocks that provided a baseline for future research. Initial damper testing was a key factor in experimentally discovering the relationship between dampers and fluids within the constraints of a standard helmet.

9.1 Key Findings

The foam padded helmet's shortcomings motivated the team to design a fluid-damper to smoothen these resistive force peaks. Although time and resources were limited, the team still performed physical testing (Chapter 6) that showed the team's hydrolastic fluid-damper took longer to compress than foam dampers given the same impact forcing.

While this finding cannot be assumed universal due the less than ideal testing conditions, the team's new hydrolastic damper design showed promise in being competitive with foam padding.

Again, referencing the physical testing results in Chapter 6, another key finding was the seemingly inverse relationship between damping effects and fluid viscosity. This makes very little intuitive sense; fluids with higher viscosities should and have historically demonstrated higher damping effects.

However, this is still a key finding because it brings further attention to the damper design and testing method. Perhaps the testing method did not perfectly simulate a football tackle collision, and thus the data is not an accurate representation of how the flow would dissipate energy. Perhaps there is some key feature at play in the current design that forces this unintuitive behavior, and perhaps researching this feature further would lead to further understanding and a potential breakthrough.

9.2 Further Research

In terms of immediate research, the team felt as if more testing on different fluid types would be beneficial to solidify results that were gathered. Due to the nature of the situation, the team did not extensively conduct research on the dampers themselves. If more time was permitted, the team would have attempted to better develop the relationship between compression times and dampening acceleration. One example to strengthen the validity of the results would be to also time different parameters of the tests already conducted on the dampers. More time results measuring time taken to fully compress and time between oscillations of the fluid within the damper would help finalize a fluid of choice for the damper. This testing method could then be accompanied by the team’s original plans for testing to discover and confirm the damper shape and fluid.

After adding the required safety measures to the original testing apparatus, the team would then conduct more experimental tests that could simulate more realistic impacts. The primary testing apparatus allowed for the team to simulate head-to-ground and head-to-head-to-ground type of impacts, providing more conclusive evidence.

Moreover, from this extensive testing, the team could then begin to optimize pipe diameters based on an optimal fluid and configuration. This would then lead the team to its original goal of reconfiguring a helmet with a hydrolastic system to replace traditional foam padding within standard parameters.

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Appendix

A1 Customer Needs Raw Interview Data

Below are transcript interviews with professionals in the fields of expertise:

A1.1 Interview with Brent Baculi (Football Player)

Personal Input from Michael in Italics

Brent played high school varsity football with Milpitas High School. He started at nose tackle and the conversation started with basic questions about the sport itself and head to head impacts that he has seen and been involved in. Being a nose tackle, he said that the greatest head to head contact that he was involved in were head to head clashes at the line of scrimmage. These hits were quick, somewhat like a jab. They did not have that much force behind them, as both players started in their three-point stands (and there was not enough time for the players to gain speed as both of their helmets were inches apart). He also said that he never really saw any big concussion hits, with little to no need for going into concussion protocol. However, he did say that he did feel some concussion-like symptoms after a play. Brent said that after a play, he got up from the ground and said he felt uneasy. He said that he felt a little disoriented and confused. However, he said that he somewhat just brushed this off and kept on playing. *This kind of mentality is that of many football players. Many choose to fight through the pain, wanting to avoid meeting with the medical team, which prevents them from playing a few snaps. Therefore, concussion data recorded may not actually represent the actual number of concussions in a given season because some players decide to forgo any type of medical check while on the field.*

Additionally, when asked about helmets, Brent said that he was issued a standard, hard foam helmet every single year that he was on the team. These helmets were team issued, standard amongst all high school players, and returned at the end of the year. He had no information about the type of helmets because they were standardized by his high school. From a fairly general search, Milpitas High School uses Riddell branded helmets. However, when asked about comfort, he said these helmets tended to get really stuffy due to the nature of the game. Further, when asked about the weight of his helmet (and about adding or losing a few pounds on the helmet) he said that “it was something that you just got used to.” He had no control over what helmet he was using in game. The school gave him a helmet and he wore it. He also stated that sometimes the helmets that he was issued were too tight on his head. *This shows that player safety at lower levels may also be overlooked. Players at any level should be able to explain to their coaches and team managers about any issues with their equipment. Sometimes, kids may be too shy to tell their coaches about some of their issues with gear. To combat this, players and coaches should be more vocal and open to equipment checks because player safety should always be a top priority in any given scenario.*

When asked about his preference regarding the size of his helmet, he felt as if it would be better if his helmet was somewhat lighter and more streamlined. He found that a lighter helmet would be beneficial for his own position (and generally beneficial for all positions). *When designing the helmet, we should attempt to find lighter weight materials that reduce the overall weight of the helmet, giving players a more natural fit. However, at the same time, player safety and concussion reduction should still be the same goal.*

A1.2 Interview with Kaleb Pattawi (Football Player)

Personal Input from Michael in Italics

Kaleb Pattawi played cornerback for his varsity football team and sustained a substantial head injury. He said that he was in pursuit of a runner (as a defensive player) when his head hit a receiver’s shoulder pads. Kaleb said he hit the ground, got up, and said he felt dazed. He then looked to his coach, who asked him if he was alright, and Kaleb had trouble answering his question. He said he could not really answer his coach, so he was taken out immediately. However, Kaleb did not leave the game, did not go into any kind of concussion protocol, and just waited a few snaps before re-entering the game. *This is a common trend amongst high school athletics. There is no real concussion protocol or safety measures for those who do sustain real injuries. Concussions as a whole could also be reduced from proper concussion recognition.* Kaleb also did not have his concussion-like symptoms diagnosed, but was pretty certain that he sustained some type of concussion or head injury.

Additionally, when asked about specifications about his helmet, he said he was issued a Riddell Speedflex helmet that was issued by the school. He had no choices when choosing a helmet, as the helmets that were provided only fit certain head types. He said his school had multiple helmets solely based on how big someone's head was. Some helmets and brands were geared toward specific players. *It is important to create a helmet that can be easily adjusted to fit different head shapes*.

When asked upon the parameters of a helmet, Kaleb preferred one that had a little more weight, as an extra measure of security. He felt as if he got used to his helmet anyways, and a little more durability and stability on someone's head would be beneficial.

A1.3 Interview with Vince Zipser (Turlock High School Football Coach)

Vince Zipser is a Turlock High School Football Coach, and specifically handles the Offense. Vince is also a THS 2003 graduate and played for football for THS at that time. This gives provides us with insight into Vince's unique perspective. Not only does he understand concussions and how the game is played now, but he also played within the last 20 years, enough time to recognize the differences and improvements of football gear.

When I asked Vince about the weight of current helmets, he said, compared to helmets during his playing years, "they're not that bad, measuring about 5 lbs.", and are not too much of a nuisance to players (Vince was coaching practice during the phone call, and asked a player on the spot, who agreed with his lightweight statement). Vince (and his player) likes the current helmet weight, and even said anything lighter might make the player feel less safe.

When I asked about helmet fitment (how well it forms around the player's head), he said current helmets are so good that he could "take a nap in one." Again, he compared current helmets to those from the early 2000s, saying the current are much better. Additionally, Vince introduced a "Xenith" helmet variant that used a type of damper (air filled) to achieve better fitment and thus player comfort.

Overall, Vince’s interview shows there is good customer satisfaction from current helmet ergonomics. It is safe to treat the current football helmet as a base for certain parameters in the design that affect ergonomics and comfort — we should not stray too far certain fundamental design aspects of the current helmet (e.g. weight and basic helmet geometry).

A1.4 Interview with Kennedy Sundberg (Santa Clara University EMT)

Kennedy is an Emergency Medical Technician at Santa Clara University. Her responsibilities include responding to emergency calls on campus and providing proficient and immediate care to critically ill and injured. In her line of work, she has dealt with sports impacts and is well versed in the care that needs to be given to someone who has sustained head trauma. Below are notes from her interview taken on 10/11/19.

When asked what were the guaranteed ways to diagnose a concussion, Kennedy responded that medical technicians "can't really tell if a person has a concussion unless you get a CT scan … but, on scene, more immediate methods such as questioning geared towards diagnosing head trauma, such as "remember hitting their head" and "blacked out" and "nauseous at all" and various physical tests, including palpating down the person's head and down the person's spine, are all ways to get a sense of whether or not a person may have a concussion." She continued on to say that "peripheral, motor, and sensory tests are next such as "Can you tell me what finger I am touching?" What toe?" and checking the pulse on wrists and feet" are other ways to continue diagnosing a potential concussion injury.

As it's important for the helmet to help medical technicians, I asked Kennedy what a helmet could do for her? I focused on the magnitude of the impact through the use of sensors and their locations as potential ways to help Kennedy assess a patient's injury severity.

She responded that "a magnitude of G's would be helpful to set an index of suspicion following the impact" and sensors "could act as an indicator of where to focus our palpitations." She told me that the EMTs definitely want to take off the helmet. She noted that "the hardest part is always the back of the helmet, which always proves to be difficult" and that an "way easier to take the front off completely" would help her. She concluded that "time of impact, and vitals are always crucial." As a final thought, she remarked that "it would be cool if the helmet could detect motion inside the head internally." She meant this as a way for the helmet to tell from the outside if the brain hit the inside of the skull. Hopefully this force would be small.

In placing dampers, I wanted to know what parts of the brain are most susceptible to concussions, so I asked her where the most susceptible part of the skull was, and she responded that "the back part, where the brain stem meets the skull, is a super important area, and this part is most susceptible when hitting the ground." I continued with whether she found that normally it is the initial hit or hitting the ground that causes the most injury. She responded that "it depends on what you hit, … but it's probably the initial hit." Continuing on damper placement, I asked her if she would put a damper where the brainstem connects. And she answered, "yes, that would be really important, because speaking in terms of whiplash, that would be really good to protect it from springing back to fast." The brain stem connects to the spine right at the base of the skull, and its location be approximated by below the hairline.

The team researched that multiple impacts do not correlate to a more susceptible person in the future. Kennedy was taught that multiple impacts makes someone more susceptible to concussions, and when asked about this, she responded that she was "happy" to hear that this study suggested otherwise, though it was just one study. When asked if she thought one large impact was worse than two or three big ones, she responded that "3 big hits vs. 5 small ones would be more concerning."

The interview ended with the placement of dampers once again. She suggested that dampers could be placed "evenly spaced along the temples, and with special attention to the cracks in the skull that connect it together." She ended with "how hard the impact was would be really interesting to know, and time would be good too, and any effects from the impact such as whether the impact came from the left or right. Finally, she said that a helmet that was "easy to take off and maybe vitals, too, heart rate being the best" would be great to see to monitor vitals before and after the impact.

A1.5 Interview with James Kelly (MA, MD, FAAN, Neurologist)

Dr. James Kelly talks about different areas of the brain affected by concussions in an online interview. Dr. Kelly says that parts of the brain most commonly affected in brain injuries are the frontal and temporal lobes because they are up against bone, and when the head rotates, and the neck is positioned that the front of the head moves more than the back of the head, the frontal and temporal lobes move greater distances than the core of the brain ie: torqueing causes more damage to those areas.

He explains that a contrecoup injury ("opposite the blow") is when you hit an immovable object, like the floor. This would happen when you fall, or when whiplash happens. The fluid mechanics during these impacts is really interesting, the injury occurs on the opposite side of the brain that hits the object due to pressure vacuum created by the blow. This would be a decompression injury on the opposite side of the impact This also happens when hitting the back of the head to the floor, and it happens less when the face hits the floor because unfortunately the face acts as an airbag to dampen the blow

He also explains that a coup injury is when you get hit by a projectile or mass object at speed, like a baseball bat. He says during the online interview that, "I hear from patients all the time that they are different, that they know they are not the same person they were before. The people that know them best, spouses and family members, will say the same thing."..."And the change is really the person's ability to do the high level interaction, the ability to engage in a fluid sense the core part of that person that allowed for the relationship to develop that they're in, if that's damaged then the relationship is damaged, that the family is damaged under the circumstances."

A2 Proposed Completion of Subsystems

A2.1 Block Head Construction

A2.1.1 Summary

These instructions show how to assemble the block head. See Figure A1 below.

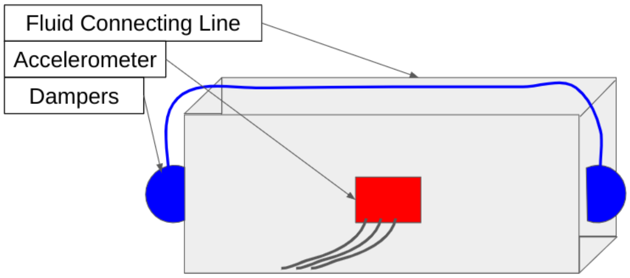

Figure A1. Completed block head.

A2.1.2 Required Parts

1. Two Dampers
2. 4' of ⅛" diameter clear tubing
3. 4' of ¼" diameter clear tubing
4. 4' of ½" diameter clear tubing
5. Wooden Block
6. Water Source (sink)
7. 200G accelerometer
8. Zip Ties
9. Super Glue
10. Masking Tape

A2.1.3 Instructions

1. Attach dampers to the sides of the wooden block using super glue, ensuring that the wider base of the conical shape is attached to the surface of the wood.
2. Ensure that fluid outlets are configured in the same fashion, with the inlet holes remaining completely upright.
3. Place the accelerometer on the side of the helmet using standard masking tape

4. Connect the accelerometer to the Arduino and to the DAQ
5. Ensure that an adequate amount of wiring is used to ensure that no people or equipment can be harmed or damaged.

A2.2 Attaching Testing Apparatus Safety Measures

A2.2.1 Summary

These instructions show how to attach the safety shield and safety interlock. Below is a photo of what we think the final testing apparatus should look like when it is completed, and we urge you to please do everything safely. More detailed images are attached at the end of the document. See Figure A2 below.

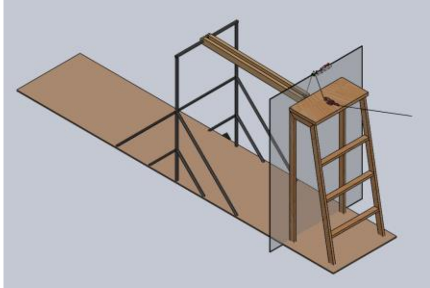

Figure A2. Completed testing rig.

A2.2.2 Required Parts

1. Completed Testing apparatus Frame
2. Step Stool Ladder
3. Safety Interlock
4. Latch
5. Clamps
6. Rope
7. 36”x72”x.093” plexiglass
8. 1” Screws
9. 1 ½” corner braces

A2.2.3 Instructions

1. Before attaching plexiglass, ensure that enough space is allotted for the pendulum arm to freely swing.
2. Attach plexiglass to bottom of the wooden base using 1” screws and 1 ½” corner braces at 4 locations at the base of the board, on both sides of the glass.
3. Attach safety interlock to top of the plexiglass sheet to allow for a rope to be threaded through.
4. Clamp a piece of excess plywood onto step stool.
5. Attach the latch to step stool using screws.
6. Thread rope from latch to safety interlock to pendulum arm.

A2.2.4 Assessment

Step stool should be propped against the safety shield to provide stability within the sheet. Additionally, if the glass is still unstable, diagonal members can be attached from the other side of the frame, using excess wood pieces and screws that are still in the shop.

A3 Preliminary Damper Designs

A3.1 Cylindrical Accordion

This damper is designed to be 2” in diameter by 1” in height with three compressible accordion folds. This damper can be printed using a flexible polymer such as TPU (thermoplastic polyurethane). Since it utilizes maximum overhang angles of 45 degrees, it can be made without needing support. The design would have a connection port to allow fluid to enter and exit via standard tubing (not pictured) and the placement of that port is flexible along the top or sides of the device. This would also enable the dampers to be connected in series of 2 or more depending on specifications desired. Changing the size of the port and ensuing diameter of the tubing would allow for better control of damping effect as well. See Figure A3 below.

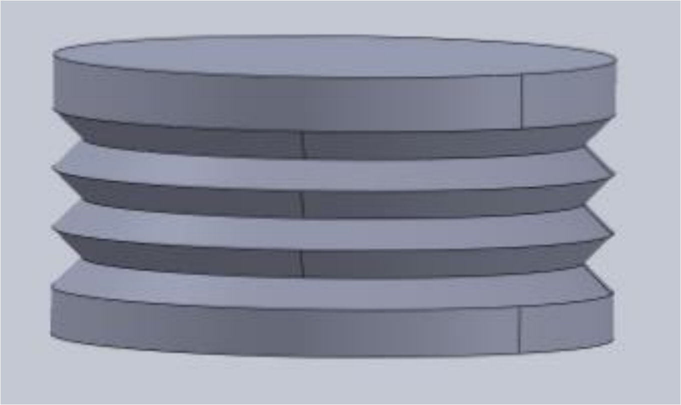

Figure A3. ½” of cylindrical accordion damper.

A3.2 Square Accordion

This damper is designed to be 2” x 2” x 1” unfolded with 3 compressible accordion folds. This damper can be printed using a flexible polymer such as TPU (thermoplastic polyurethane). Since it utilizes maximum overhang angles of 45 degrees, it can be made without needing support. The design would have a connection port to allow fluid to enter and exit via standard tubing (not pictured) and the placement is flexible along the top or sides of the device. This would also enable the dampers to be connected in a series of 2 or more depending on specifications desired. See Figure A4 below.

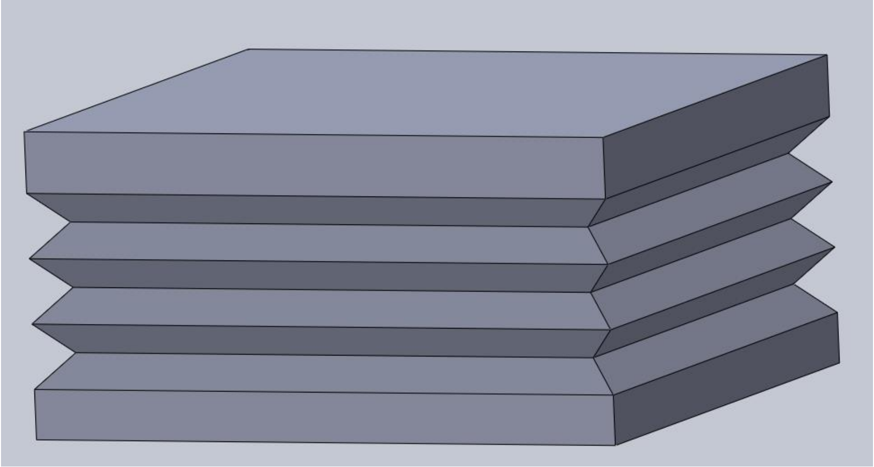

Figure A4. ½” of a rectangular based connected damper system

A3.3 Syringe

This system utilizes large-diameter Luer-lock syringes that would be connected in series or parallel using tubing. In order to get them to fit inside the helmet, the ends of large-diameter syringes where the plunger extends would have to be cut to short lengths then padded. The padding would prevent the stress concentration from the x-shaped style of the plunger from posing a safety hazard. With this design, multiple iterations would likely need to be tested to find the ideal amount of syringe to be cut so that the damping effect and size of the helmet is optimized. There is also the risk that the force would cause the syringe to fail. Since Luer-lock syringes are also at a preset outlet diameter, the amount of fluid that could be transferred via tubing is limited. See Figure A5 below.

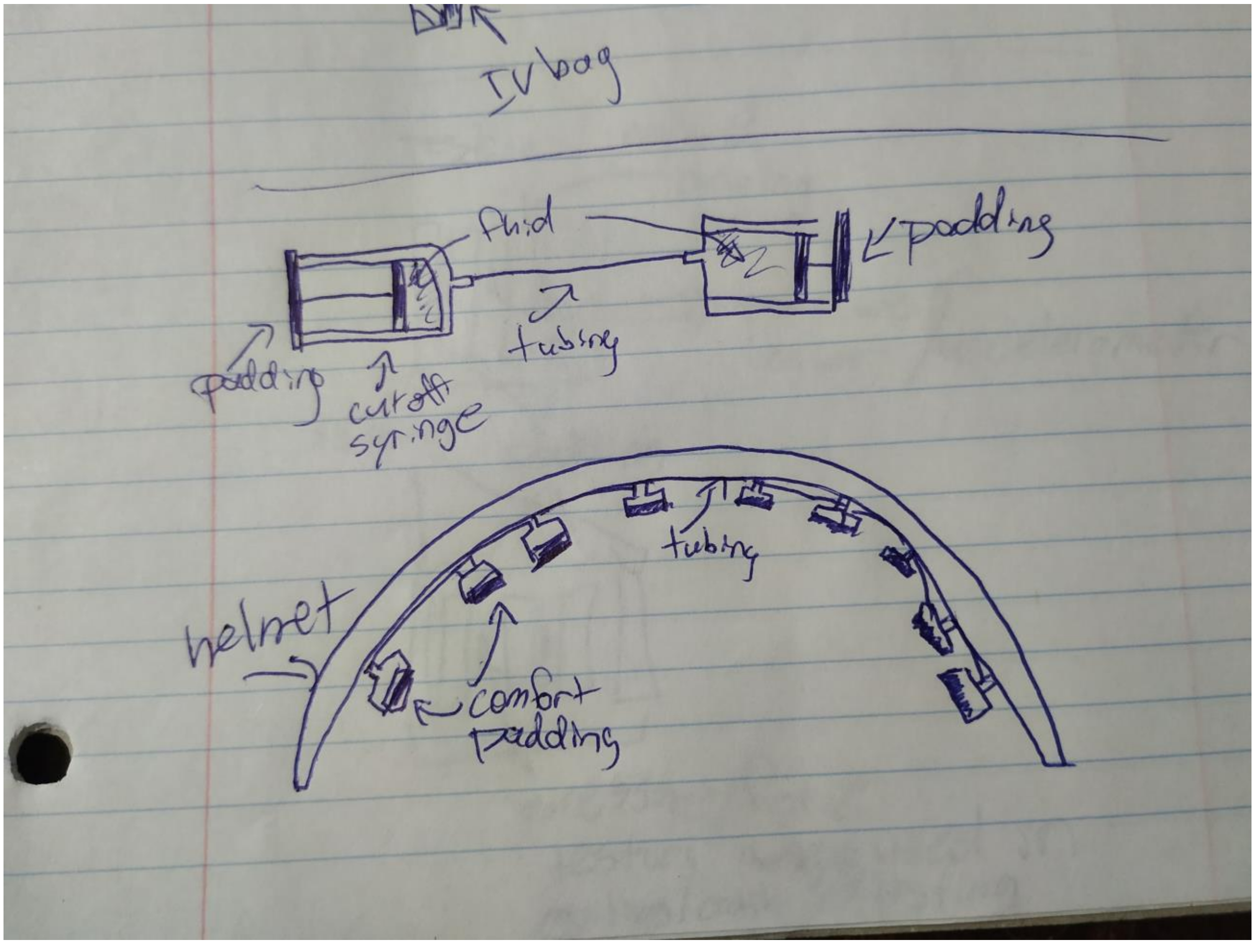

Figure A5. Syringe-based damper system

A3.4 Flexible Shells

This design uses 3D-printed hemispheres which would collapse under axial loading which would then force fluid out through an exchange port. These hemisphere shells use overhangs of less than 45% which would allow them to be 3D printed using a flexible polymer such as TPU without the need for support. The benefit of a spherical design is that as the force causes compression, the contact surface area increases as the rounded section becomes flat, therefore causing the amount of fluid transferred to be exponential rather than linear. As a result, the effect is likely similar to that of a progressive spring system. In order to function properly, the shells would have to be mounted with the least contact area natively facing the outer shell with the largest contact area sitting against the comfort liner of the inner helmet. See Figure A6 below.

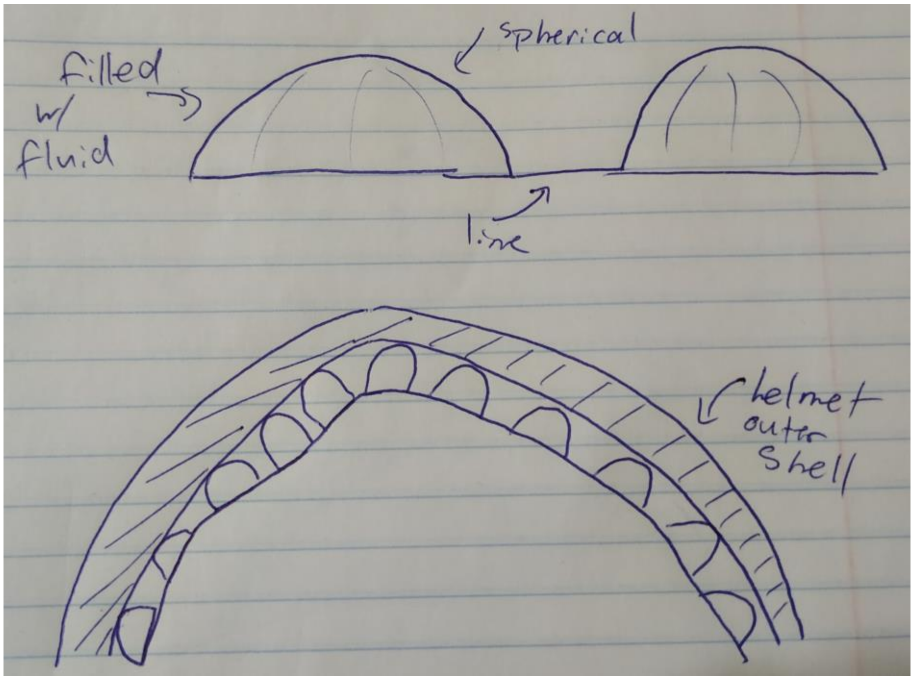

Figure A6. Flexible 3D printable balloons

A3.5 IV Bag

An IV bag lined through the proper opposing sides of the helmet (2 in front, 2 towards the back, and cross-connected) would give an effective damping solution. The bags can be filled with various fluids and transferred efficiently from bag to bag since the bags are already designed for quick and seamless fluid transfer. The bags themselves could be mounted to the helmet using a silicone or similar based adhesive to account for the flex when being worn. The benefits of such a system is that the parts are readily available. However, there is also the chance that the force from the impact would cause the fluid to transfer to the sides of the same IV bag or cause the IV bag to reform rather than transfer the fluid from one bag to another which is necessary for the damping effect desired. See Figure A7 below.

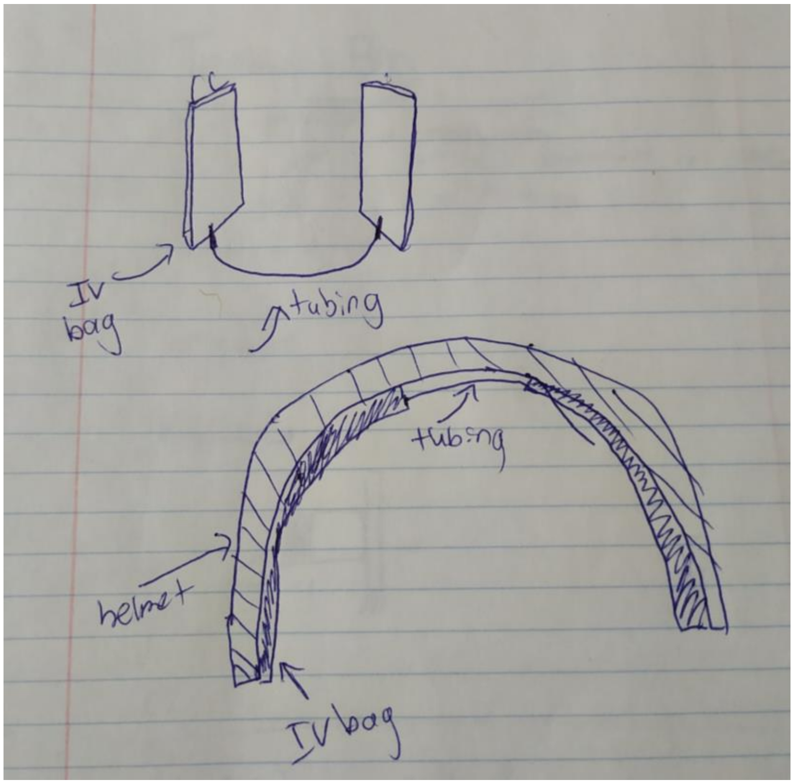

Figure A7. IV bag-based damping system

A3.6 Diner Ketchup Bottle

The damping system uses the bottles' preexisting nozzle as connection points for tubing to transfer fluid. As a force hits the helmet, the bottle is compressed forcing fluid to the other bottle while also creating a damping effect. The upside of this design is that it is both cheap and readily available. However, this design might be too large to act as an efficient damper inside of a helmet due to size and weight constraints (internal volume of a ketchup bottle is large (at least 12oz). Other sized bottles (not ketchup) could be substituted in to help counteract the size and weight limitations. See Figure A8 below.

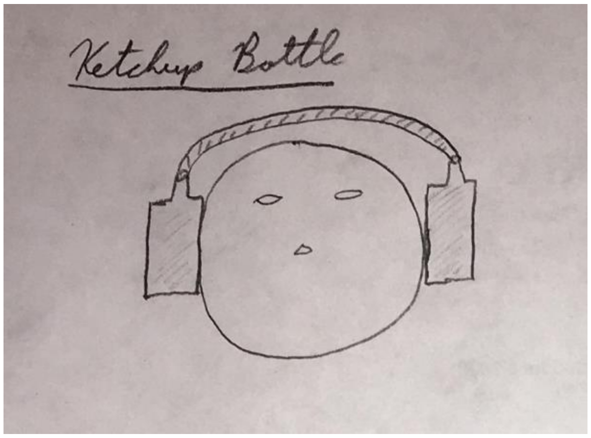

Figure A8. Sketch of a Diner Ketchup Bottle damping system.

A3.7 Water Balloon

This damping system does not use communicating hoses and instead picks one large body to act as the damper. As a result, this is both easier to mount and produce since it does not require a network of tubing. The bags could be filled with liquid or gases to produce the damping effect desired. The potential downside of such a system is that during impact, the energy of the impact could go into expanding the bag rather than resulting in the fluid providing the damping effect desired. See Figure A9 below.

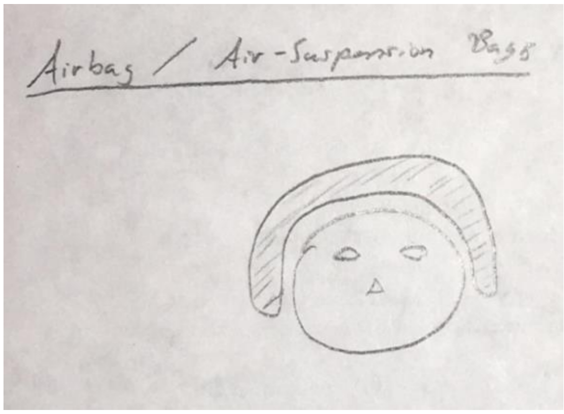

Figure A9. Sketch of Airbag/Air-Suspension bag damping system. Inner Tube

The damping system is inspired by the ring safety technique used in automotive safety engineering. The damping system does not use communicating hoses and instead picks one large body to act as the damper. In addition, by using inflatable rings, it’s possible to use pre-existing heavy-duty hoses (ex. Inner tire tubes) that would limit the likely-hood of damage during repeated usage. By using several tubes layered on top of each other, the damping effect would be contained to only a select number of tubes which constrains the damping effect to only acting upon the proper plane of the force, likely resulting in more efficient damping compared to the Water Balloon design). See Figure A10 below.

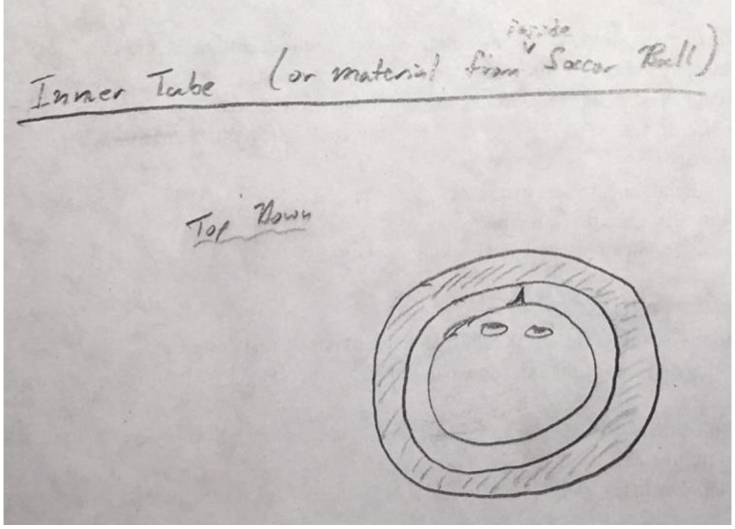

Figure A10. Top-down sketch of the Inner Tube damping system.

A3.8 Spinal Connection

Rather than being limited to just the helmet, this system uses a fluid-filled membrane running the length or part of the length of the spine. The damping system within the helmet is just a series of small fluid-filled bags or pockets connected with tubing to each other and the membrane in series parallel then in series. During the case of a front or back-facing impact, the membrane would compress causing fluid to flow to the helmet, causing a greater level of damping. At the same time, during side impacts, the fluid sacs connected in parallel would cause a damping effect within each other. Testing would have to be conducted to fully understand the degree of damping in a variety of impacts since there are so many degrees of freedom in this design. See Figure A11 below.

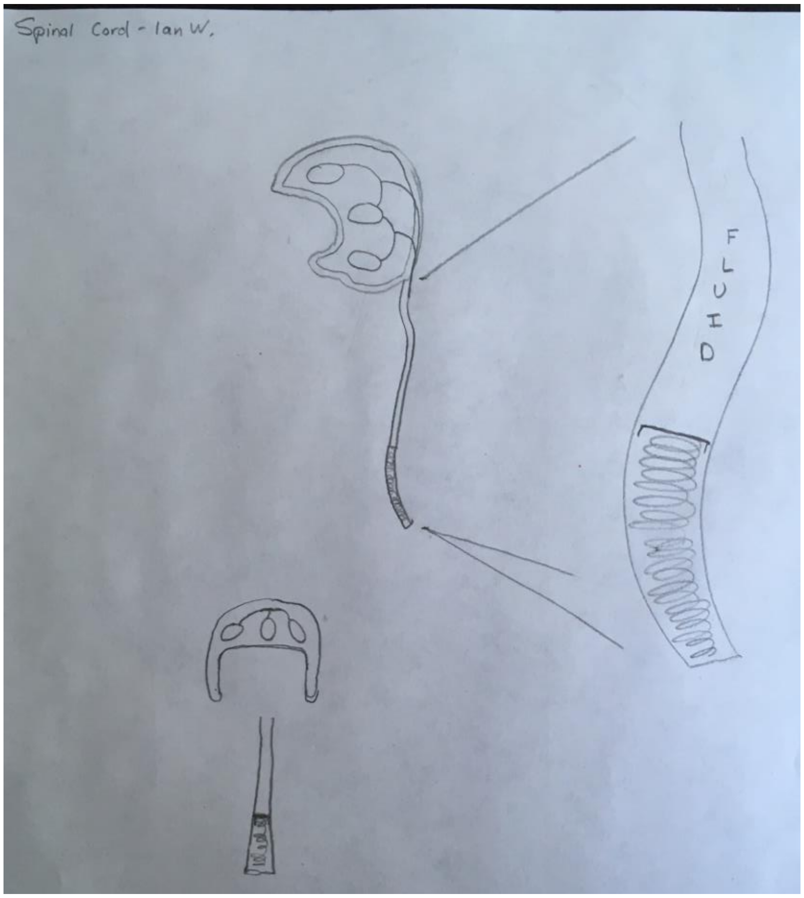

Figure A11. Front and side views of "Spinal Connection" damping system concept sketch.

A3.9 Helping Hand

This system uses a series of "hands" connected in parallel with three "fingers". Each of the hands is a fluid filled sac placed at key positions in the helmet (top, sides, and back) connected in parallel with each other by tubing "fingers". During impact, the "hands" would absorb the brunt of the force and the "fingers" would transfer the fluid to help generate the damping effect desired. In addition, by using thick tubing, each set of "fingers" could provide its own damping effect depending on the location of the impact. See Figure A12 below.

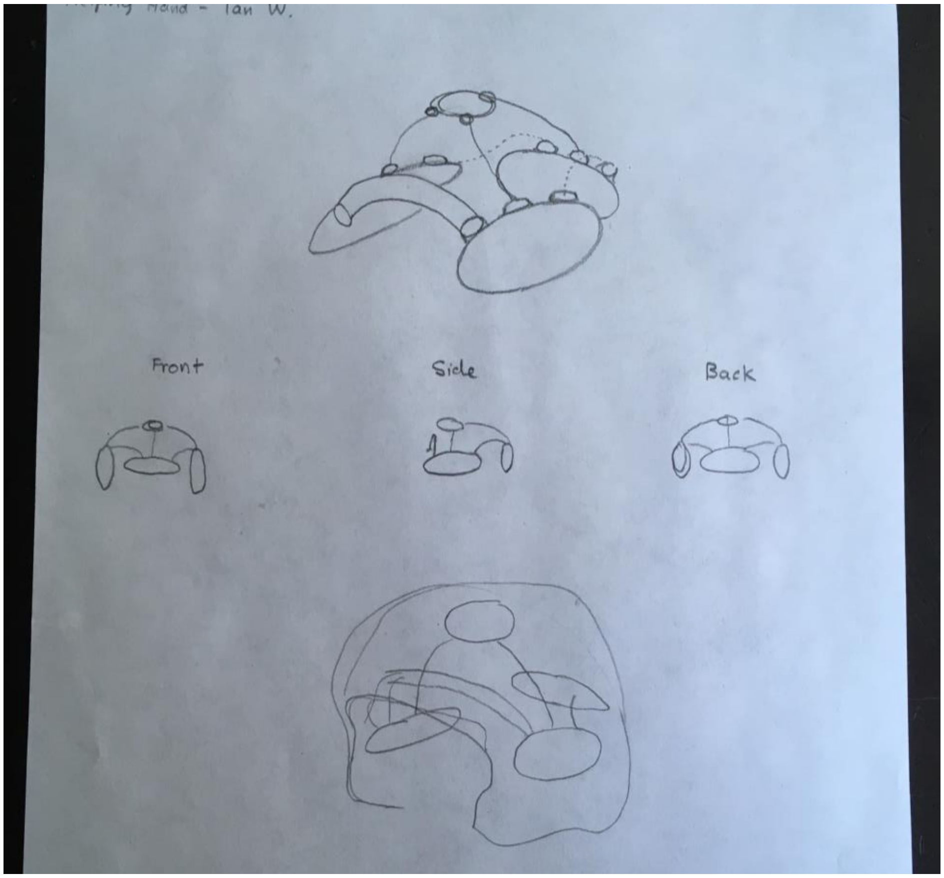

Figure A12. Front, Side, Back, and Isotropic views of "Helping Hand" damping system concept sketch.

A3.10 Bubble Boy

This design effectively adds either gas-filled or liquid-filled bubble wrap around and throughout the lining of the helmet, connected in series to each other in rows. During the initial impact, the fluid would have to travel from cavity to cavity, causing a degree of resistance that could be modulated by the design to create the damping effect desired. This design is cheap and readily available. The downside of such a design is that since the bubble wrap is connected in series, a single leak could pose a significant safety risk. In addition, since bubble wrap is only intended to be used in shipping, durability for use in such high-force impacts repeatedly is questionable. See Figure A13 below.

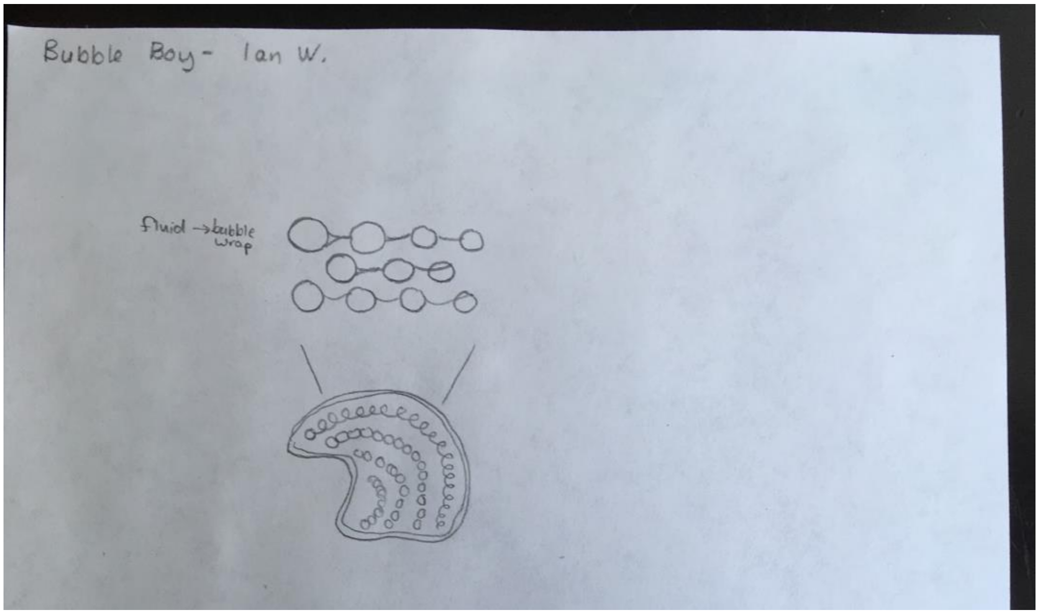

Figure A13. Side-view of "Bubble Boy" damping system concept sketch.

A3.11 VICIS 2.0

The VICIS helmet uses columns that are connected to each other by a rigid inner shell and a partly rigid outer shell which allows the columns to work together well. These columns and shell could be 3D printed with a harder material (PLA or ABS) while the columns could be printed with flexible polymer (TPU). The 3D print should be able to hold liquid as well which when connected in series or parallel, could provide the damping effect desired. The downside of such a design is that the weight of the liquid could go over design constraints and the size of the 3D printer needed to print all the columns effectively. Due to the curvature as well, the print might need internal or external support which would decrease the ease of production and installation. See Figure A14 below.

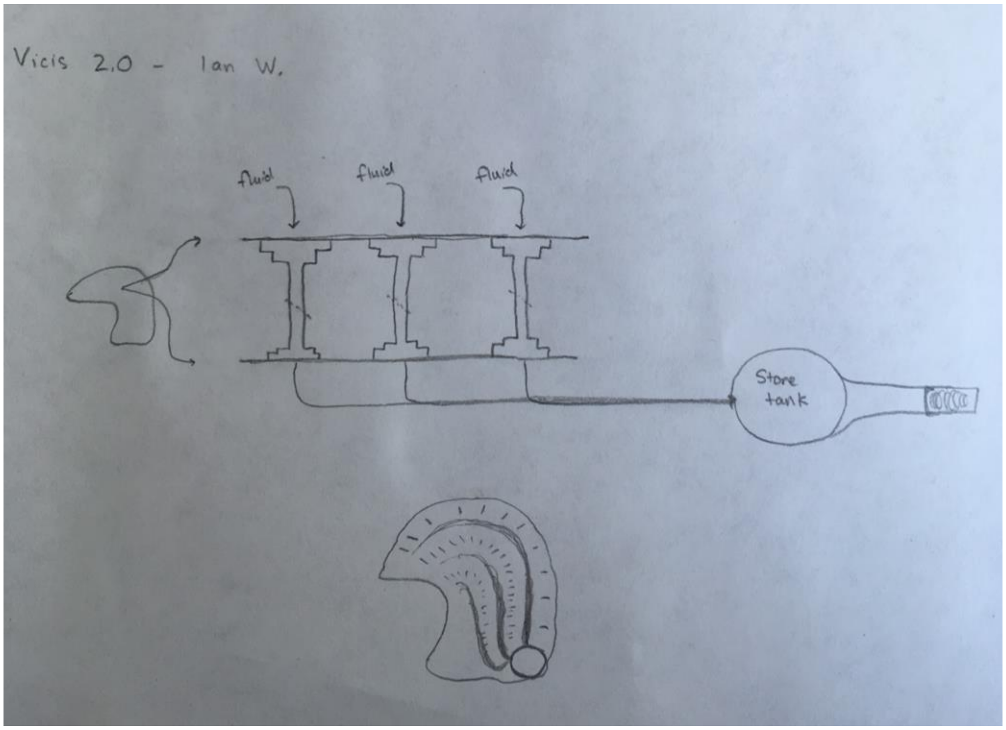

Figure A14. Concept sketch of "Vicis 2.0" damping system

A4 Budget Breakdown

```
More saving.
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2435 LAFAYETTE ST SANTA CLARA, CA. 95050
             (408)492-9600

0630  00002  78069    11/02/19  10:48 AM
CASHIER SABRINA

754826027368 ABS PIPE <A>
   1-1/2" X 10' ABS-DWV PE PIPE
   3@5.48                            16.44
728927300026 1X3 RED OAK <A>
   0.75IN X 2.5IN-R/L OAK BOARD
   9@2.32                            20.88
0000-999-735 CA LBR FEE <A,U>
   CA LUMBER FEE
   9@0.02                            0.18N
   NLP Savings    $0.00
038753309026 ABS CEMENT <A>          12.98
   32OZ ABS CEMENT MEDIUM BLACK
   NLP Savings    $0.22
030699732265 MASON LINE <A>           8.77
   #18X425' TWISTED MASON LINE
039923207548 ABS WYE <A>
   1-1/2" ABS WYE HXHXH
   8@3.38                            27.04
039923208163 ABS DBL WYE <A>
   1-1/2" ABS DBL WYE HXHXHXH
   4@5.58                            22.32
039923207029 ABS EL <A>
   1-1/2" ABS EL 90DEG VENT HXH
   2@2.66                             5.32
039923196521 ABS EL <A>
   1-1/2" ABS EL 90DEG HXH
   2@1.34                             2.68
887480023145 COMBO PACK <A>           3.56
   5/16" CUT WASHER (25) PACK BAG
887480023541 COMBO PACK <A>           3.08
   5/16" HEX NUT (25) PACK BAG
038753335001 PIPE STRAP <A>
   1-1/2" GALV PIPE STRAP 2 HOLE
   8@0.50                             4.00
887480037647 U-BOLT <A>               4.38
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887480064711 SHEET SCREW <A>
   SHEET MTL SCR PN HD PH ZINC #10X5/8"
   4@1.18                             4.72
887480166316 SCREW EYE <A>
   #212 ZINC SCREW EYE
   2@1.18                             2.36
887480165616 SCREW EYE <A>            1.18
   SCREW EYE #10 ZINC
030699432646 3/16"SWG SLV <A>
   FERRULE & STOP SET 3/16 ALUM
   2@1.98                             3.96
887480035643 EYEBOLT/NUT <A>          2.54
   "EYEBOLT/NUT 1/4""X2-5/8"" SS 2PK"
887480037746 U-BOLT <A>
   "U-BOLT 5/16""X1-1/2""X2-5/8"" SS"
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   "S-HOOK .260"" X 2-1/2"" SS"
   2@2.54                             5.08
887480070163 TRNBKLEYE <A>
   7/32"X6-1/4" TRNBKL EYE/EYE 13
   2@2.07                             4.14
887480172317 SCREW EYE SS <A>         1.18
   #12 STAINLESS STEEL SCREW EYE
030699433445 FAST EYE <A>             3.46
   FIXED PULLEY 1-1/4 NICKEL
887480036442 S HOOK <A>               2.54
   "S-HOOK .260"" X 2-7/8"" SS"
0000-273-051 WIRE ROPE <A>
   WIRE ROPE PLAIN 3/32"X1'
   10@0.27                            2.70
AMD          5/16X21/2HBL <A>
   HEX BOLT 5/16X2-1/2
   12@0.29                            3.48

              SUBTOTAL              178.55
              SALES TAX              16.05
              TOTAL                $194.60
XXXXXXXXXXXX3169 DEBIT
                              USD$ 194.60
```

```
More saving.
More doing.

2435 LAFAYETTE ST SANTA CLARA, CA. 95050
             (408)492-9600

0630  00001  69656    11/04/19  03:56 PM
CASHIER ALANA

841804100332 10' VINYL <A>             3.25
   3/80DX1/4IDX10' VINYL TUBE
841804100264 20' VINYL <A>             4.93
   5/160DX3/16IDX20' VINYL TUBE
841804100295 VINYL TUBE <A>            8.87
   1/20DX3/8IDX20' VINYL TUBE
076818364139 E6000 ADH <A>             4.29
   E6000 2 OZ
4715409150107 1" MOUNT PAD <A>        16.18
   1"X1" UV BLACK MOUNTING PADS 100PK
4715409150350 CABLE TIES <A>           9.88
   650PC CABLE TIES-ASSORTED SIZES
841804100271 20' VINYL <A>             3.73
   1/40DX.170IDX20' VINYL TUBE
073257012782 9X12 2M GARD <A>
   9'X12' 2MIL CLEAR PLASTIC DROP CLOTH
   2@3.18                              6.36
742366999764 DUCT TAPE-2P <A>         10.98
   NASHUA HEAVY DUTY-1.89"X120YD(2ROLL)
078575103044 SS CLMP 10PK <A>          6.24
   #004 SS CLAMP 1/4"X5/8" DIA 10PK
078575126029 SS CLAMP <A>
   #004 SS CLAMP 1/4"X5/8" DIA
   12@0.93                            11.16

              SUBTOTAL               85.87
              SALES TAX               7.73
              TOTAL                 $93.60
XXXXXXXXXXXX3169 DEBIT
                               USD$ 93.60

AUTH CODE 260799
AID A0000000980840              US DEBIT
```

Figure A15. The grand total of these two receipts was $288.20.

More saving.
More doing.℠

2435 LAFAYETTE ST SANTA CLARA, CA. 95050
(408)492-9600

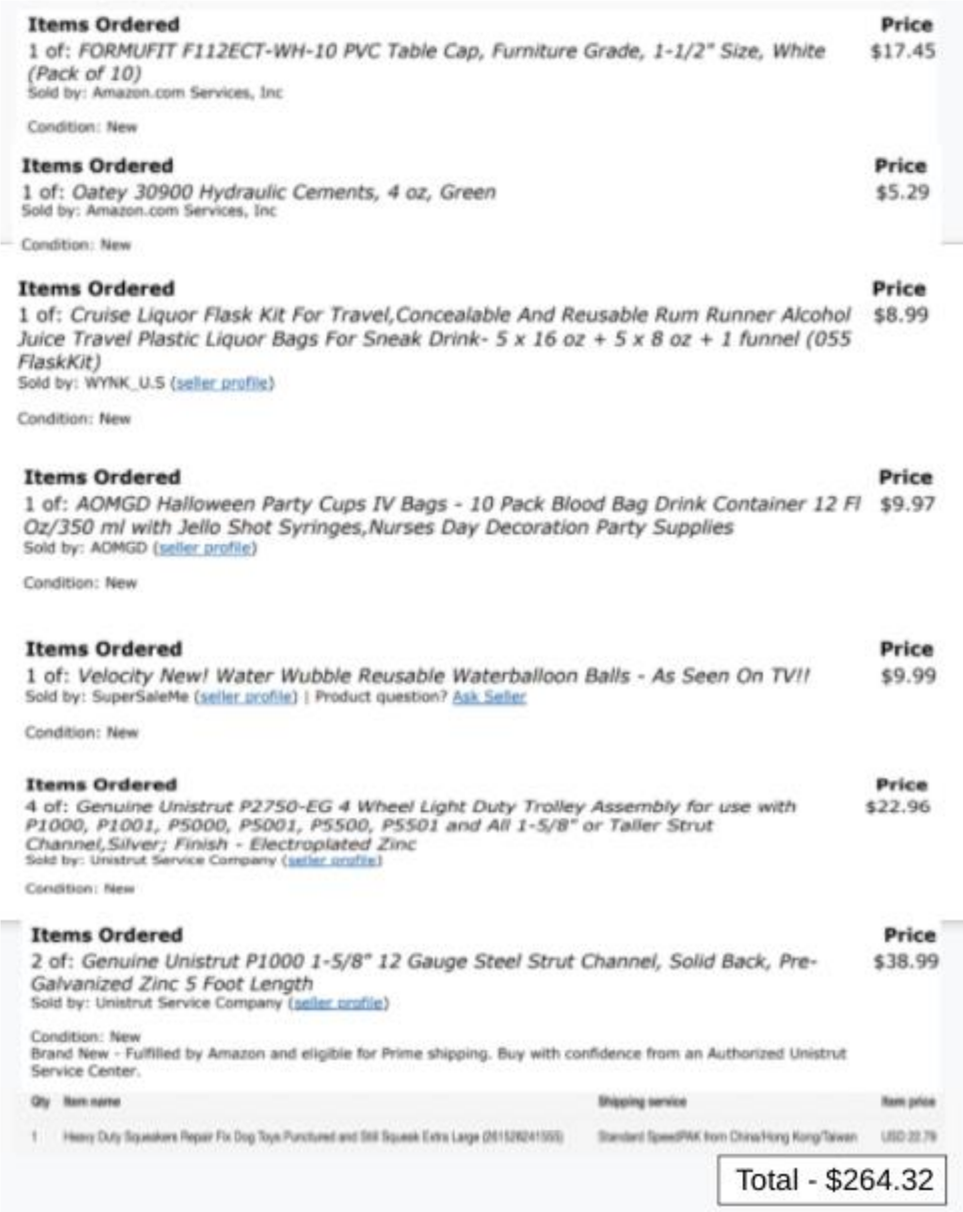
0630 00002 88332 11/04/19 04:08 PM
CASHIER DAVID

728927300026 1X3 RED OAK <A>
0.75IN X 2.5IN-R/L OAK BOARD
9@2.32 20.88
0000-999-735 CA LBR FEE <A,U>
CA LUMBER FEE
9@0.02 0.18N
0000-332-941 4X8 BIRCH <A> 54.98
0.703IN X 48IN X 96IN; BIRCH PLYWOOD
00-999-735 CA LBR FEE <A,U> 0.54N
CA LUMBER FEE

SUBTOTAL 76.58
SALES TAX 6.83
TOTAL $83.41
XXXXXXXXXXXX3169 DEBIT

AUTH CODE 731204 USD$ 83.41
AID A0000000980840
US DEBIT

Figure A16. The grand total of this receipt was $83.41.



Items Ordered **Price**
1 of: *FORMUFIT F112ECT-WH-10 PVC Table Cap, Furniture Grade, 1-1/2" Size, White (Pack of 10)* $17.45
Sold by: Amazon.com Services, Inc

Condition: New

Items Ordered **Price**
1 of: *Oatey 30900 Hydraulic Cements, 4 oz, Green* $5.29
Sold by: Amazon.com Services, Inc

Condition: New

Items Ordered **Price**
1 of: *Cruise Liquor Flask Kit For Travel,Concealable And Reusable Rum Runner Alcohol Juice Travel Plastic Liquor Bags For Sneak Drink- 5 x 16 oz + 5 x 8 oz + 1 funnel (055 FlaskKit)* $8.99
Sold by: WYNK_U.S (seller profile)

Condition: New

Items Ordered **Price**
1 of: *AOMGD Halloween Party Cups IV Bags - 10 Pack Blood Bag Drink Container 12 Fl Oz/350 ml with Jello Shot Syringes,Nurses Day Decoration Party Supplies* $9.97
Sold by: AOMGD (seller profile)

Condition: New

Items Ordered **Price**
1 of: *Velocity New! Water Wubble Reusable Waterballoon Balls - As Seen On TV!!* $9.99
Sold by: SuperSaleMe (seller profile) | Product question? Ask Seller

Condition: New

Items Ordered **Price**
4 of: *Genuine Unistrut P2750-EG 4 Wheel Light Duty Trolley Assembly for use with P1000, P1001, P5000, P5001, P5500, P5501 and All 1-5/8" or Taller Strut Channel,Silver; Finish - Electroplated Zinc* $22.96
Sold by: Unistrut Service Company (seller profile)

Condition: New

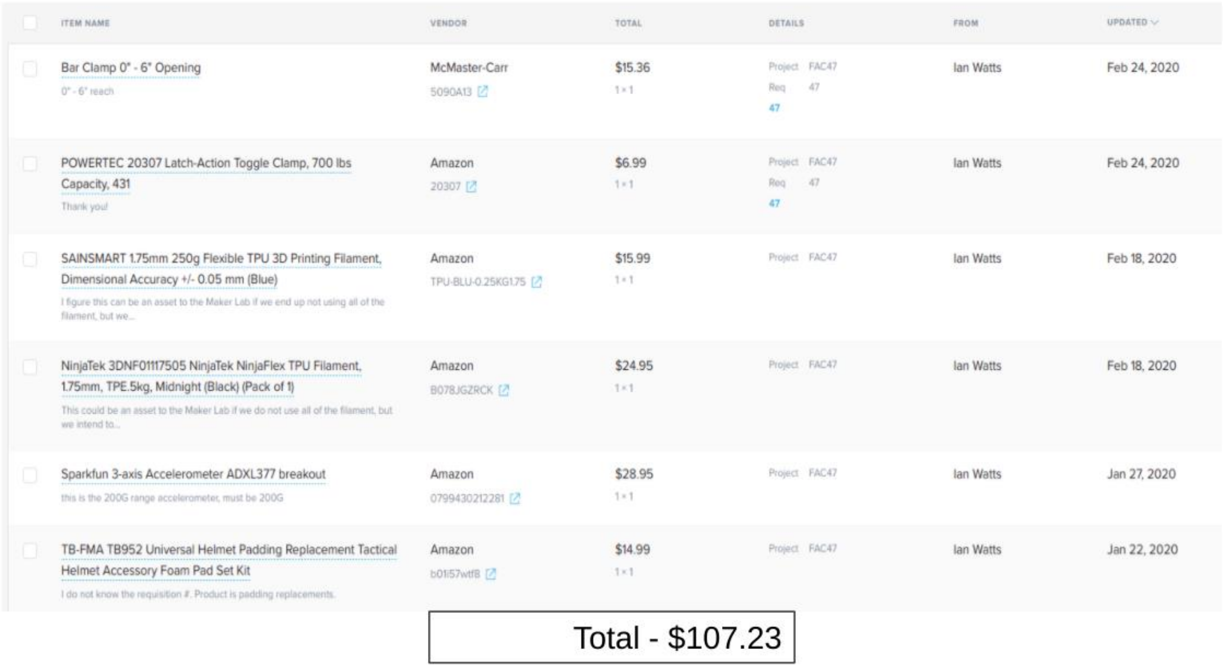
Items Ordered **Price**
2 of: *Genuine Unistrut P1000 1-5/8" 12 Gauge Steel Strut Channel, Solid Back, Pre-Galvanized Zinc 5 Foot Length* $38.99
Sold by: Unistrut Service Company (seller profile)

Condition: New
Brand New - Fulfilled by Amazon and eligible for Prime shipping. Buy with confidence from an Authorized Unistrut Service Center.

Qty	Item name	Shipping service	Item price
1	Heavy Duty Squeakers Repair Fix Dog Toys Punctured and Still Squeak Extra Large [illegible]	Standard SpeedPAK from China/Hong Kong/Taiwan	USD 22.79

Total - $264.32

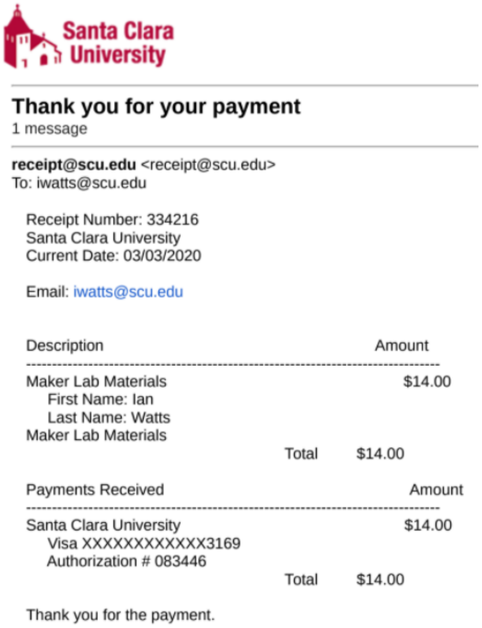
Figure A16. The grand total of this receipt was $264.32.



☐	ITEM NAME	VENDOR	TOTAL	DETAILS	FROM	UPDATED
☐	Bar Clamp 0" - 6" Opening 0" - 6" reach	McMaster-Carr 5090A13	$15.36 1 × 1	Project FAC47 Req 47 47	Ian Watts	Feb 24, 2020
☐	POWERTEC 20307 Latch-Action Toggle Clamp, 700 lbs Capacity, 431 Thank you!	Amazon 20307	$6.99 1 × 1	Project FAC47 Req 47 47	Ian Watts	Feb 24, 2020
☐	SAINSMART 1.75mm 250g Flexible TPU 3D Printing Filament, Dimensional Accuracy +/- 0.05 mm (Blue) I figure this can be an asset to the Maker Lab if we end up not using all of the filament, but we...	Amazon TPU-BLU-0.25KG1.75	$15.99 1 × 1	Project FAC47	Ian Watts	Feb 18, 2020
☐	NinjaTek 3DNF01117505 NinjaTek NinjaFlex TPU Filament, 1.75mm, TPE.5kg, Midnight (Black) (Pack of 1) This could be an asset to the Maker Lab if we do not use all of the filament, but we intend to...	Amazon B078JGZRCK	$24.95 1 × 1	Project FAC47	Ian Watts	Feb 18, 2020
☐	Sparkfun 3-axis Accelerometer ADXL377 breakout this is the 200G range accelerometer, must be 200G	Amazon 0799430212281	$28.95 1 × 1	Project FAC47	Ian Watts	Jan 27, 2020
☐	TB-FMA TB952 Universal Helmet Padding Replacement Tactical Helmet Accessory Foam Pad Set Kit I do not know the requisition #. Product is padding replacements.	Amazon b01i57wtf8	$14.99 1 × 1	Project FAC47	Ian Watts	Jan 22, 2020

Total - $107.23

Figure A18. The grand total of this receipt was $107.23.



Santa Clara University

Thank you for your payment
1 message

receipt@scu.edu <receipt@scu.edu>
To: iwatts@scu.edu

Receipt Number: 334216
Santa Clara University
Current Date: 03/03/2020

Email: iwatts@scu.edu

Description	Amount
Maker Lab Materials First Name: Ian Last Name: Watts Maker Lab Materials	$14.00
Total	$14.00

Payments Received	Amount
Santa Clara University Visa XXXXXXXXXXXX3169 Authorization # 083446	$14.00
Total	$14.00

Thank you for the payment.

Figure A17. The grand total of this receipt was $14.00.

A5 Raw Data from Experimental Testing

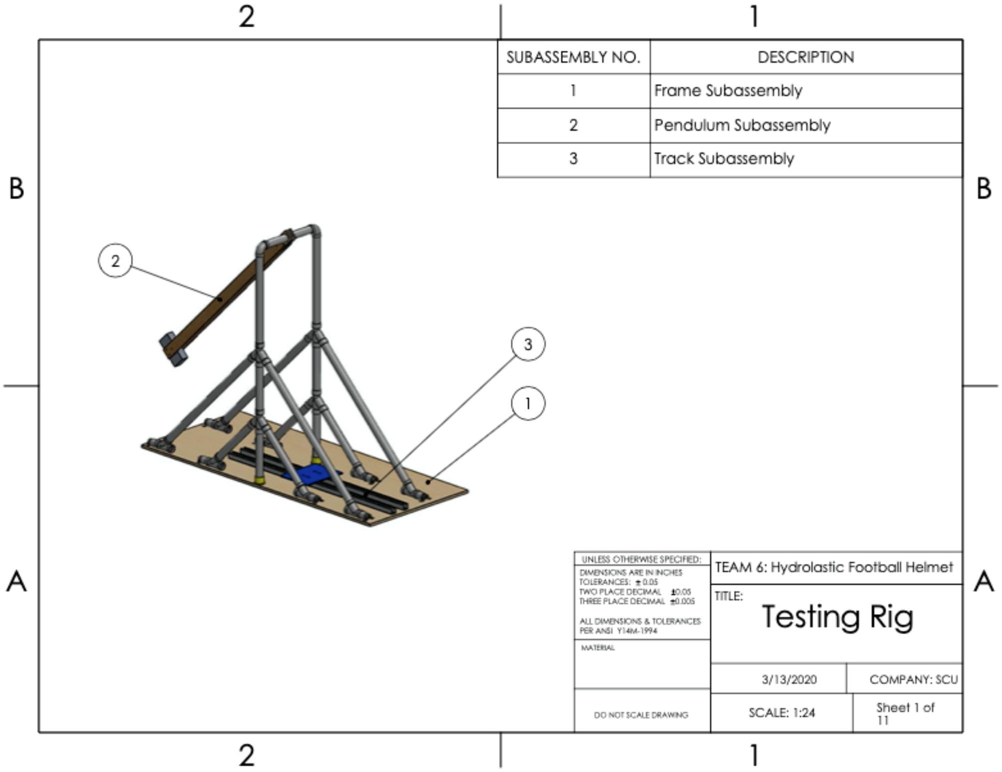
Drop Distance	0.92 in							
Drop Weight	10 lbs							
Flat No Water								
File #	Trial	Distance Start [cm]	Distance End [cm]	Distance Traveled [cm]	1	2	3	Time to Stop
5522	1	26		-26	13.03	13.96	12.85	13.28
5521	2	26		-26	14.79	15.49	14.2	14.83
5520	3	26		-26	14.18	13.32	14.91	14.14
5519	4	26		-26	13.93	14.3	13.91	14.05
5518	5	26		-26	12.89	12.78	12.83	12.83
5517	6	26		-26	n/a	n/a	n/a	*video not working
5516	7	26		-26	8.25	8.22	8.57	8.35
5515	8	26		-26	12.5	12.94	12.75	12.73
5514	9	26		-26	15.38	15.31	15	15.23
5513	10	26		-26	15.32	15.22	15	15.18

Pointed No Water								
File #	Trial	Distance Start [cm]	Distance End [cm]	Distance Traveled [cm]	1	2	3	Time to Stop
5526	1	26		-26	13.53	13.96	13.54	13.68
5534	2	26		-26	7.05	8.56	8.43	8.01
5533	3	26		-26	12.89	13.05	12.67	12.87
5532	4	26		-26	14.95	14.8	12.77	14.17
5530	5	26		-26	8.74	8.46	8.41	8.54
5529	6	26		-26	13.98	14.02	14.03	14.01
5528	7	26		-26	13.81	13.67	13.76	13.75
5525	8	26		-26	12.91	13.84	13.61	13.45
5524	9	26		-26	13.89	14.03	14.17	14.03
5523	10	26		-26	14.07	14.92	14.13	14.37
Flat With Water								
File #	Trial	Distance Start [cm]	Distance End [cm]	Distance Traveled [cm]	1	2	3	Time to Stop
5537	1	26		-26	11.03	11.09	13.89	12.00
5536	2	26		-26	7.17	6.94	7.19	7.10
5540	3	26		-26	6.73	6.91	7.17	6.94
5539	4	26		-26	14.17	13.37	15.27	14.27
5538	5	26		-26	11.55	11.25	10.95	11.25

Flat With Syrup								
File #	Trial	Distance Start [cm]	Distance End [cm]	Distance Traveled [cm]	1	2	3	Time to Stop
5552	1	26		-26	10.71	11.27	10.76	10.91
5551	2	26		-26	10.6	10.57	11.01	10.73
Padding								
Video Time Stop	Trial	Distance Start [cm]	Distance End [cm]	Distance Traveled [cm]	1	2	3	Time to Stop
5574	1			0	5.58	6.13	5.49	5.73
5566	2			0	n/a	n/a	n/a	*not a valid test, wrong base material
0:10	3			0	1.73	1.92	1.66	1.77
1:28	4			0	7.17	7.14	7.41	7.24
3:34	5			0	5.85	6.33	5.94	6.04
6:10	6			0	6.41	6.12	6.26	6.26
7:52	7			0	6.28	5.56	5.38	5.74
9:43	8			0	5.51	5.4	5.43	5.45
11:30	9			0	6.05	6.46	6.56	6.36

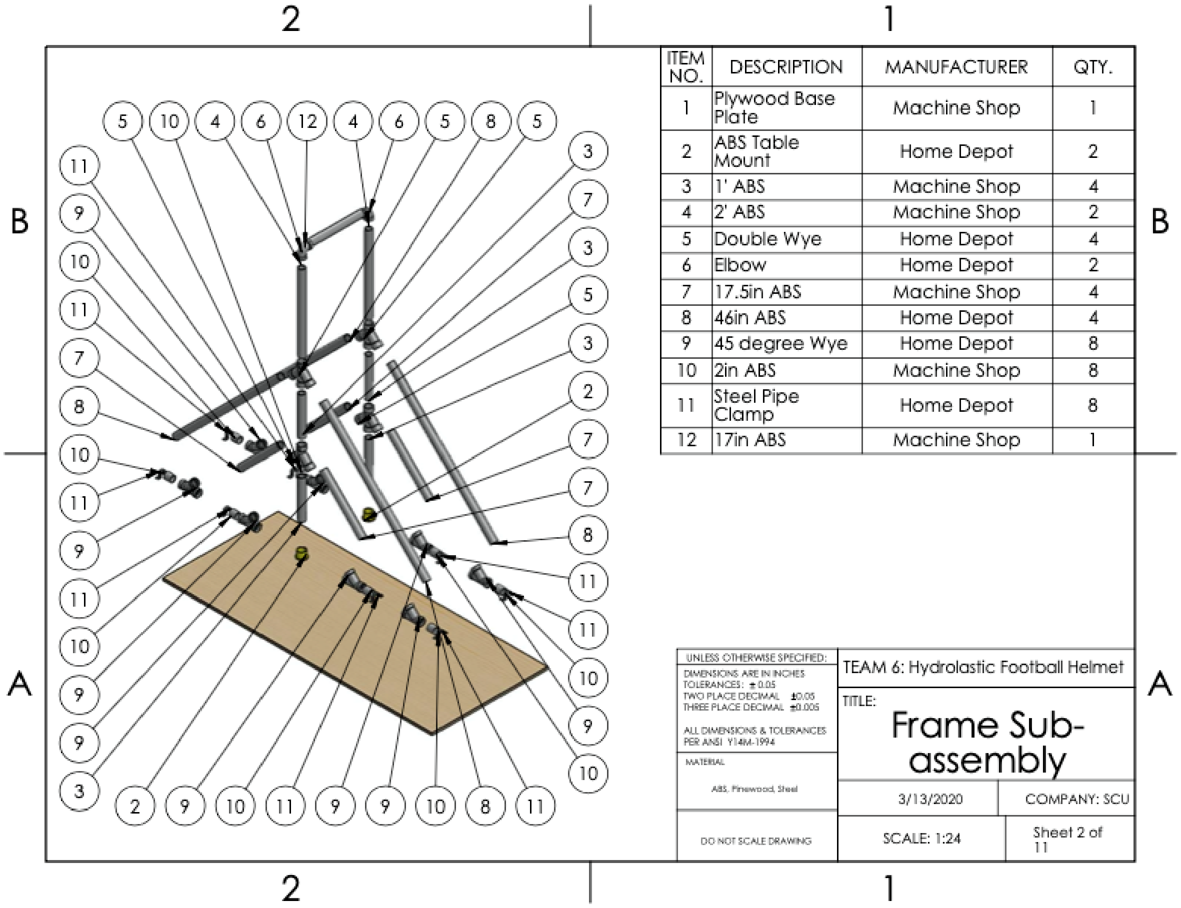
CONNECTION TESTS								
Water Connect			Results					
Did an impact fill the other damper?			No					
Time to take to fill damper with sustained impact:			DNF					
Syrup Connect								
Did an impact fill the other damper?			No					
Time to take to fill damper with sustained impact:			40.82	*just seconds off the video, not double slowed				
			5.1025	*seconds real time				

A6 Detailed CAD models



SUBASSEMBLY NO.	DESCRIPTION
1	Frame Subassembly
2	Pendulum Subassembly
3	Track Subassembly

Figure A20. Final CAD drawing of the entire testing apparatus.



ITEM NO.	DESCRIPTION	MANUFACTURER	QTY.
1	Plywood Base Plate	Machine Shop	1
2	ABS Table Mount	Home Depot	2
3	1' ABS	Machine Shop	4
4	2' ABS	Machine Shop	2
5	Double Wye	Home Depot	4
6	Elbow	Home Depot	2
7	17.5in ABS	Machine Shop	4
8	46in ABS	Home Depot	4
9	45 degree Wye	Home Depot	8
10	2in ABS	Machine Shop	8
11	Steel Pipe Clamp	Home Depot	8
12	17in ABS	Machine Shop	1

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES: ± 0.05
TWO PLACE DECIMAL ±0.05
THREE PLACE DECIMAL ±0.005

ALL DIMENSIONS & TOLERANCES
PER ANSI Y14M-1994

MATERIAL
ABS, Pinewood, Steel

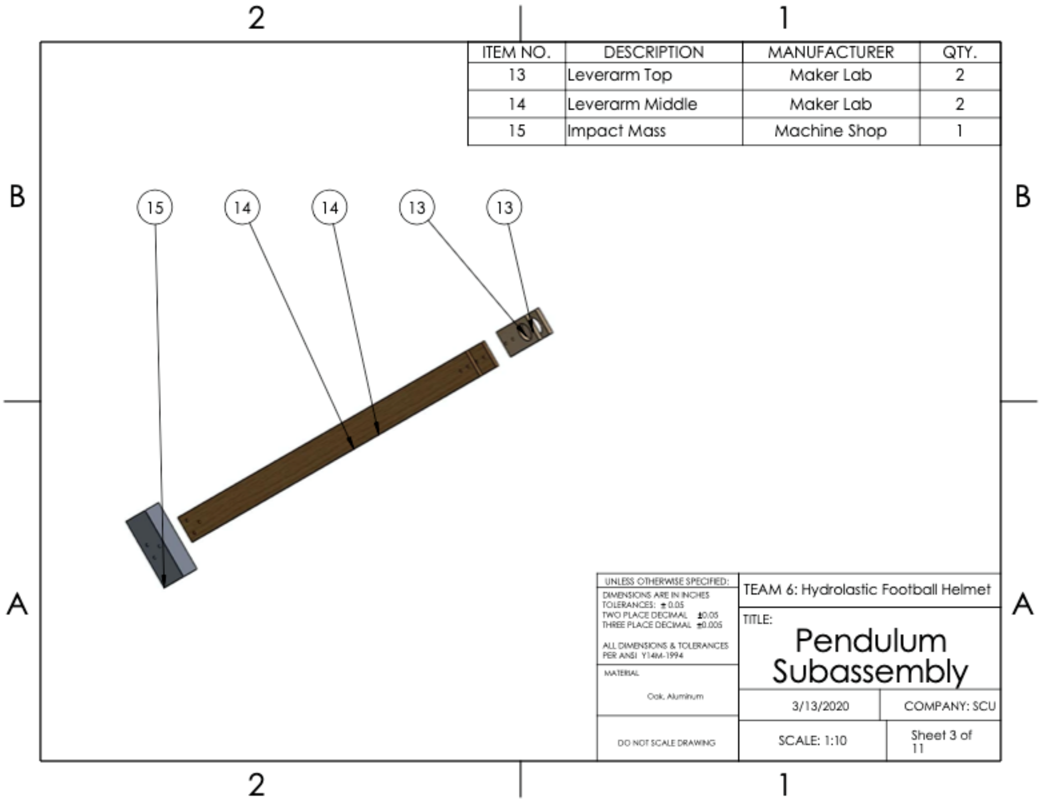
DO NOT SCALE DRAWING

TEAM 6: Hydrolastic Football Helmet

TITLE:
Frame Sub-assembly

3/13/2020
COMPANY: SCU
SCALE: 1:24
Sheet 2 of 11

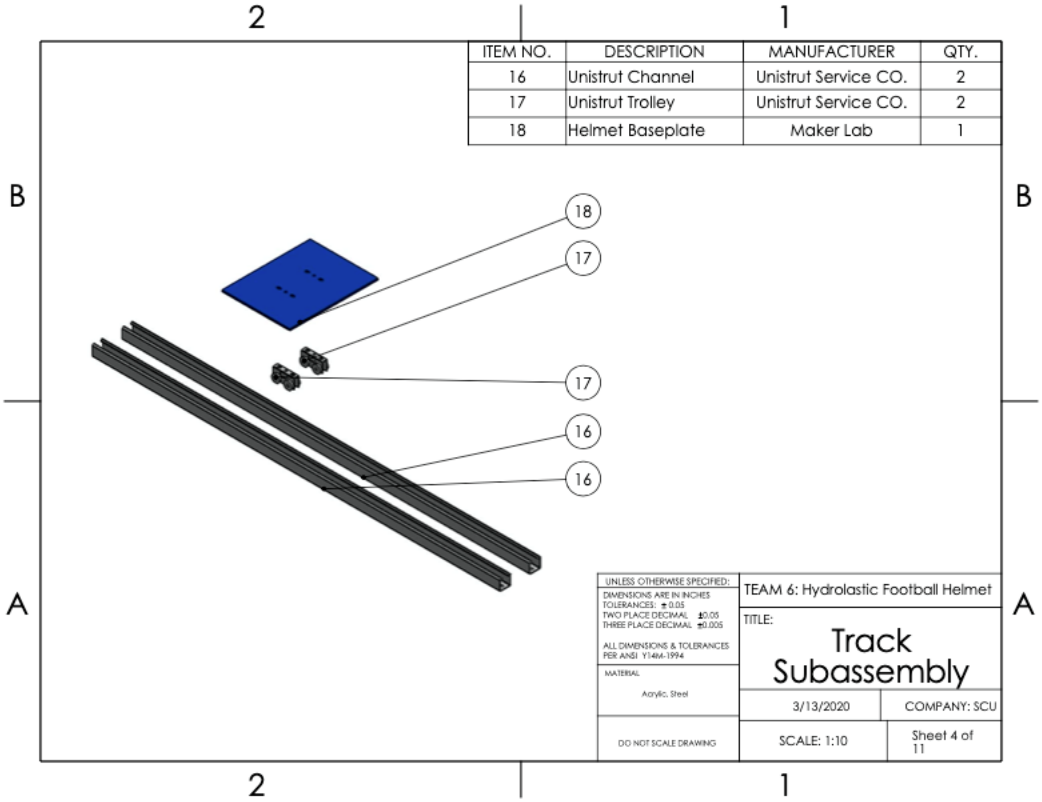
Figure A21. Final CAD drawing of the entire testing apparatus, broken up into pieces.



ITEM NO.	DESCRIPTION	MANUFACTURER	QTY.
13	Leverarm Top	Maker Lab	2
14	Leverarm Middle	Maker Lab	2
15	Impact Mass	Machine Shop	1

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES: ± 0.05
TWO PLACE DECIMAL ±0.05
THREE PLACE DECIMAL ±0.005
ALL DIMENSIONS & TOLERANCES PER ANSI Y14M-1994
MATERIAL: Oak, Aluminum
DO NOT SCALE DRAWING
TEAM 6: Hydrolastic Football Helmet
TITLE: Pendulum Subassembly
3/13/2020
COMPANY: SCU
SCALE: 1:10
Sheet 3 of 11

Figure A22. Final CAD drawing of the pendulum assembly.



ITEM NO.	DESCRIPTION	MANUFACTURER	QTY.
16	Unistrut Channel	Unistrut Service CO.	2
17	Unistrut Trolley	Unistrut Service CO.	2
18	Helmet Baseplate	Maker Lab	1

Figure A23. Final CAD drawing of the track assembly.

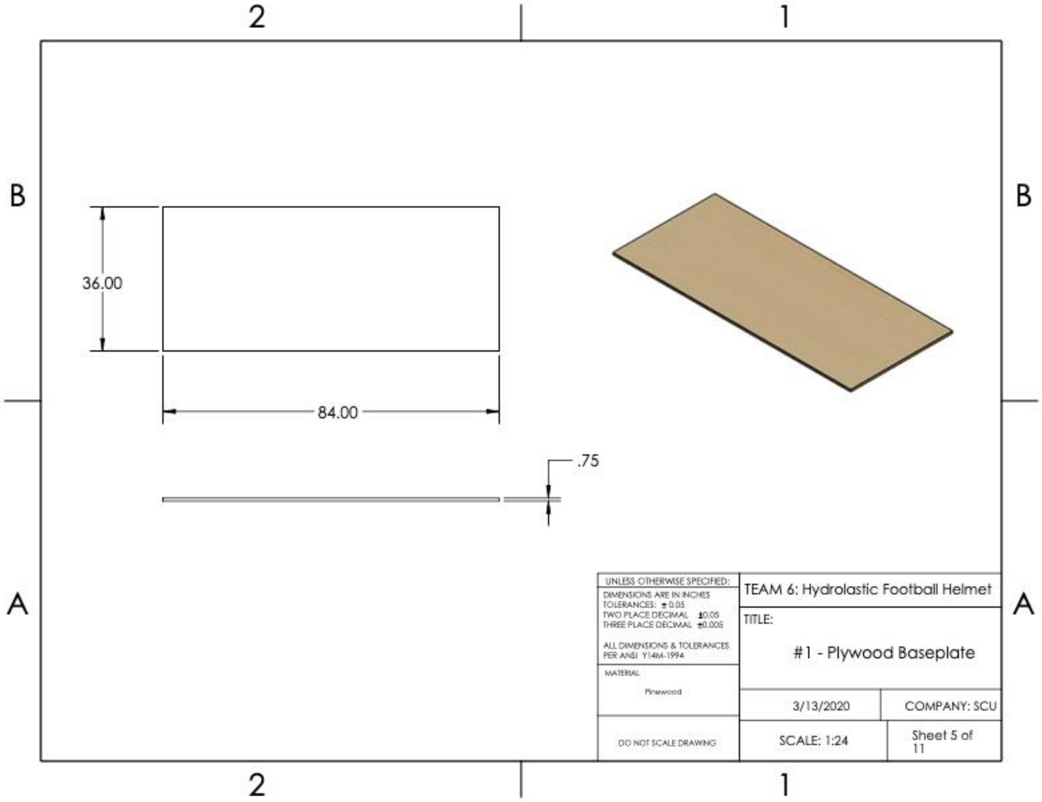


Figure A24. Final CAD drawing of the baseplate.

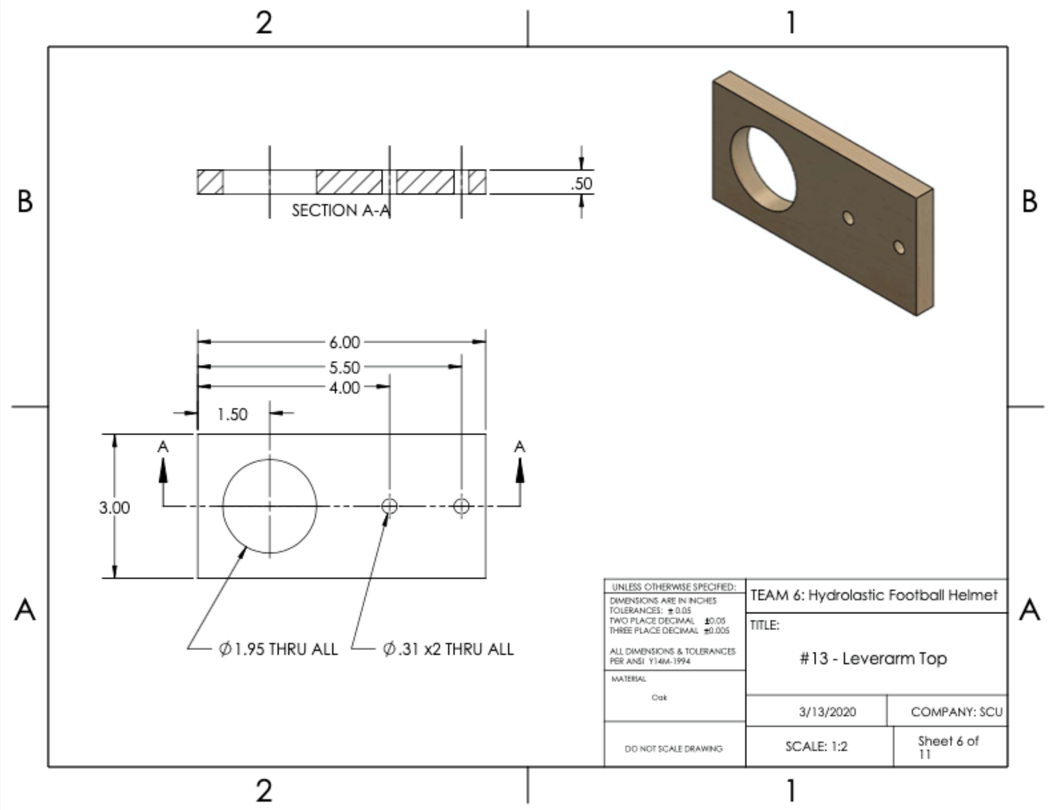


Figure A25. Final CAD drawing of the wooden bearings to support the pendulum mass.

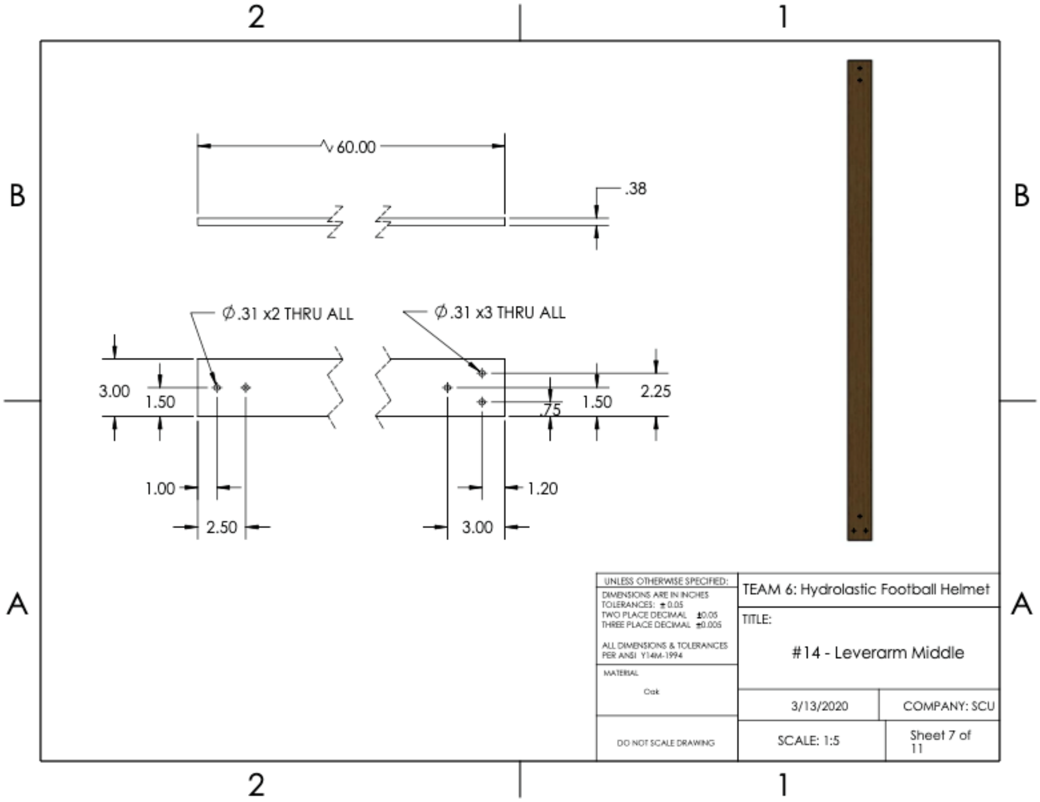


Figure A26. Final CAD drawing of the machined pendulum arm.

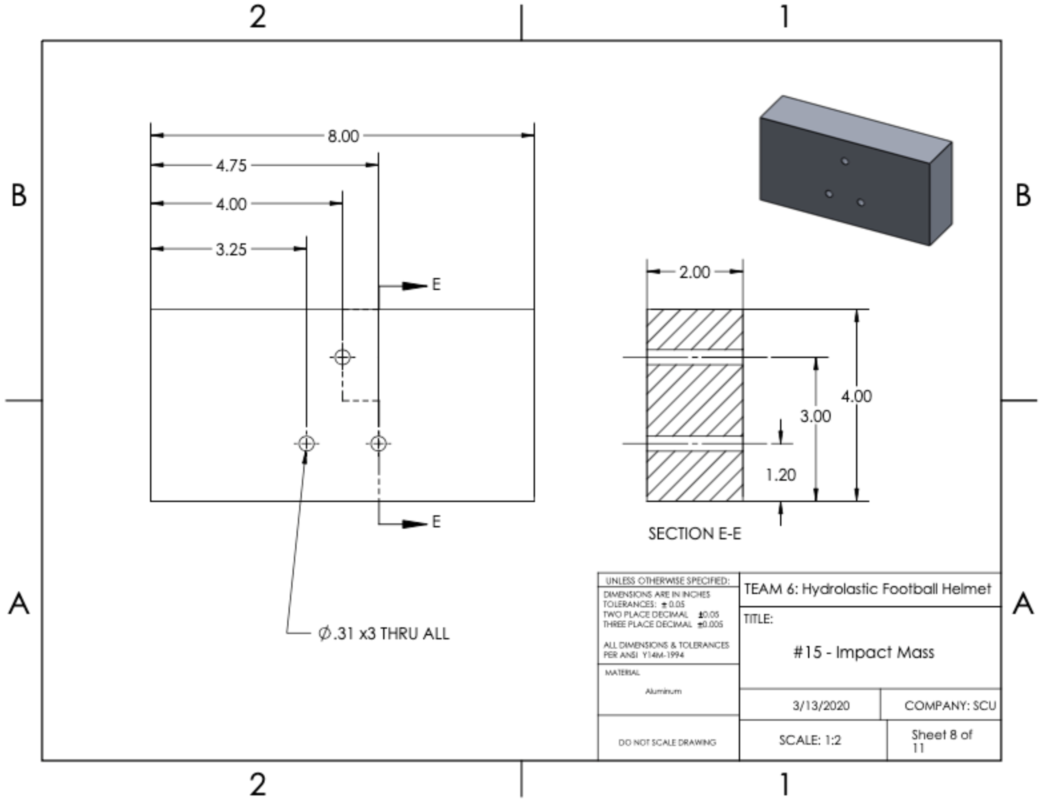


Figure A27. Final CAD drawing of the aluminum impact mass.

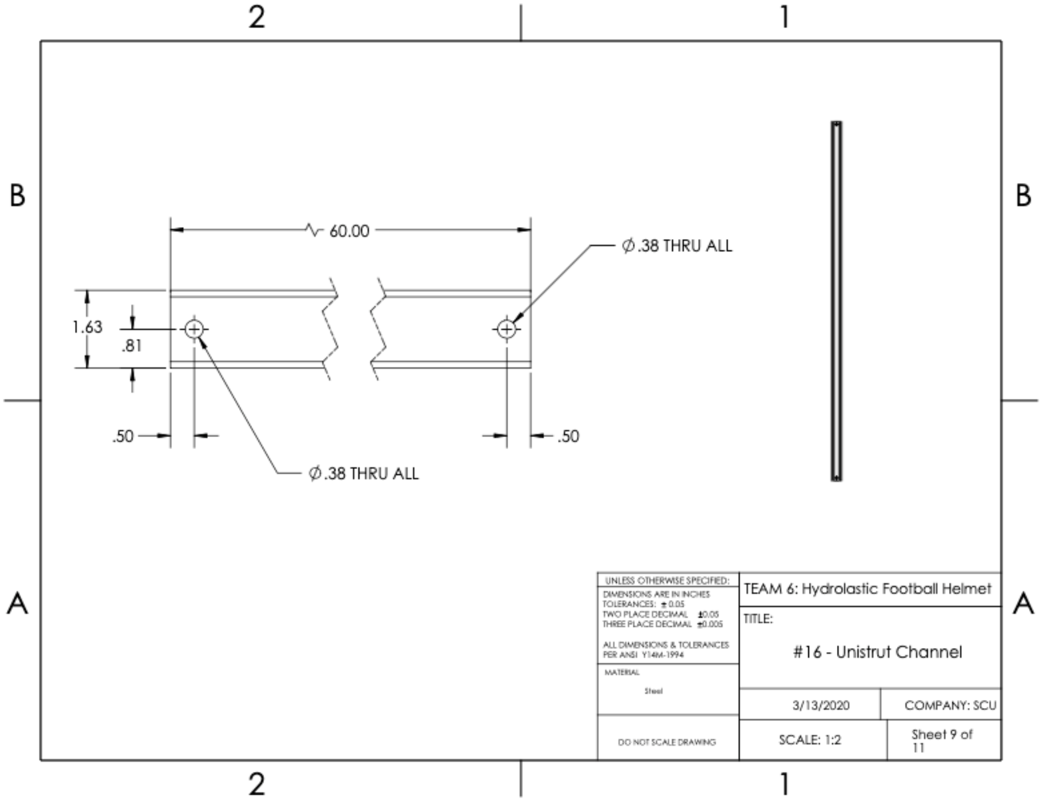


Figure A28. Final CAD drawing of the machined Unistrut channel.

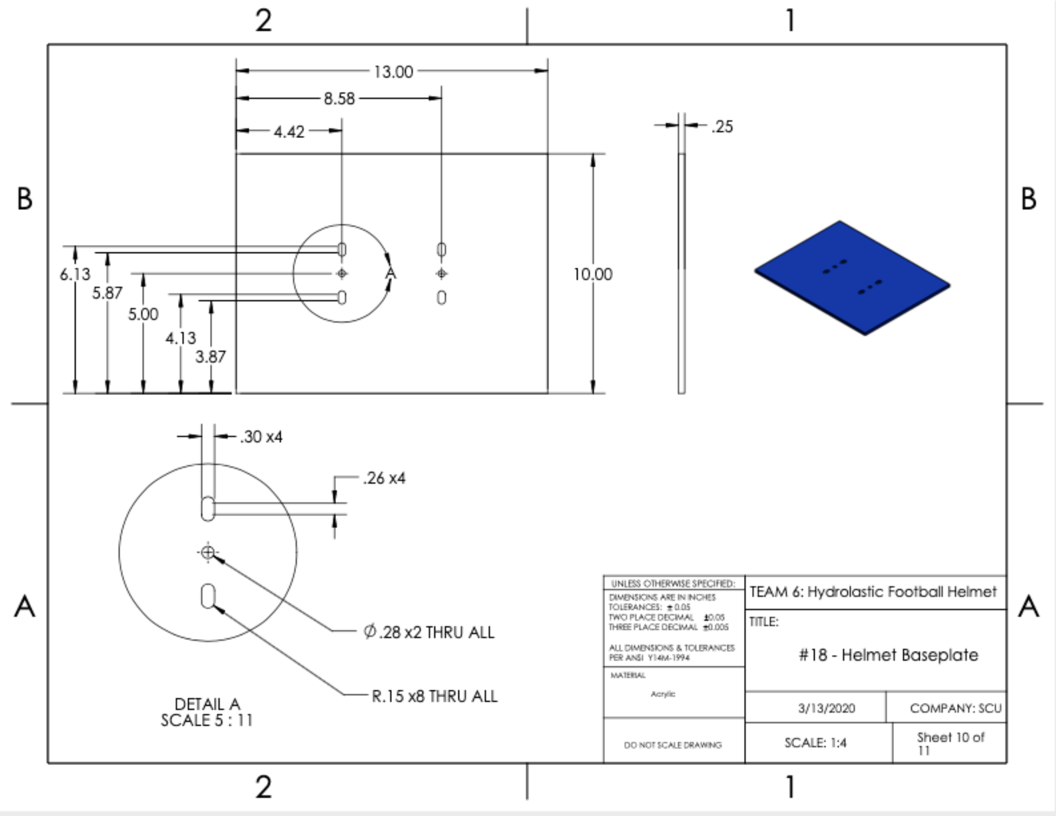


Figure A29. Final CAD drawing of the helmet baseplate.

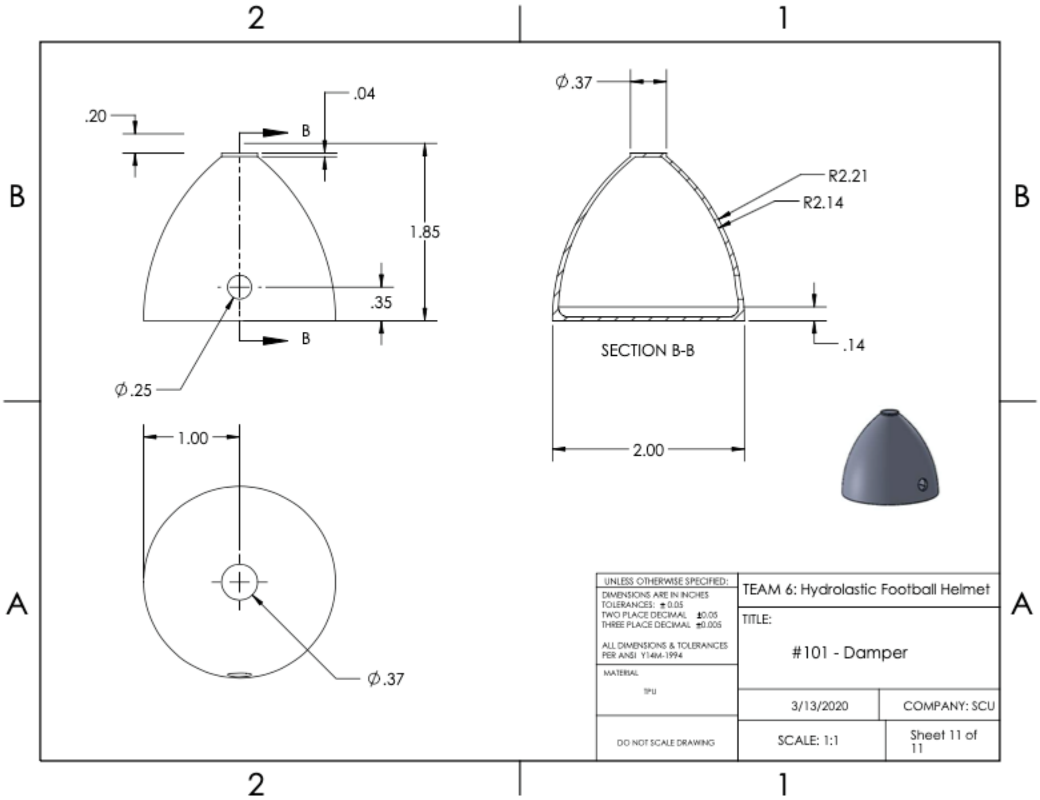


Figure A30. Final CAD drawing of the 3D printed damper.