# Reducing Head Injuries - Catchers Helmet

A MAJOR QUALIFYING PROJECT

Submitted to the Faculty of
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in partial fulfillment of the requirements for the
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in
Mechanical Engineering

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## Abstract

Concussions are a prominent issue within most sports. Our project focuses on creating a catcher's helmet that will reduce head injuries and keep athletes safe. Our design replaces the foam used in current helmets with nonlinear springs attached to the face cage as well as nonlinear springs within the helmet itself. These changes allow for greater displacement of the impact on the helmet, and therefore by the work-energy theorem, greater force is absorbed by the helmet as opposed to the athlete's head. On the exterior of the helmet, we explored different materials of the shell and coatings that would reduce the overall weight and torsional forces. This helmet is promising for reducing head injuries and keeping athletes safe, without impacting performance.

## Authorship

Josh Herlands, Austin Lindner, and Doug Rives contributed equally in the completion of this project and report.

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## Executive Summary

The focus of this project was designing and creating a catcher's helmet that would reduce concussions and head injuries. In order to help resolve this issue, we began developing a design for new technology inside of the helmet by utilizing Constant Force Members (CFM) in replacement of the standardized polyester foam. The CFM's use the work-energy theorem and improve performance upon the force absorbed compared to the impulse.This technology would be able to be applied to many other styles of helmets beyond baseball and benefit other sports or activities that require a helmet.

We began by using Axiomatic Design process, which allowed us to identify functional requirements and design parameters based on the customer need. We could then break down all possible solutions and determine which one would be able to satisfy the most amount of requirements. Once the design decompositions were created for both the overall catcher's helmet and CFM, we were able to begin prototype manufacturing. The prototyping process consisted of 3D printing and a series of iterations to create the desired outcome. The project involved many aspects, including the outer shell, CFM, head band, face cage, and Euler's columns. Overall, our project successfully accomplished several goals: Successfully integrating a non-linear spring into a helmet to reduce risk of traumatic brain injuries, reducing the usage of foam within the helmet compared to similar models on the market, and maintaining the performance of the player.

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# 1. Introduction:

## 1.1 Objective

The objective of this project is to design and create a catcher's helmet that will reduce the risk of concussions from a baseball or a bat. This helmet will not inhibit the ability of the player to perform.

## 1.2 Rationale

Our product was developed with intentions of reducing the number of baseball players receiving concussions and reducing impact loads and rotational forces. Further, the technical advancements can spread to other applications and protect more people from injuries. With over 2.4 million kids playing Little League in more than 80 countries, it is important that these young players have the best protection as they learn to play the game (Little League, 2018). After these players graduate from playing Little League, around 490,000 people continue on to play in high school (NCAA, 2018). While the players are more mature their brains have not finished developing, making concussions more severe.

This catcher's helmet can also be useful to the professional level player/ every player representing the investment by their organization. For instance, when a player is diagnosed with a concussion in the MLB, they are required to go on the seven-day disabled list (Press, 2011). Each day that the player is unable to compete, organizations does not receive a large amount of the value of what they pay for. The Giants, who pay Buster Posey, the highest salary of any catcher in the MLB, stand to lose $958,000 if he misses seven games by going on the disabled list with a concussion (Spotrac, n.d.).

With a need for a better catchers helmet, both at the amatuer and professional level, there is a large market that would benefit from our design. The helmet will help young players that are developing mentally continue proper growth.  Major league players would need the helmet to keep them in the game for a longer time. No matter the level, the helmet would be beneficial to any ball player.

**1.3 State of the Art**

The National Operating Committee on Standards for Athletic Equipment (NOCSAE) is responsible for the research and development on injury prevention for athletic equipment and headgear. Before each catchers helmet can be certified for most leagues and become certified for game use, it must pass both a projectile and a drop test. For instance, when the helmet undergoes a drop test, the helmet is oriented in six positions and during a projectile/ impact test, the headform is oriented in three positions. Testing these different orientations measures the linear head acceleration, which is believed to cause a brain injury. To pass these standards, “no helmet can be structurally altered or damaged during the test and that the SI shall not exceed 1200.” (Standard Performance Specification for Newly Manufactured Baseball/Softball Catcher's Helmet, 2018). If a helmet passes the NOCSAE tests then the helmets are approved for most leagues and baseball games across the country. The NOCSAE standard will be important for passing regulations in many baseball organizations, and must undergo the standard tests.

The Zero1 Football Helmet is a product of $20 million in research and development, and the most impact resistant football helmet available for athletes. The helmet design incorporates system of layers, including a soft outer shell that absorbs the impact and distributes the forces more than the traditional hard plastics. The helmet design is currently only tested for football and military helmets.

The Zero1 football helmet is designed with “a soft outer shell and an underlying layer of columns designed to mitigate collisions from multiple directions,” (ZERO1, 2018). The shells are made up of different layers with each layer serving its purpose. The outermost shell, the Lode Shell is impact absorbing and deforming, similar to a bumper of a car. The next layer, VICIS RFLX, is “a soft outer shell and an underlying layer of columns designed to mitigate collisions from multiple directions,” (ZERO1). The next level is the Arch Shell, which uses “the relationship between head length and breadth measurements” to have the appropriate fitting of the helmet on the players head. Lastly, the Form Liner is to distribute the forces to the head more uniformly. Overall, the difference between the ZERO1 helmet and all other helmets in use today, is the technology between each of the individual layers constructed inside the helmet.

The Force3 Pro Gear is an innovative catchers helmet design that uses springs as a way of reducing impact to the head. This mask has reduced the severity index score by more than 50% over traditional masks (Force3 Catchers Gear, 2018), and has been game worn by major leaguers, Tyler Flowers, Brian McCann, and Salvador Perez. The Force3 Helmet is made with six linear springs and a steel cage that is separated from the mask further than any previous style. The newest product available from Force3, the Defender Hockey Style Mask V2, adds a top bar to the cage of the mask, which is different than any other traditional mask. This additional area increases the chance of contact with the baseball on an location that the force can be absorbed by the springs.

The catchers mask has proven its ability to be one of the safest mask available to players, but there are some disadvantages to this model as well. In comparison to the most popular products worn, the Force3 is much heavier than other models.  The Force3 Hockey style mask becomes distracting due to the overall weight and weight distribution on the head. The spring area and choice of foam/ materials make the helmet weigh more than any of the existing models. As far as the inside of the Force3 Helmet, the foam is non-removable,which makes the overall cleanliness and ability to be washed difficult. The padding covers the catchers ears, which muffles sounds coming from outside the helmet. Lastly, the welding for the mask is not to maximum efficiency, selected metal bars exposed on the outside in comparison to the inside.

Highlighted in Table 1.1 and 1.2 below are the comparisons of the different products that were used to base our design from. As seen in Table 1.1, there is a side-by-side comparison of which technologically advanced helmet addresses limiting direct impact loads, where Table 1.2 shows mostly the physical comparisons of each product.

| Comparison of Products Chart | | | | |
|---|---|---|---|---|
| **Product:** | **ZERO1** | **FORCE3** | **ALL-STAR** | **RAWLINGS** |
| **Limiting Direct Impact Loads?** | Yes - soft outer shell/ foam deformation | Yes - Spring | No | No |
| **Shell Type** | Soft | Hard | Hard | Hard |
| **Weight** | 64 oz | 57.4 oz | 45.2 oz | 43.6 |
| **Inside Helmet** | Non- removable Soft padding/ deformation | Non- removable Padding | Removable Airflow Padding | Non- removable Padding |

Table 1.1: Comparison of Products Chart

| Comparison of Existing Catchers Helmet Products | | | |
|---|---|---|---|
| **Company:** | **Force3 Pro Gear** | **All-Star Sports** | **Rawlings** |
| **Model:** | Defender Hockey Style Mask V2 | MVP4000 | Velo |
| **Advantages:** | - Spring<br>- Absorbs direct impact load | - Titanium facemask option (two-piece helmet ONLY) | - Cheap / Most Known Brand |
| **Disadvantages:** | - Heavy weight<br>- Uncomfortable fit<br>- Unusual Shape Design<br>- Distracting FOV<br>- Spring- bottom out and does not limit direct impact loads | - Traditional style<br>- Does not limit direct impact loads | - Does not limit direct impact loads<br>- Uncomfortable<br>- Cheap materials |
| **Weight:** | **57.4 oz** | 45.2 oz | 43.6 oz |
| **Notes:** | - Safest helmet available<br>- Weight reduction<br>- Not an advantage for catcher | - Lightest catchers mask available | - Weight reduction<br>- Needs to be more comfortable<br>- Cheap and widely available |

Table 1.2: Comparison of Existing Catchers Helmet Products

### 1.3.1 Existing Patents

Included in the figures below are existing patents for some of the helmets analyzed during the State of the Art section. Included in these patents are the Force3 helmet, as shown in Figure 1.1, and the VICIS football helmet, as shown in Figure 1.4, but beyond these two helmets, the technology provided by these other helmets has proved useful as well. The technology presented by a hockey helmet incorporating a linear spring, Figure 1.2, and a fireman's helmet with advancements on the inner/ absorptive layer, shown in Figure 1.3, have all contributed to creating our final design..

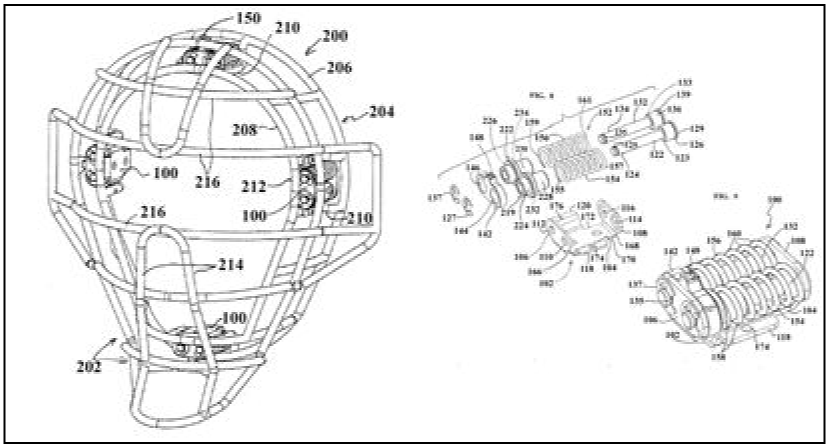


Figure 1.1: Force3 Catcher’s Helmet Patent Art, (Klein et al, 2014)

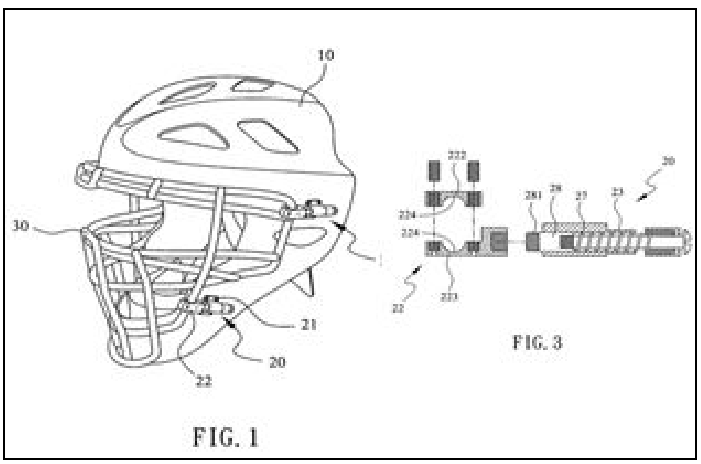


Figure 1.2: Ice Hockey Helmet with Absorbing Spring, (Yu Hsun Enterprise Co Ltd, 2006)

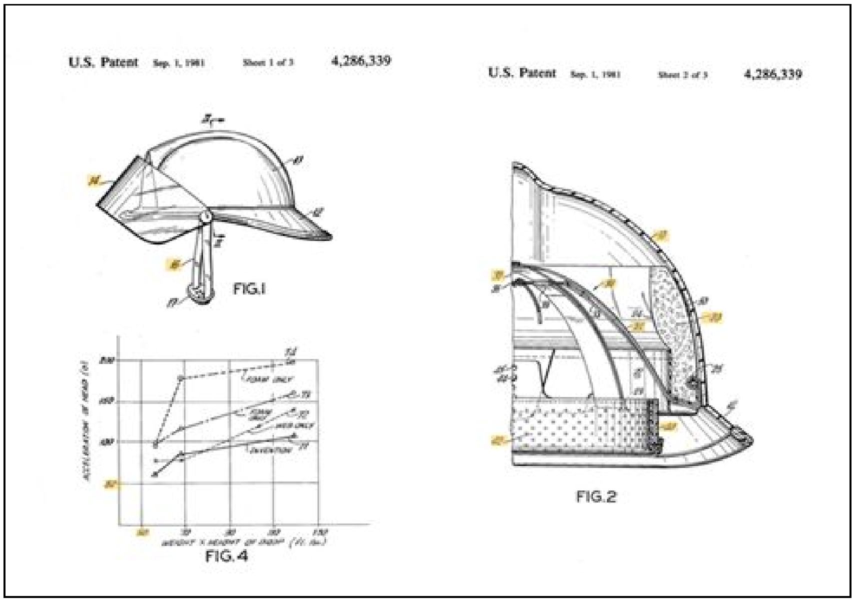


Figure 1.3: Fireman's Helmet Art (Coombs, 1978)

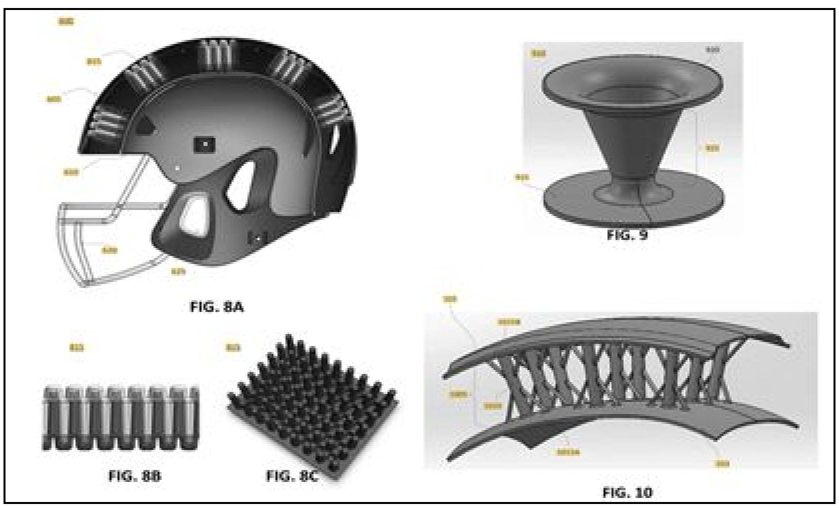


Figure 1.4: Absorbing Structures within a Football Helmet Art (Glover, 2017)

## 1.4 Approach

To create a helmet that helps reduce the risk of concussions when the player endures impact from the baseball or a bat without affecting the player's ability to perform, we have conducted extensive research on existing helmets. Through analyzing the most technologically advanced and most popularly worn helmets, we were able to determine the advantages and disadvantages that each of the helmet provides. Although there are different styles of catcher's helmets, a one-piece (hockey- style) mask, and a two-piece mask, the distribution of forces can equally be applied to each, therefore, we will be creating our prototype based on the one-piece style.

Each helmet has shown different approaches to distributing forces to the head to avoid injury and enhancing the catchers ability to perform. The most research and development has gone into creating the Vicis ZERO1 football helmet. This helmet incorporates different layers, and most importantly, a soft outer shell. This soft outer shell allows deformation and increasing the surface area/ time before impact. Our helmet will be using three layers, an outer shell, an absorptive layer with supports that deform on impact, and then a layer directly in contact with the head, which will be a cap that cover the entirety of the head. These different layers increase the time before impact, as well as dispersing the impacts to a new location on the head.

As seen in the Force3 Pro Gear Helmet V2, the distribution of forces is directly from the deformation of linear springs. The linear spring incorporation can provide a longer time before impact, but when the springs bottom out, there is no difference between a helmet without them. Our helmet incorporates the use of constant force members (CFM) developed by WPI. These CFM's can be mounted in the same positions, but instead of having the springs bottom out, they will deform and increase the time before impact.

Lastly, the All-Star MVP4000, has proven to withstand impacts up to 100mph, which means that the materials used to assemble the mask are strong and durable over time. The All-Star mask has a titanium cage for lightweight and durability. Using this lightweight/ durable material allows the players to be more comfortable when moving their head. Overall, the light weight can increases performance while incorporating a material that is more durable than the current standard.

## 2. Design Decompositions and constraints

We used axiomatic design to decompose our project into functional requirements and design parameters based on the following customer need: The customer needs a helmet that reduces the risk of traumatic brain injury while keeping the user mobile and alert.

### 2.1 Design Process: Axiomatic Design

There are several important areas that absorb force when an object collides with the helmet. Our decomposition is based on impulse absorption in three areas, the facemask, the chin, and the forehead. The reason we focused on impulse is because current products already look at the work-energy theorem to reduce the energy absorbed by the head. By increasing the distance the helmet deforms, energy is absorbed, however, our nonlinear springs also limit the impulse of the collision. Using this theme, we generated the following functional requirements:

FR 0: Limit loads transferred to the head

- FR 1: Limit impulse of impact on facemask
  - FR 1.1: Increase time of impact
  - FR 1.2: Limit radial forces
  - FR 1.3: Limit tangential forces
- FR 2: Limit impulse of impact on chin
  - FR 2.1: Increase time of impact
  - FR 2.2: Limit radial forces
  - FR 2.3: Limit tangential forces
- FR 3: Limit impulse of impact on forehead
  - FR 3.1: Increase time of impact

FR 3.2: Limit radial forces

FR 3.2: Limit tangential forces

From these functional requirements, we accounted for linear and rotational forces, the latter which is more responsible for concussions and other traumatic brain injuries. Further, we also looked to increase the time over which the collision occurs. Because these requirements are present at several locations, we used the forces as children to higher level functional requirements based on the location.

Once we were satisfied with our functional requirements, we created a list of design parameters, shown below.

DP 0: System to limit loads transferred to head

DP 1: System to limit impulse of impact on facemask

DP 1.1: Constant force springs mounted to sides of facemask

DP 1.2: Titanium facemask

DP 1.3: Flat face cage

DP 2: System to limit impulse of impact on chin

DP 2.1: Constant force members between chin and outer shell

DP 2.2: Thin layer of cushion to stop deformation

DP 2.3: Angled constant force members

DP 3: System to limit impulse of impact on forehead

DP 3.1: Constant force members between outer shell and “mesh”

DP 3.2: Carbon fiber outer shell

DP 3.2: Coating on outer shell to reduce friction

These were the design parameters we determined to be the best options for our product. The constant force members were fairly easy to produce and offered more energy and impulse absorption than any other option. The material choices all optimized strength, cost, and appearance. Finally, coating the outer shell to reduce friction maximizes the surface area over which the ball can slip.

The list above contains the design parameters we used, however, they were not all the design parameters we generated. Below is a list of alternative design parameters we considered.

DP 0: System to limit loads transferred to head

- DP 1: System to limit impulse of impact on facemask
  - DP 1.1: Collapsible sides
  - DP 1.2: Soft facemask that is able to deform
  - DP 1.3: Teflon coating on facemask to reduce friction
- DP 2: System to limit impulse of impact on chin
  - DP 2.1: Valve system within chin pad
  - DP 2.2: Hardening foam that because stiffer on impact
  - DP 2.3: Angled constant force members
- DP 3: System to limit impulse of impact on forehead
  - DP 3.1: Deformable members between head mesh and outer shell
  - DP 3.2: Soft outer shell that allows deformation on impact
  - DP 3.2: Angled sides to the helmet that ball would slide off of

These design parameters were not chosen mostly due to our optimization criteria where we wanted to reduce cost and weight. The collapsible sides would need hinges and additional pieces that would complicate manufacturing and increase weight. The soft facemask requires injection molding and would increase the cost. Teflon coating would be better suited for covering the outer shell as it adheres better to non-metals and would cover a greater surface area. The valve system within the chin pad and the hardening foam would increase complexity and increase cost. Angled constant force members could interfere with force absorption in the radial direction. The deformable members and the soft outer shell would increase the cost, and may violate a patent for a football helmet we found in our previous research. The angled sides may create more force if the impact were to come from an unexpected direction, such as a baseball bat hitting the helmet on the hitter's back swing.

Finally, we considered several constraints for the helmet, shown in the figure below.

| | |
|---|---|
| 0 | Other requirements |
| 1 | Selection/Optimization Criteria |
| 1.1 | Minimize weight |
| 1.2 | Minimize Cost |
| 1.3 | Aesthetically Pleasing |
| 2 | Contraints |
| 2.1 | No features that stick out and "catch" impact forces |
| 2.2 | Durable |
| 2.3 | Low Maintenance |
| 3 | Non-functional Requirements |
| 3.1 | Not interfere with play |

Figure 2.1: Additional Considerations for Design Decomposition

## 2.2 Design Decomposition

| # | [FR] Functional Requirements | [DP] Design Parameters |
|---|---|---|
| 0 | Limit loads transferred to head | System to limit loads transferred to head |
| 1 | Limit impulse of impact on facemask | System to limit impulse of impact around facemask |
| 1.1 | Increase time of impact | Constant force springs mounted to face cage |
| 1.2 | Limit radial forces | Titanium face cage |
| 1.3 | Limit tangential forces | Flat face cage |
| 2 | Limit impulse of impact on chin | System to limit impulse of impact around chin |
| 2.1 | Increase time of impact | Constant force members between chin and outer shell |
| 2.2 | Limit radial forces | Thin layer of cushion to stop deformation |
| 2.3 | Limit tangential forces | Angled constant force members |
| 3 | Limit impulse of impact on forehead | System to limit impulse of impact around forehead |
| 3.1 | Increase time of impact | Constant force members attached between outer shell and inner "mesh" |
| 3.2 | Limit radial forces | Carbon fiber/polyurethane outer shell |
| 3.3 | Limit tangential forces | Coating on shell to reduce friction |

Figure 2.2: Design Decomposition for Overall Helmet

Although we used this specific constant force member in our design, we also considered using pneumatic, hydraulic, and electromagnetic devices to absorb the impact forces. Our design options are shown in figure above.

| # | [FR] Functional Requirements | [DP] Design Parameters | FR Measurement |
|---|---|---|---|
| 0 | Choose best design for constant force member | | |
| 1 | Absorb force by displacing | | |
| 1.1 | Resist by mechanical | | |
| 1.1.1 | Displace at constant rate | Changing pitch/diameter spring | |
| 1.1.2 | Displace circumferentially | Surgical tubing/ elastic material | |
| 1.1.3 | Displace rotationally | Tape measure | |
| 1.2 | Displace using valve system | Container that lets out substance through | |
| 1.3 | Dispalace using compressible fluid system | Fluid-Sac system | |
| 1.4 | Displace using electromagnetic system | Magnets with same polarity | |
| 1.5 | Displace using pneumatic system | Air pressure | |
| 2 | Return to original position | | |
| 2.1 | Return by material properties | Metal rotational stiffness | |
| 2.2 | Return using electrical/mechanical component | Air/Fluid pump | |
| 2.3 | Return using gravity | Angle spring so that gravity pushes it back | |
| 3 | Connect shell and head | | |
| 3.1 | Connect with rigid member | Rigid post, string, screws, grommets | |
| 3.2 | Connect with dynamic piece of member | Piston attached directly to shell | |

Figure 2.3: Design Decomposition for CFM

Further, to decrease friction within the constant force member, we considered lubrication as well as a series of wheels along the inside of the casing to use rolling friction within the constant force member. Another consideration we had was to use linear springs in conjunction with the constant force member to further reduce the force transferred to the head. Moreover, because we've had some difficulty in returning the constant force member to its original position, we used a secondary eyelet located at the thick end of the torpedo where a preloaded linear spring can be attached to return the torpedo to the starting position. Finally, although these constant force members are tensile, compressive members are also feasible options for our design.

# 3. Physical Integration

## 3.1 Conceptual Design

The helmet consists of a hard outer shell, made out of a hard plastic, as with current helmets, or a composite, such as carbon fiber and epoxy, and a fabric cap that fits snugly around the head, and a series of springs connecting the two, oriented and arranged to adsorb impacts and provide performance. The springs could be linear, preloaded linear, nonlinear or preloaded nonlinear. The latter could approximate constant force or be tunable to adjust the load displacement relations between the outer and inner layers for performance and protection.

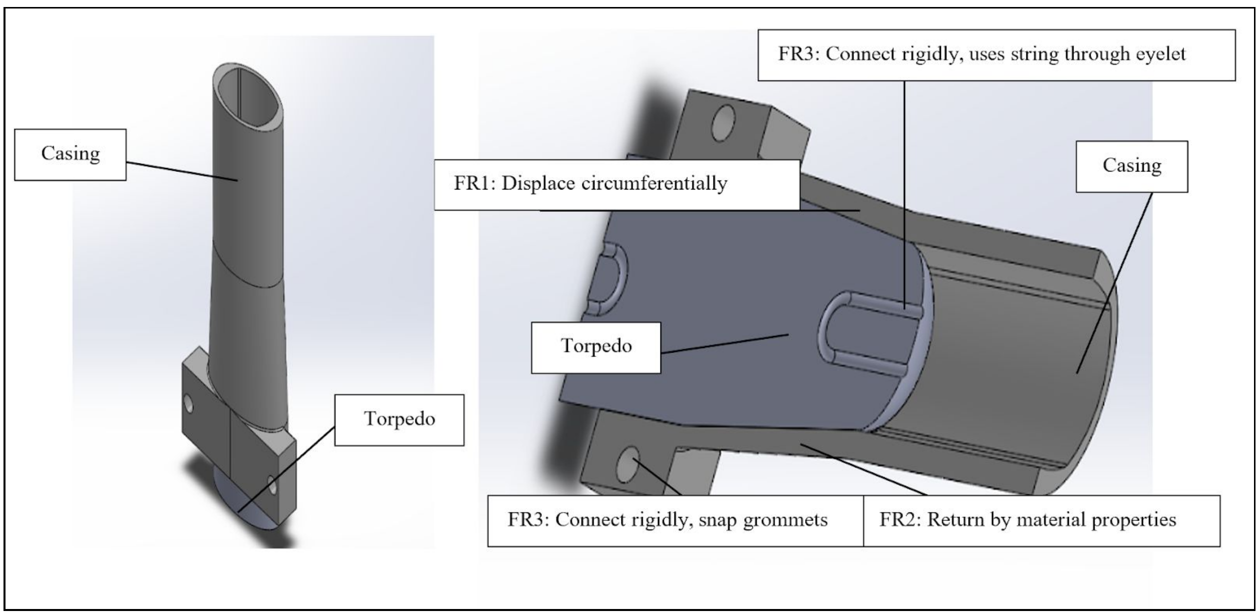


Figure 3.1: 3D Model of CFM

Figure 3.1 above shows the major concepts of the constant force member. The label showing FR 3 shows an eyelet where fishing line is attached, and the holes where the snap grommets attach the outer casing to the headband of our helmet. This allows the torpedo to pull through the outer casing and create the deformation we want. Further, the taper (labelled as FR1) causes the circumferential displacement which absorbs the forces of the impact. The taper also pushes the torpedo back into the starting position because of the change in size.

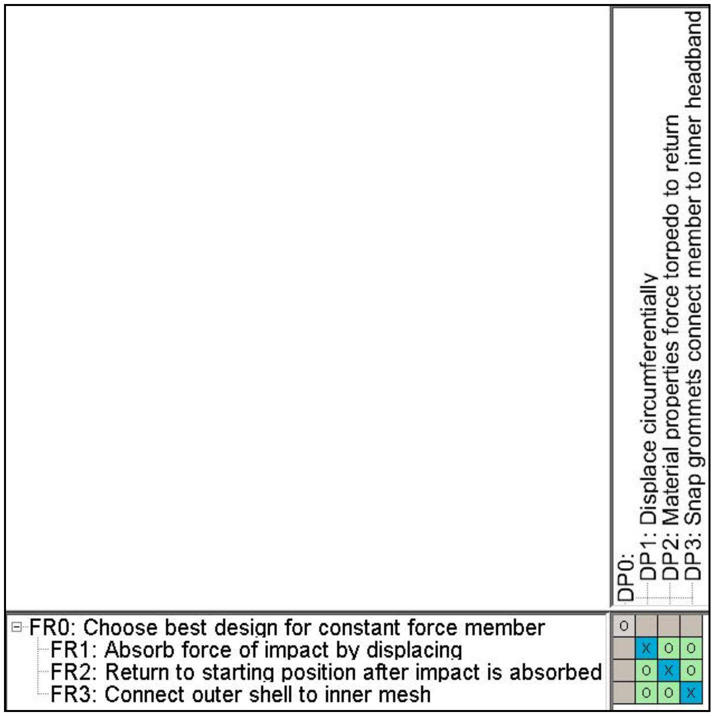


Figure 3.2: FR-DP Matrix for CFM

As seen in Figure 3.2 above,, the constant force member we designed is mutually exclusive. The sides of the constant force member ensure that the torpedo only returns to our starting position due to the material properties of the outer casing. Several of our previous designs had difficulty with this, and would return due to linear properties of the spring itself.

In order to increase the time after impact before the constant force members inside of the helmet is used, we added a nonlinear spring to the face cage. With the help of a newly developed nonlinear spring, The Goats Head Spring, would be able to act in with a constant force. The Goats Head Spring is shown in Figure 3.3 below and connects to the catcher's helmet by attaching the spring to the face cage and outer shell.

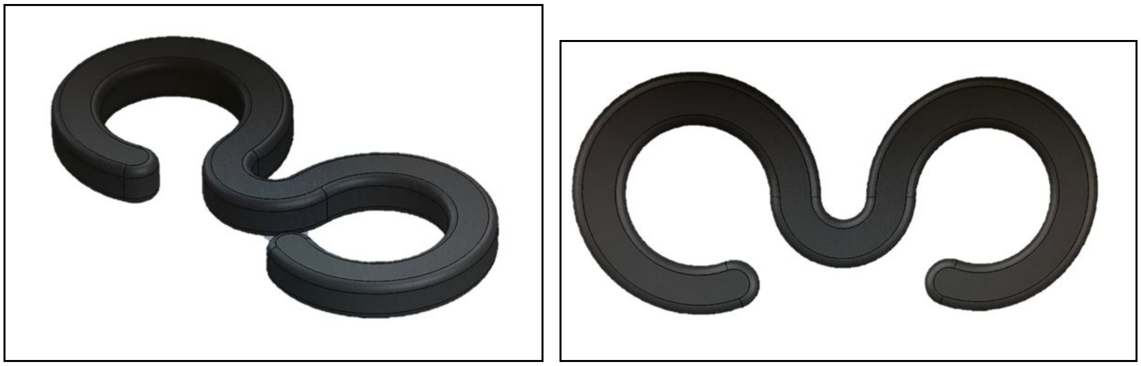

Figure 3.3: WPI's Goats Head Spring

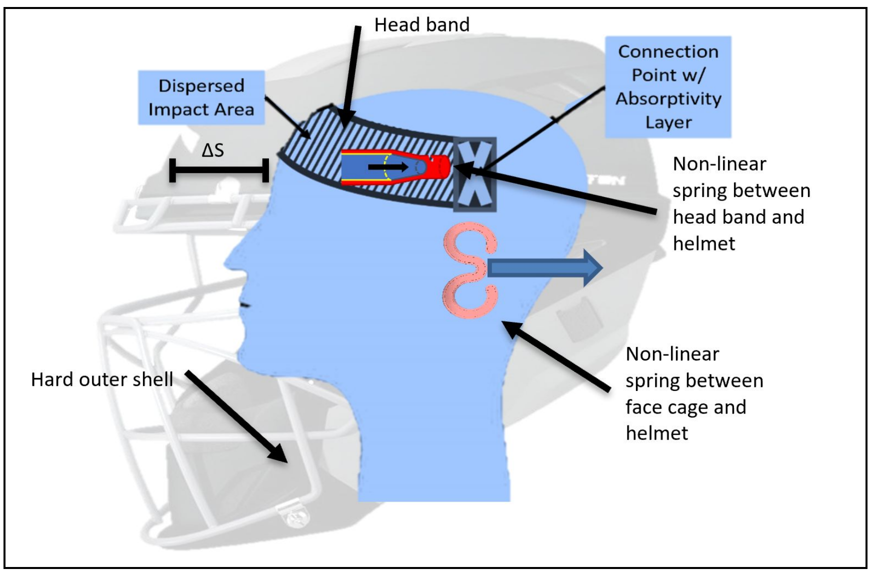


Figure 3.4: Helmet Model with Nonlinear Spring Locations

We focused on the displacement of the helmet relative to the player's head during impact, as this displacement will reduce the head acceleration. Our first physical solution is a constant force or tunable force, i.e., nonlinear, spring attached the front cage of the helmet which displaces when the ball strikes the front of the mask. Our next solution uses constant force members as the interface between the helmet's "shell" and an elastic band in contact with the player's head. The constant force or tunable force members reduce the force transferred to the band and therefore limit the acceleration of the head. Compared to a linear spring, the nonlinear absorb impacts at higher, safer loads, potentially doubling the energy that can be absorbed by the spring.

### 3.1.1 Material Selection

The material selection for this helmet became important and changes the overall quality and results of the final product. The selection of material came down to choosing the most manufacturable and most appropriate material for its use. Table 3.1 below highlights the materials used for each of the corresponding parts of the catchers helmet.

| Comparison of Materials | | |
|---|---|---|
| **Facemask Material** | Titanium | Steel |
| **Facemask Coating** | PTFE coating | Powder coating |
| **Color** | Matte Black | |
| **Springs** | Constant Force | Linear |
| **Outside Shell Material** | Carbon Fiber | Plastic |
| **Outside Shell Coating** | PTFE Coating | |
| **CFM** | Rigid “Torpedo” | |
| | Flexible Casing | |
| | Silicon Lubrication | |
| | Fishing Line | |
| **Third Layer (contact with head) Material** | Elastic Headband | |
| **Chin Pad** | Foam | |

Table 3.1: Comparison of Materials

Surface Friction:

The static coefficient of friction of leather and metal is 0.6 (Static), (Engineering Division, Berkeley Lab, 2007). With PTFE coatings, the static coefficient of friction can be reduced to 0.10 - 0.15 (PTFE Coatings, 2016), which can be applied to facemask and outside shell materials. For an effective design, a lower static coefficient would be ideal, therefore PTFE coatings on the face cage and outer shell would be beneficial.

Face Cage Material:

The face cage material is important for creating a product with the best performance. The current options for materials include carbon steel, stainless steel, and titanium. Titanium is the ideal choice for a material and will allow athletes to move their heads faster, because it is 60% lighter and stronger than traditional masks made of carbon and stainless steel. Other sport helmets currently use titanium face cages that are coated with a thin plastic layer.

Face Cage Coating / Color:

The current standard is a powder coating method. The powder coating method creates a smooth, and durable coating that is applied through a heating process of the paint. The end product results in a hard gel that is bonded with metal and creates an extremely durable layer of protection. The preferable color choice would be black, because it would reflect the least and be the least interfering to the players vision. A coating with a lower frictional coefficient is a PTFE coating. This coating is applied to metals such as Aluminum, Steel, Titanium, Stainless Steel, Brass, and select plastics, in order to reduce the static coefficient of friction between 0.12 - 0.15 and dynamic coefficient of friction between 0.05 - 0.10, which only adding 0.002” of thickness and minimal weight. (PTFE Coatings, 2016).

Outside Shell Material:

A lightweight, and tough material is needed. The outside shell will receive impacts beyond 100 mph and the helmet must be durable enough to withstand these conditions. The standard catcher's helmet is made of plastic, but carbon fiber has significant advantages. Carbon fiber and plastic are comparable in weight, but the durability and reduction of vibration are major reasons why carbon fiber should be the first material of choice. Carbon fiber can provide the durability, strength and lightweight needed in the outer shell of the helmet. Both of these materials are comparable and provide no significant differences.

Outside Shell Coating:

Along with the materials for the cage, the materials for the outer shell should be similarly chosen. The outside coating can reduce the rotation of the head after contact with the ball. There is no coating used on the existing helmets, but PTFE/ Teflon coatings will decrease the coefficient of friction between the outside shell coating and the leather of the ball.

Absorptive Layer:

This absorptive layer uses a rigid torpedo shaped plastic inside a well lubricated flexible casing. These supports will connected from the impact areas of the shell to the sides of the headband using a strong adhesive or screws.

Third Layer (Contact w/ Head) Material:

An integrated headband is used for the third layer. This is made of elastic material surrounding plastic, which is adjustable for the specific players need.

### 3.2 Final Design

Figure 3.5: *Catchers Helmet Prototype Front View*

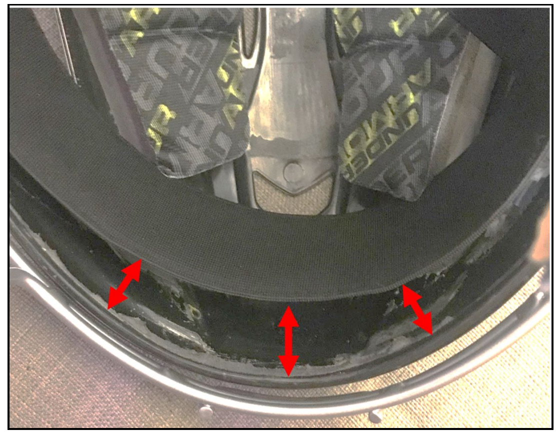

Figure 3.6: *Dispersed Impact Area on Prototype*

Shown in Figure 3.5 above is the final prototype helmet for our project. Shown above is the incorporation of the CFMs, headband piece, nonlinear springs (Goats Head Springs), and Euler's columns. The prototype was created by using an existing outer shell of a helmet and applying our modifications. Shown in Figure 3.6 the red arrows highlight the space created between the outer shell and head band piece, which allows for the increased dispersed impact area ($\Delta s$) needed for the CFM.

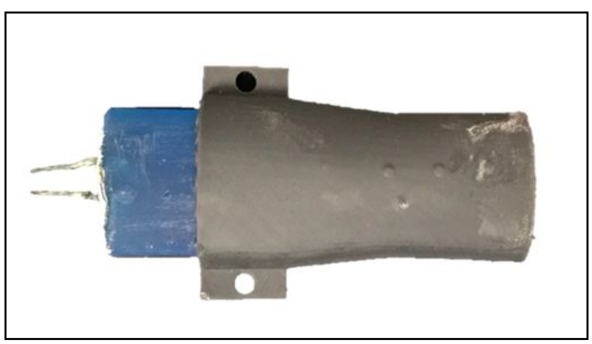

Figure 3.7: *CFM Prototype*

In Figure 3.7 above, the CFM prototype that was integrated into our helmet is shown. This CFM was created on a SLA printer from the conceptual design shown in Section 3.1 of this report. The CFM was modified after multiple shape and material designs.

Figure 3.8: *Headband Prototype Front View*

Figure 3.9: *Headband Prototype Back View*

In Figure 3.8 and Figure 3.9 above is the headband prototype for our helmet. The headband was incorporated into the standard back piece for a catcher's helmet. Two holes were drilled into the back piece and then a thin plastic band was created for adjustable head sizes. This headband is adjustable for any size head while still allowing room for the CFM, as shown in Figure 3.10 below.

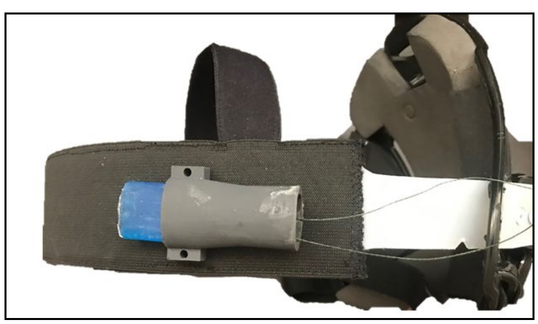

Figure 3.10: *Headband Prototype with CFM Integration*

Shown in the red box in Figure 3.11 below is the Euler column used in the our prototype helmet. The Euler's columns were created from latex tubing and polyester foam. The prototype fits within the helmet and fits snuggly, but comfortably on the players face.

Figure 3.11: *Euler's Columns Prototype*

# 4. Prototype production

## 4.1 Final Design Process

In the final design, the CFM's within the helmet were created using 3D printers. A SLA printer was used as the ideal choice to acquire a better surface finish for the torpedo and casing. The accuracy and the efficiency of the printer allowed for testing different design concepts and determine which design performed the best. This allowed us to test different overall torpedo lengths as well as the steepness of the taper. The steepness changed the speed of the force dispersion and its ability to return. Printer allowed for creating our prototype in different materials, and then test each material to see which would be ideal for the specific use. Using the printers, the torpedo and casing were able to be made quickly.

The inner headpiece was sewn together using an elastic material wrapped around plastic which was attached to adjustable notches. The headband is integrated into the back shell of a standard catchers helmet. The CFM would then be able to mount to the headpiece by sewing them into both sides of our elastic. The torpedoes were lubricated using silicone lubrication and were then placed in the CFM casing and the string within the piece is attached to the outside of the shell of the helmet.

The face cage would be attached to the shell using WPI's Goats Head Springs. These nonlinear springs are 3D printed and are able to withstand high impact and are extremely light weight. These springs mount to the shell itself and to the cage as well using screws.

On the interior side of the shell, the Euler's columns were mounted. These were created using generic foam that other helmets also utilize. Attached to the foam, using standard adhesives such as super glue, surgical tubing was attached to the foam as well. The surgical tubing was cut to the same length as the foam. Once the tubing and foam were fully cured, the columns were mounted to both sides of the helmet where the jawline would be. This would be completed using the same adhesive using to complete the column.

To provide comfort and keep a proper distance from the shell and head, a strip of standard foam was applied using super glue. Once dried, the prototype would be completed by attaching the headband to the outer shell. The clips were snapped into place and the pieces would hold together securely.

**4.1.1 Final Design Material Selection**

The first material we tested was named Tango Plus, a flexible material that would be able to return to position when no force was applied. This could not be used as it was too flexible. It would not be able to resist the forces that the helmet would have to endure. The materials that we selected for our final design named Flexible Black. This material, while sturdy, was able to bend in the proper directions that we desired. To create the torpedo, either Rigid White or Rigid Blue were used. Both were the same material, just had different colors. This material was firm and able to expand the base and hold its figure through any force that it would endure.

| Material Selection for Final Prototype | |
|---|---|
| **Part** | **Material** |
| Base of CFM | Flexible Black |
| Torpedo | Rigid Blue |
| Head Band | Elastic<br>Plastic Band<br>Catcher's Helmet Piece |
| Euler's Column | Foam<br>Surgical Tubing |

Table 4.1: *Material Selection for Final Prototype*

## 5. Testing of the final design

In order to test many of the designs, we lubricated both the base and torpedo of the CFM. We attempted pushing the torpedo through the base in order to see if the base expands. After this was completed, the torpedo would be pulled out. If it was difficult to pull the piece out, we could determine that materials did not work well together or a difficult lubrication needed to be attempted. To test the other aspects of the helmet, we would test for comfort. We were able to do this with other models of catcher's helmets as one of our group members is a collegiate catcher. Having many years of experience with the position, he was able to give valuable information and opinions as to how the helmet functioned and how comfortable it was. He was able to use an All-Star Helmet and the Force3 helmet during practices and games. Unfortunately, due to not having any certifications to be game ready, he was unable to wear it at any practices or in any games. All of the group members were able to try the helmet on and give their own opinion of how the helmet felt, and it was agreed that the helmet was comfortable and could easily fit all of the varying head sizes.

## 6. Iteration

While testing our designs, we made many minor modifications to better our final product. The first modification that was needed was creating a piece to mount our base. We were able to extend the sides of the base and place holes in it to create a place to apply pieces to mount to the headband. Once that was added, the inside of the base was adjusted. Through multiple different attempts, we tested pieces with longer bases and altering how steep the slopes are. Changing how our long the piece was allowed us to increase the time of impact. Helping to decrease any momentum from the impact that occurs, the steepness of slope on the interior of the base will allow this to be altered. The steeper slopes slowed the forces down at a higher rate, while a gradual decrease allowed for the impact to be absorbed at a much slower rate. This dispersed the most amount of force as possible. With so many angles to test, we went through many different iterations with minor design changes to test. Other modifications that were made was the type of material that we were utilizing. As previously discussed, we tested a material called Tango Plus. Our next attempt, we used Flexible Black and saw much better results. It was a bit sturdier allowing it to return back to its original shape quicker and would resist the force at a better rate.

## 7. Discussion

Our design, although lacking in many areas, made progress towards increasing the safety of the helmet's user. Primarily, the prototype is incomplete and requires further research into material selection and integration into the helmet. The design method, however, was fairly strong, with little overlap in the functional requirements and design parameters as shown by the design matrices. Therefore, there are several improvements that can be made to the design.

First, designing the prototype itself was difficult because the 3D printers on campus did not have materials with the correct properties. Original prints of the constant force member ripped because they were too stiff to handle the rapid expansion of the torpedo travelling down the casing. Further, the Goats Head Spring mounted to the face cage was brittle, and shattered when we testing it. Due to the brittle material, we were unable to properly mount the Goats Head Spring to the helmet, and rather, used a strong adhesive to show the location of where it would be located on a finished model.

The design process was much more successful as we did not need a full range of materials. As you can see from Section 2.2, a thorough decomposition was done of the helmet to ensure all possible solutions were accounted for before we selected design parameters for our project. Not only did we account for the decomposition of the helmet, we also considered a decomposition for the constant force member (shown in Figure 2.3), as it was the most significant component of the helmet. When implementing into the design process, manufacturing a scale prototype was fairly simple, as most obstacles were solved during the design phase, but the implementation failed due to lack of resources and materials as said before.

In terms of constraints, further testing can be done, although we believe that all are met with our design. Because we used a shell that is already on the market, the durability is still the same as all other models. Further, because the constant force member is self-reloading, little maintenance is required for the helmet. The largest constraint that we missed was the features that stick out and "catch" impact forces. Our face cage was taken directly from an existing model, so there are bars that will increase the impact force as opposed to letting the ball slide off. With more time, however, we would be able to manufacture our own cage that would fit within this constraint.

Our helmet, when complete, should reduce traumatic brain injury risks in multiple fields. First responders going into dangerous areas wear helmets with conventional foam, however, if non-linear springs were properly integrated into the helmet design, the risk for head injuries would be reduced. Furthermore, concussions in athletics, a common occurrence, will hopefully drop as a result of better technology and impact absorption.

From our prior art, most patents use linear springs or foam to protect the head from large impacts. The use of nonlinear springs, which can act as constant force, or tunable force, members integrated into the helmet greatly reduce the risk of concussion compared to the standard catcher's helmet. The current models only use cushions or foam padding inside the helmet which acts as linear springs, and as the impact velocity increases, the effectiveness of the springs becomes significantly lower.  In addition, the use of foam causes ageing and the foam must be replaced and is currently unrecyclable, therefore making our invention more sustainable than current helmets. As there are many companies that are competitively trying to create a safer helmet, we believe that this commercial use would extend to companies such as Adidas, All Star, Bauer, Easton, Force 3, Mizuno, Nike, Rawlings, Riddell, Schutt, STX Lacrosse, and Under Armor.

## 8. Conclusions

Our project accomplished several goals: Successfully integrating a non-linear spring into a helmet to reduce risk of traumatic brain injuries, reducing the usage of foam within the helmet compared to similar models on the market, and maintaining the performance of the player. As shown in Section 3.2, the constant force member was attached to the headband, and the Goats Head Spring was mounted to the outer shell and face cage. This headband limited the foam required for our prototype, as it fit securely on the player's head and was connected to the outer shell. The only foam was used on top of the player's head for comfort, and along the cheekbones to prevent rotation while the player turned their head. The foam attached to the outer shell along the cheekbones maintained player performance as it allowed rapid movement while keeping the face cage directly in front of player and not blocking vision at any point. Further, the lack of foam reduced the weight significantly, keeping performance levels up.

### 8.1 Significant Findings

Throughout the design process, we found that a non-linear spring should reduce the total force absorbed during an impact with the player's head. While this correctly uses the work-energy theorem, we improved upon the design by implementing CFM's. The non-linear springs also use the work-energy theorem but additionally improve upon the force absorbed compared to the impulse. Because the slope of a non-linear spring can be tuned, we are able to lower the maximum force level while absorbing the same amount of impulse. The integral of the force time curve will have the same value, however, because the graph is not linear, the highest point on the y-axis will be lower than a linear spring, therefore limiting the force absorbed by the user.

**8.2 Future Progress**

If we were to pass along this project to another group, some of the tasks we would supply the would be to continue testing more types of materials for both the torpedo and base. While we were able to find the best ones that were available to us, there are many more that the school does not have immediate access too. Another task that would be finding a new way to create the shell of the helmet. This way, better materials could be used to create a stronger, lighter prototype. The last task for the design would be to creating a better face cage. Whether this be the overall design of the how the cage is made or which material would be used. This would complete the necessary changes to the design of the helmet.

Once the final prototype is created, proper testing would need to be done on the helmet. This would include things such as applying sensors to the helmet and to a mannequins head that withstands the same force as a humans head. There would be forces applied in different directions and at stronger and stronger forces. After these measurements, the torsional forces would the need to be calculated in order to determine if higher forces would cause concussions. This would cover the necessary tests that would need to be measured.

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## Appendix A: Prototype Attempts

To create the prototype, there were many different methods that were tried and used. During our initial designs, we used a lathe to thin the torpedo along with creating the tapered ending. Once the shape was properly made, the lathe could also allow us to create threading on the torpedo. This would allow us to  If the torpedo needed any adjustments, fine sandpaper was used. A hacksaw was used to cut the piece to proper lengths. A thin hole was drilled in using a drill press so that fishing line could be put through it.

Began with other 3D prints

1. **Idea 1**
   - 1.1. 2mm ID x 4mm OD Surgical tubing outside ⅛" ID x 3/16" OD vinyl tubing
   - 1.2. 3 mm diameter Delrin Torpedo
     - 1.2.1. Lubrication
     - 1.2.2. Adhesive between Delrin and surgical tubing
     - 1.2.3. Threaded vs. Unthreaded Torpedo
   - 1.3. Reasons for failure
     - 1.3.1. Acting as linear spring
2. **Idea 2**
   - 2.1. 3mm ID x 6mm OD Surgical tubing outside ¼ " ID x 3/8" OD vinyl tubing
   - 2.2. ⅕" diameter Delrin Torpedo
     - 2.2.1. Lubrication
     - 2.2.2. Fishing line to connection
     - 2.2.3. Threaded vs. Unthreaded Torpedo

2.3. Reasons for failure

2.3.1. Difficulty on having the torpedo return

**3. Idea 3**

3.1. 3mm ID x 6mm OD Surgical tubing outside ¼ ” ID x 3/8” OD vinyl tubing

3.2. ⅕” width Delrin- parallel flat surfaces w/ tapered tip

3.2.1. Lubrication

3.2.2. Fishing line to connection

3.2.3. Threaded vs. Unthreaded Torpedo

3.3. Reasons for failure

3.3.1. Difficulty with torpedo freely moving/ returning

**4. Idea 4**

4.1. 3mm ID x 6mm OD Surgical tubing outside ¼ ” ID x 3/8” OD vinyl tubing

4.2. ⅕” diameter Delrin torpedo w/ extended tip

4.2.1. Lubrication

4.2.2. Fishing line to connection

4.2.3. Threaded vs. Unthreaded

4.3. Reasons for failure

4.3.1. Did not act any differently than previous attempts

**5. Idea 5**

5.1. 3mm ID x 6mm OD Surgical tubing outside ¼ ” ID x 3/8” OD vinyl tubing

5.2. ⅕” diameter Delrin torpedo w/ addition of elastic sewn around surgical tubing in hopes of preventing lateral movement

5.2.1. Lubrication

5.2.2. Fishing line to connection

5.2.3. Threaded vs. Unthreaded

5.3. Reasons for failure

5.3.1. Can't sew elastic around surgical tubing or it weakens the elastic and breaks at seam

5.3.2. Issues prototyping the correct size torpedo with the ability to return back to the vinyl tubing

5.4. Attempts to fix the issues

5.4.1. Measure tubing and make elastic fit the circumference

Throughout our design process, many designs and ideas were tested to find the best possible solution. The main idea was in attempt to use a torpedo design and utilize the elasticity of surgical tubing, to have the delrin torpedo drive through the surgical tubing, act as a constant force spring, and return after impact. We began by finding a way to stabilize the delrin, so vinyl tubing was inserted within the surgical tubing. Due to the rigidity of the vinyl tubing, it guides the torpedo and the low friction surface allows the delrin to move freely before getting it is pulled into the surgical tubing.

The initial design utilized surgical tubing that was ⅛" inner diameter (ID), 3/16" outer diameter (OD), and a delrin torpedo had a length of 3" and a diameter of 3mm, as shown in Figure A.1 below. The delrin was then attached to the surgical tubing using a strong adhesive. The tubing was then lubricated to help the delrin glide frictionless through the tubing. When pulled from either endes, the Delrin rod freely moves and returns to its original position. Although this idea proved successful in creating a spring, it unfortunately only worked because of the elasticity of the surgical tubing, not acting as a constant force spring. Many problems occurred when building this design, and one main issue is that the material sizes were too small, and it was difficult to manufacture the proper shapes for each piece.

Figure A.1: Surgical tubing w/ 3/16" OD

For idea 2, we began by working with new sizes of materials, which included 3mm ID x 6mm OD Surgical tubing,  around ¼ " ID x 3/8" OD vinyl tubing, which is shown in Figure A.2. We then increased the size of the Delrin torpedo to ⅕" diameter and used fishing line to extend from the tip, which is shown in Figure A.3. The fishing line ensures that the Delrin will be pulled during impact, with the ball. We then inserted the torpedo into the surgical/ vinyl tubing and added lubrication to low surface friction within the tubing. This idea was hopeful, but the biggest issue was that the torpedo had difficulty returning to its original position on its own.

Figure A.2: Surgical Tubing w/ Vinyl Tubing

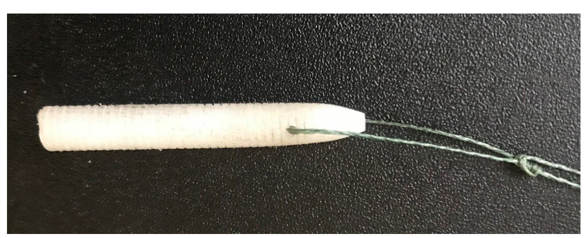

Figure A.3: Delrin Rod w/ Fishing Line

For idea 3, we began by using the same size surgical tubing and vinyl tubing, but using a different shape made from delrin. We started with the same size, ⅕” diameter, torpedo as used in idea 2, then flattened the top and bottom sides of the delrin, and left the full tapered tip, creating the shape shown in Figure A.4. The delrin was attached using the same fishing line method used in previous attempts, but this idea still failed. Issues with this design included the difficulty of the delrin returning to its original position on its own, and its inability to move freely throughout the tubing.

Figure A.4: Flattened Delrin Rod

For idea 4, we began by using the same size surgical tubing, vinyl tubing, and diameter of delrin, but extended the length of the tip on the delrin torpedo. From the ⅛” delrin rod, a new design had a taper of 1” long and the overall length was 4”, and can be seen in Figure A.5 below. This idea had worked the best and was closest to working as expected, but still lacked the ability to return on its own.

Figure A.5: Longer Torpedo Shape from Delrin Rod

For idea 5, we used a combination of a few of the ideas presented above.