Worcester Polytechnic Institute
Mechanical Engineering Program

DESIGN PROJECT TITLED:

Impact Reduction Design

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Abstract

The objective of this project was to design a new type of headgear for field hockey that reduces the injuries caused by the field hockey ball's facial impacts. The protective abilities exceeded the protective abilities of field hockey headgear that is currently utilized. Consisting of an aluminum frame with a layered foam lining, this facemask design was found to reduce HIC values from impact by as much as 75%. This was tested by using a pendulum with an attached field hockey ball that could achieve the same momentum as an average field hockey ball impact. The pendulum's repeatability allowed for several testing trials that swung against a designed model head wearing the facemask with a simulated neck; this allowed the testing of the headgear to be as close as possible to the real world scenario while providing enough data to confirm the initial results.

Key Words: impact, headgear, facemask

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1. Introduction

The primary goal of this Major Qualifying Project (MQP) was to design, build, and test personal head protection equipment for field hockey players that can reduce the incidence of nasal fractures and severity of concussions during gameplay. While the use of protective equipment to reduce injuries has long been a widespread practice, the technologies behind their production have yet to catch up. While fatal or extremely severe injuries are generally prevented, milder injuries such as bone fractures, tendon breaks, and particularly brain injuries are still very common. In the case of the former, it may be because these are seen as an inherent risk of physical activities; in the case of the latter, it is primarily due to a lack of understanding on what causes brain injuries, and consequently how to protect against them (without impacting the actual sport). The National Operating Committee on Standards for Athletic Equipment (NOCSAE), which sets standards for many kinds of American athletic equipment, including protective headgear, has criteria focused on breakage and impact forces, but has no standards for testing and reducing concussions. Even the National Football League (NFL), which has sponsored research into the matter for several years now, has failed to reduce brain injury to acceptable levels. In terms of field hockey, current National Collegiate Athletics Association (NCAA) rules prohibit use of helmets outside of certain plays, due to the lack of an accepted helmet standard and disinclination to let some players wear helmets while others do not. In addition, the rules prohibit intentionally lifting the ball off the ground; this reduces the incidence of head impacts, but does not entirely prevent them.

2. Background

2.1. Existing Designs

In preparation for the design of a new protective headgear for field hockey players, it made sense to not only look at the existing field hockey face masks but to also other sports' versions of head protection. The team looked into the equipment of baseball, football, ice hockey, firefighting Self Contained Breathing Apparatus (SCBA) and field hockey when attempting to decide how to optimize the design for the application of field hockey. Based on the review of the aforementioned sports/physical activities the team was able to extract certain design criteria to improve the current state of technology for field hockey headgear.

2.1.1 Baseball: Catcher's Face Mask

A standard catcher's face mask in baseball usually covers at least fifty percent of the catcher's head, and some available masks cover upwards of seventy-five percent of the player's head. The mask touches the player's head against the base of the chin and the top of the forehead to the crest of the head. The mask itself is made from a wire cage (typically a hard metal) and the contact points are padded with foam or sponge materials. Masks that cover roughly 50 percent of the head are usually attached with a fabric harness or a strap system. Masks cover more of the player's head resemble a wire cage-helmet blend and are donned by sliding it on to the head or with a simple strap.

The wire frame cage for a catcher's mask is designed to allow for maximum visibility while still being capable of protecting the player from a strike of a baseball moving at 90 mph or more. Therefore designers use very hard metals for the cage, which allow the bars of the cage to be more spaced out. Some designs, such as the Rawlings Coolflo, have a matte finish on the wire cage such that the player will have further improved visibility through the mask by reducing the glare from each bar. The size of the padding and the area over which it enabled the mask to distribute force was beneficial in the reduction of the impact damage to the player. The shape of a catcher's mask is generally described as comfortable for most players. The catcher in baseball is not intended to move much throughout the game so motion is not a large consideration in the design. This is evident in the fact that the straps are simple and only lightly hold the mask in place. As for the padding, it is designed to prevent the cage or the ball from directly impacting the head of the player and to spread out the force of the impact itself. Absorption of impulse is minimal due to the fact that the pads are typically high density foam which act as more of a protection for broken bones as opposed to absorbing impact.

2.1.2 Football: The VICIS Zero1 Helmet

Figure 1: VICIS Zero1 Helmet

Figure 1 above shows a new design for impact reduction. Standard football helmets have a hard exterior shell, made out of a hard polymer to resist fracture, lined with hard and soft foams to distribute and reduce the impulse. The VICiS Zero1 does not follow this same structure; the outer layer of the helmet is a flexible rubberized polymer connected to a center layer of viscoelastic polymer columns and the inner layer is a hard plastic as a final measure to distribute remaining impact force over a greater area. This style of padding allows for the impulse of the impact to be distributed both over time because the impact will last longer and over more area because the deformation of the helmet is far greater. The deformation of the helmet is greater in the Zero1 in comparison with the traditional style because the viscoelastic columns caremain in an elastic state for a far greater range than traditional materials and the exterior shell's flexibility causes contact with a greater number of columns than a hard shell would allow for.

2.1.3 Field Hockey: Face Masks

The three main types of face masks are wire frame, goggles, and full face. The wire frame is made with a steel and soft metal alloy which required that the cage of the mask have a greater number of bars for substantive strength. The padding of the wire frame is a soft foam which only covers a small area. Additionally, the pads can not be removed and replaced. When the pads are ruined the wire frame mask has to be replaced. There is no padding above the bridge of the nose. Players reported this as a potential problem for prevention of a broken nose.

The clear goggles resemble a set of safety glasses typically used in a shop environment. They are essentially fully transparent and due to the small size they offer the little impairment of vision. They are made from a safety glass, resistant to fracture, and are attached to the head via an elastic band. They are meant only to protect the player from eye damage and in no way guard the remainder of the face or head.

The full face mask, commonly referred to as the face off mask because it is almost exclusively used for face-offs, is a hard polymer with minimal padding attached to the player's head using an elastic harness. This mask is designed solely to prevent a strike from a ball or stick from directly impacting the face of the player.

2.1.4 Ice Hockey Helmet

The design offers full head protection as a helmet plus a face mask typically of a wire frame or a safety glass. It attaches to the player's head using a chin strap. Airflow is not a concern in the design of ice hockey helmets due to the low temperature at which the game is played at. This becomes an issue when the design is borrowed or transferred for the application of other sports. The design of the helmet in this case must be refitted to allow for proper cooling of the player. The padding is the same type of soft and hard foams commonly used throughout the other sports previously mentioned.

2.1.5 US Navy Regulation SCBA Harnesses

The US Navy has a Self-Contained Breathing Apparatus (SCBA) for firefighting and disaster situations. The apparatus itself is attached to the head using a fabric harness. The harness is adjustable to any head size and shape; it is designed to go over a woman's hair but can be fitted down to a bald head. The harness is highly reliable and simple in its design: three straps attach to the mask at the top and one on each side at the bottom. The three straps all join to a triangular mesh harness which fits snugly to the lower back of the head. While this apparatus does not affect impact reduction specifically, it provides a reliable attachment for wearable face protection.

2.2 Impact Absorbing Materials

2.2.1 Distributing vs. Dissipating Impact Energy

When selecting the materials for a helmet or mask, it is essential to remember an "impact is transmitted to the brain as a pressure wave that enters the skull and enters the brain. The impact also has an impulse associated with it so there's energy carried with it as well and that energy is transmitted through the helmet into the skull and into the brain. The purpose of the helmet is to try to mitigate or lessen both that pressure and that impulse." (UM, 2016) Reducing the pressure or force of the impact is usually the central design criteria for helmet design and certification, and not without reason; a large peak force can break bones, even crushing the skull, and most helmets are designed to limit peak force. However, the force of an impact does not correlate well with brain injury or concussion. Brain injuries are caused by brain deformation, which is governed by the impulse of the impact. Impulse is the integral of force over time, and represents the total energy transferred from the projectile to the target, regardless of how long the process took. A traditional helmet spreads out the impact over a longer period of time. This decreases the peak force (and prevents broken skulls) without decreasing overall impulse (which controls brain injury). Traditional helmets save lives, but they don't prevent brain injury well.

The energy of an impact is defined by the mass and speed of the objects involved, and that energy must go somewhere. It can be reflected, spread out over time or space, or dissipated as heat by the projectile, the helmet, or the head as they deform. Conventional helmet and mask designs allow the energy to be dissipated primarily by the human head. Single-impact helmets, used for rare impacts in sports such as bicycling or horseback riding, dissipate the energy by permanently plastically deforming the helmet (BHSI, 2017). New football and military helmet designs explore dissipating the energy in viscoelastic helmet materials sandwiched between harder materials.

For reference, without a helmet impacts occur within 0.5-2 millisecond, but a decent conventional helmet will stretch that impact into 6 milliseconds or so. A field hockey ball carries 40-60 Joules of energy, which is about 2000 Newtons of force over 2 millisecond or 670 Newtons of force over 6 milliseconds. About 2900 Newtons is considered instantly fatal, and 450-850 Newtons will break an adult male's nose, depending on the force distribution (NCBI, 2010).

2.2.2 Conventional Foam Padding Distributes the Force

Conventional helmet design spreads out an impact force over space and time to decrease peak pressure. Materials with different acoustic impedances are layered in a helmet, reflecting the pressure wave to decrease peak pressures. This is governed by Equation 1.

Equation 1: Pressure Wave Reflection Ratio

$$R = \left(\frac{Z_2 - Z_1}{Z_2 + Z_1}\right)^2$$

where R is the fraction of the pressure wave reflected and are the acoustical impedances of the materials. Acoustical impedance Z is equal to pV where p is density and V is acoustic velocity or the speed of the pressure wave in that material. The larger the difference between the acoustical impedances of the materials, the more the pressure wave is reflected and the lower the peak force (BHSI 2017). Using a conventional helmet design to prevent brain injury is like using a mirror to dim a light; the light is spread out but its total energy is not diminished. The force of the impact is distributed, but the impulse is undiminished. Distributing the force prevents broken bones, but preventing brain injury requires the energy of the impact to be absorbed by other materials.

Single use helmets, such as bicycle helmets, absorb energy by permanently plastically deforming the liner's padding material (usually a crushable foam), which converts the impact's energy into heat. (Some helmets use an inner shell to survive multiple impacts without replacement.) Most helmets use 2 cm of Expanded Polystyrene (EPS) to take impact forces below fatal levels, which means that sustained forces still cause brain injury or concussion despite these helmets (BHSI, 2017). EPS liners are made by expanding EPS beads and may be reinforced with nylon or metal mesh. The liner sometimes has multiple layers of EPS, each with a different density. The less-dense layers absorb energy and decrease forces from smaller impacts but bottom-out and plateau at higher forces. The denser layers absorb energy from larger impacts but pass the energy along undiminished at lower forces. The change in density also somewhat diffuses the peak force of the impact. Generally, lower density foams offer better concussion protection. “In short, the ideal foam is just thick enough for your crash impact, and just firm enough to minimize your g's without bottoming out” (BHSI, 2017). A crushable foam reaches its crushing force at about 25% strain. Foam density is measured by weighing the foam, then measuring the water it can displace when submerged (BHSI, 2017). Theoretically, varying the densities and thicknesses of the EPS padding may enable them to prevent brain injuries, but the thicknesses may be prohibitive.

Some designs, such as the Kali motorcycle helmet, layer or combine the foams in deliberately engineered ways, taking advantage of changing shape factors. A shape factor accounts for the way foam squishes out when compressed, like a balloon when it is squeezed. Shape factor is important for smaller geometries. The Kali liner shown in Figure 2 uses cones of gray low-density foam sticking into the white high-density foam layer, creating a helmet that responds like a softer foam in small impacts but a high-density foam when the soft foam bottoms out in large, potentially fatal impacts. This also allows for a lighter helmet, though it does not decrease thickness.

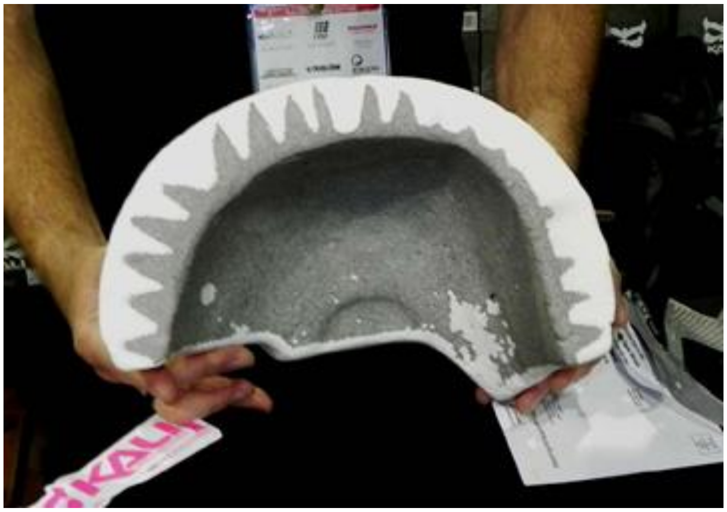


Figure 2: Kali Liner (BHSI 2017)

Kali also makes helmets with low-density foam in the front and rear but high-density foam on top, protecting from concussion from the front or rear, and death from above. Again, this is an either-or proposition, limited by helmet thickness.

In addition to the classic ESP, other foam materials, such as Expanded Polypropylene (EPP), Expanded Polyurethane (EPU or PU), and rate-sensitive slow rebound foams are also used. EPP is likely the preferred crushable for this application if it can be manufactured. “EPP is a multi-impact foam, recovering its shape and most of its impact protection slowly after a crash. It can be trickier to work with than EPS [requiring pentane and particular pressures and temperatures to expand properly], costs a little more, and has a modest amount of rebound (in technical terms a less favorable coefficient of restitution) that usually requires a little bit thicker helmet than one using EPS. Most of the rebound takes place after test rigs have stopped measuring the impact severity, so that characteristic is not well documented. In 2004 Pro Tec introduced a modified EPP that they are calling SXP...that permits them to meet multi-impact standards without thickening their helmets.” (BHSI, 2017)

Rubbery foams are used for multiple impact protection, and are used for football, hockey and skateboarding helmets. “For a given thickness the rubbery foams are less protective in a very hard impact, but more protective in a lesser impact, where they deform while stiffer EPS is still resisting. The lining in rubbery foam helmets can deteriorate with many impacts, however, and must be reconditioned on a regular schedule by replacing the liners” during the off season (BHSI 2017). One company, “W Helmets” uses a rate-sensitive foam called Zorbium that deforms easily in a lesser impact to prevent milder injuries, while stiffening in a harder impact to prevent bottoming out” but the foam is heavy and absorbs sweat, making it impractical (BHSI, 2017).

Some helmets use air and plastic designs instead of foam, creating multiple-impact lightweight helmet designs that again spread out the impact rather than absorbing energy. Designs include small cylinders, crushable plastic straws, air bladders, freely moving beads, and an air gap. Although worth mentioning, these methods are considered more original than they are revolutionary or useful (BHSI, 2017).

Field hockey is a non-contact sport and even minor collisions are considered fouls (although petty fouls occur so frequently that play hardly stops for the whistle and change of possession before the players are off again). Field hockey is not football. Head impacts are decently rare and currently require stopping play and replacing the now-injured player, so coaches and players may accept a one-impact mask that offered superior protection for the nose and brain, but more market research would be required, and multiple impact equipment is preferable and more sustainable. This project focus on multiple-impact protection.

2.2.3 Viscoelastics Absorb Energy

Viscoelastic materials may have more ability to prevent brain damage than conventional padding. Brain damage is a function of total impulse or total energy in. Viscoelastic materials actually dissipate energy as heat, rather than merely redistributing energy over time and space. Viscoelastic materials possess both the properties of elastic materials and of viscous fluids. The force required to change their shape is time-dependent. A fast strain absorbs more energy than a slow return releases. “Purely elastic materials do not dissipate energy (heat) when a load is applied, then removed; however, a viscoelastic substance does.” (Sorbothane, 2017)

Viscoelastic materials include “Synthetic polymers, wood, and human tissue, as well as metals at high temperature” and their damping effectiveness is often summarized with a tangent delta, as shown in Figure 3 below (Sorbothane 2017). Materials soft enough to be useful for field hockey masks would fit only in the lower right quarter of the graph.

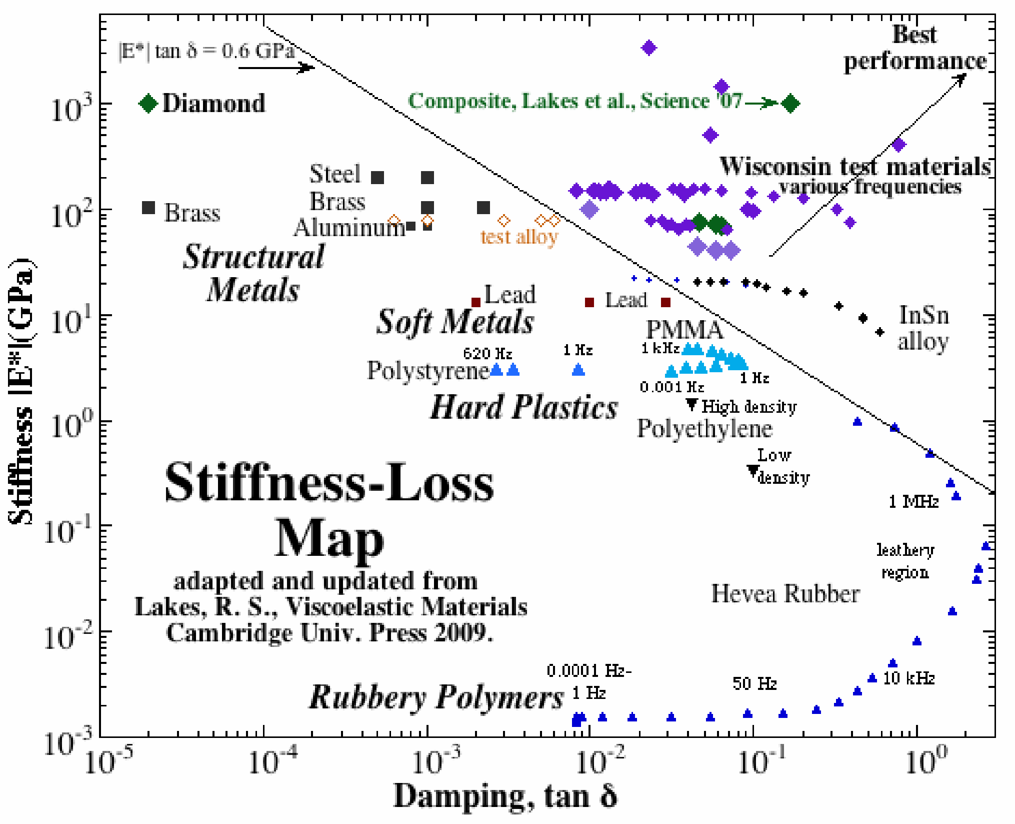
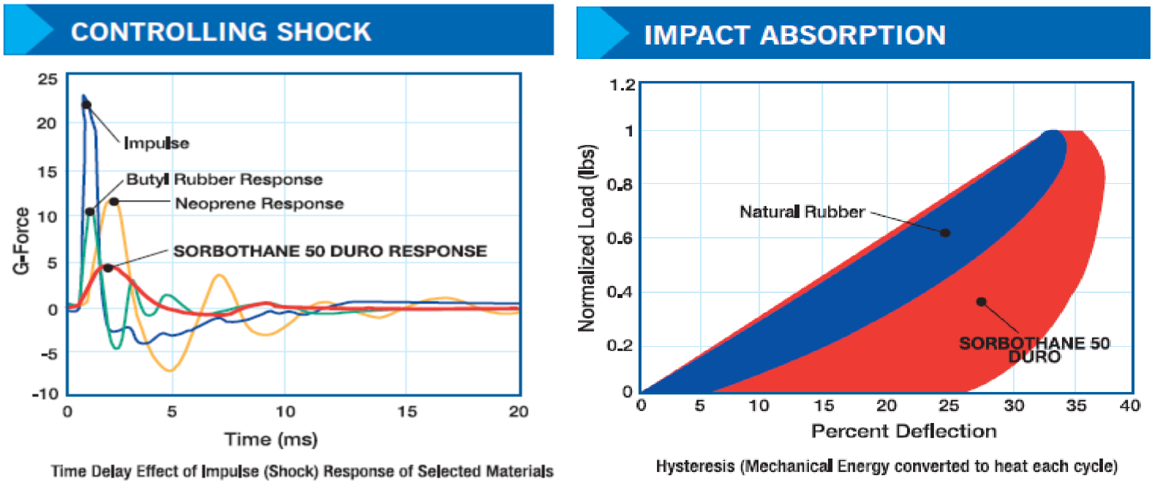


Figure 3: Stiffness-Loss Map (Wisconsin, 2009)

A reusable design also requires an anelastic material. “Anelastic solids represent a subset of viscoelastic materials: they...ultimately recover fully after removal of a transient load. After being squeezed, they return to their original shape, given enough time....The time scale for recovery may be very short, or it may be so long as to exceed the observer's patience or even lifetime” (Wisconsin 2009). An anelastic material has perfect “memory” for its original shape, and only materials with good or excellent memory will be considered for this application.

The most familiar viscoelastic material is memory foam, which is made from the same chemicals as polyurethane foam. As with the foams in the previous section, viscoelastic foam comes in various durometers that block and transmit different ranges of force. Just as with conventional foams, if the durometer is too hard the foam will transmit force of the impact without attenuating it significantly, and if the durometer is too soft the foam will bottom out and pass the force right along. Figure 4 shows how the different materials react when impacted.

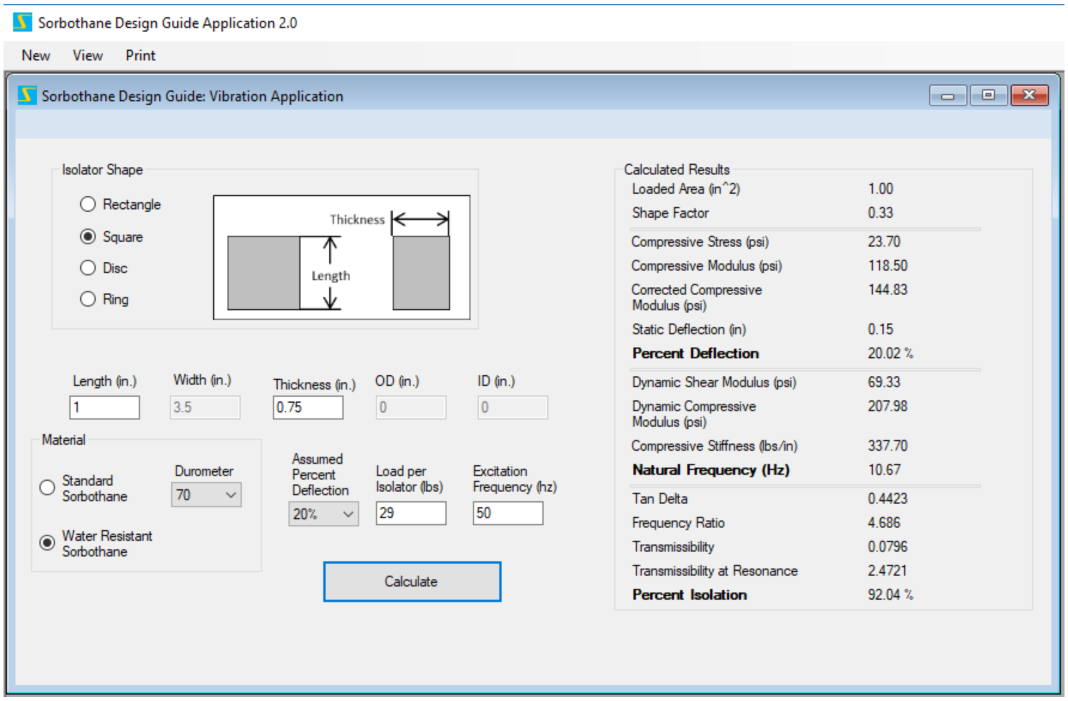


Time Delay Effect of Impulse (Shock) Response of Selected Materials

Hysteresis (Mechanical Energy converted to heat each cycle)

Figure 4: Controlling Shock and Impact Absorption (Sorbothane, 2017)

Viscoelastic materials are often used to dampen vibration, control sudden shocks, and absorb impact. One viscoelastic material available off-the-shelf is Sorbothane. “Sorbothane® is a thermoset, polyether-based polyurethane solid that flows like a liquid under load” but can return to its original shape once release, and can survive millions of cycles” (Sorbothane 2017). It is used in baseball glove pads by Wilson Sporting Goods, and is available in various shapes online. The damping capabilities of Sorbothane can be calculated for simple shapes using the Sorbothane Design Guide Application 2.0 located on the company’s website and shown in Figures 5 and 6, but accurate results require the natural frequency of the impact. The software predicts overall energy reduction from 25% to 95% is possible with 70 durometer for 0.75 inch thick padding.



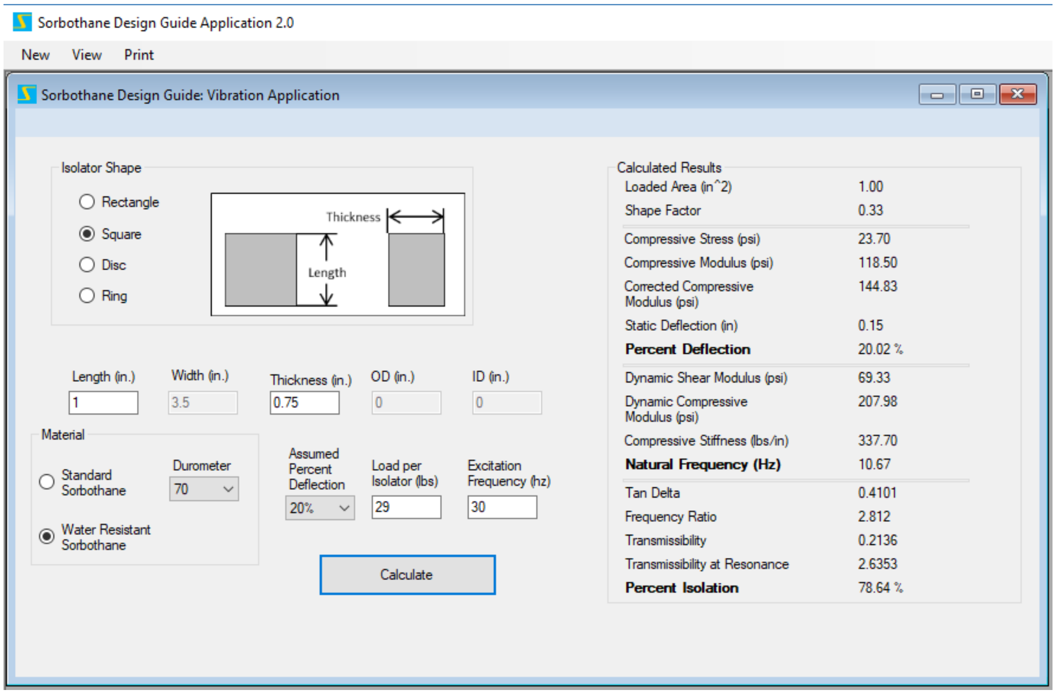
Isolator Shape
○ Rectangle
● Square
○ Disc
○ Ring

Length (in.): 1
Width (in.): 3.5
Thickness (in.): 0.75
OD (in.): 0
ID (in.): 0

Material
○ Standard Sorbothane
● Water Resistant Sorbothane
Durometer: 70
Assumed Percent Deflection: 20%
Load per Isolator (lbs): 29
Excitation Frequency (hz): 50

Calculated Results	
Loaded Area (in^2)	1.00
Shape Factor	0.33
Compressive Stress (psi)	23.70
Compressive Modulus (psi)	118.50
Corrected Compressive Modulus (psi)	144.83
Static Deflection (in)	0.15
Percent Deflection	20.02 %
Dynamic Shear Modulus (psi)	69.33
Dynamic Compressive Modulus (psi)	207.98
Compressive Stiffness (lbs/in)	337.70
Natural Frequency (Hz)	10.67
Tan Delta	0.4423
Frequency Ratio	4.686
Transmissibility	0.0796
Transmissibility at Resonance	2.4721
Percent Isolation	92.04 %

Figure 5: Sorbothane Design Guide Application 2.0 for Excitation Frequency of 50 Hz



Isolator Shape
○ Rectangle
● Square
○ Disc
○ Ring

Length (in.): 1
Width (in.): 3.5
Thickness (in.): 0.75
OD (in.): 0
ID (in.): 0

Material
○ Standard Sorbothane
● Water Resistant Sorbothane
Durometer: 70
Assumed Percent Deflection: 20%
Load per Isolator (lbs): 29
Excitation Frequency (hz): 30

Calculated Results	
Loaded Area (in^2)	1.00
Shape Factor	0.33
Compressive Stress (psi)	23.70
Compressive Modulus (psi)	118.50
Corrected Compressive Modulus (psi)	144.83
Static Deflection (in)	0.15
Percent Deflection	20.02 %
Dynamic Shear Modulus (psi)	69.33
Dynamic Compressive Modulus (psi)	207.98
Compressive Stiffness (lbs/in)	337.70
Natural Frequency (Hz)	10.67
Tan Delta	0.4101
Frequency Ratio	2.812
Transmissibility	0.2136
Transmissibility at Resonance	2.6353
Percent Isolation	78.64 %

Figure 6: Sorbothane Design Guide Application 2.0 for Excitation Frequency of 30 Hz

However, the software cannot calculate the capabilities of other shapes or multiple foams. Various thicknesses, durometers, and geometries would need to be tested empirically.

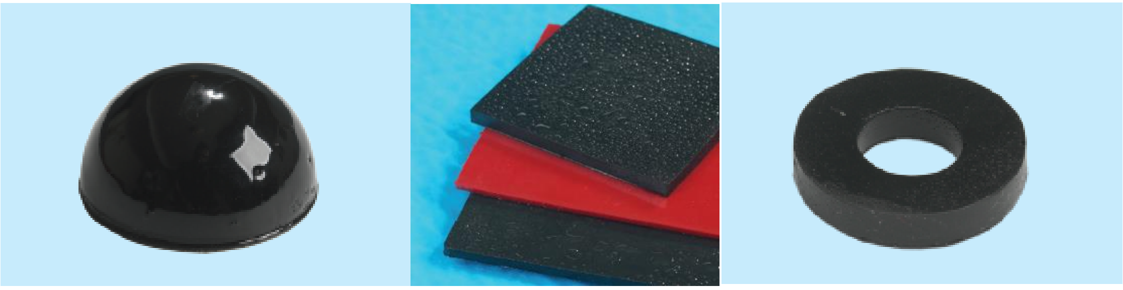


Figure 7: Examples of Viscoelastic Materials (Sorbothane, 2017)

Other viscoelastic materials are not as well documented, as they are used for comfort, in devices such as such as seat pads, ankle braces, and shoe insoles. Epoflex® and Poron® advertise viscoelastic properties 15 times as effective as foam, but independent testing would be required and their weight may be prohibitive (Cambion, 2017).

2.2.4 Hard Shells and Other Materials

If a clear plastic design is chosen for the face mask, Poly(methyl methacrylate) (PMMA) may be an excellent choice. PMMA is somewhat viscoelastic, lightweight, and impact resistant. It is also called Plexiglass, Acrylic, or Lucite, and is more transparent than silica-based glass (PSLC). PMMA is also shatterproof, and it is cheaper than polycarbonate, although not as impact-resistant as polycarbonate. It can be cut with a laser cutter, such as the one in Washburn Laboratories on campus.

Normally Polycarbonate is used in safety glasses because it is shatterproof, strong, and less than half the weight of glass. It is commonly used in sports safety equipment, especially prescription safety glasses, and precut glasses shapes are available off-the-shelf (all about vision).

Opaque helmet shells are often stamped out of Polyethylene Terephthalate (PET), after which the liner is glued or taped in. Shells can also be made of ABS, polycarbonate plastics, fiberglass, or even epoxy with Kevlar fibers. Although the process requires higher temperature plastics than PET, stronger helmets expand their liners in the shell, using all available space and adhering to the shell. (BHSI, 2017) The shell can also be viscoelastic. Butyl rubber could be made into an outer skin, and PMMA also may also be a quality choice.

2.3 Testing Effectiveness of Protection

2.3.1 Injury Simulation

More than 1.35 million children are sent to the hospital each year for sports related injuries. These injuries include: sprains, fractures, abrasions, concussions and more. Of these injuries, about 21% are to the head and face; these are further broken down into categories in Figures 8 and 9. Of these cases, there was a 50% risk of fracture to the nose when a force of 450 to 850N was applied (Healy, 2013).

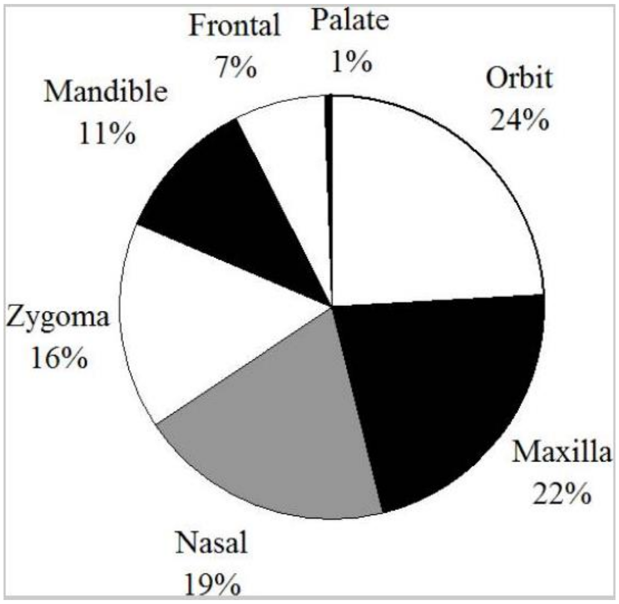


Figure 8: Distribution of Facial Fractures (Cormier and Mannogian, 2014)

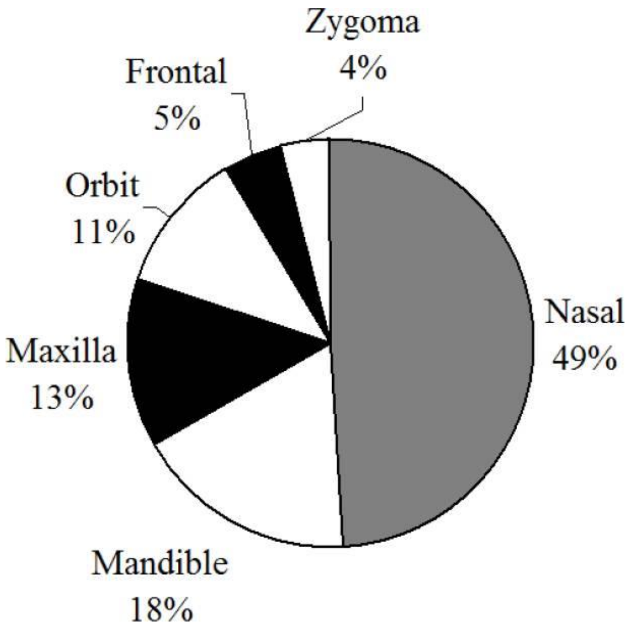


Figure 9: Distribution of Facial Fractures in Frontal Impacts (Cormier and Manoogian, 2014)

2.3.2 Field Hockey Injury Rates

When asked about the rate at which head injuries occur in field hockey during play, the Worcester Polytechnic Institute Athletics Trainer stated that general head and face trauma incidents number at an average of 2 to 3 per year and concussions number at an average of 1 to 2 per year. In order to properly test the impacts that would be the cause of these injuries, various aspects of the game must be taken into account. This is to provide insight on the method of testing that may be most accurate to the situational characteristics at hand. If that is not feasible due to size, structure, repeatability, or other reasons, then information on how to best approximate the situation in a representational model.

2.3.3 Field Hockey/Ice Hockey Differences and Commonalities

Like ice hockey, the game is played with the appropriate sticks and field of view of the players at ground awkward as that is where the projectile lies for scoring (AOSSM, n.d.). In field hockey, the projectile is a ball instead of a puck, but like a puck, the ball can be lifted from the ground after a hit from the player. This is how many of the aforementioned head injuries occur (Miller, 2015). Impact caused by a ground level angled strike at the speed and force of a player hitting the ball was taken into account. There is little concern about the possibility of a strike directly from a field hockey stick because of the rule that a player may not raise the stick above hip level.

2.3.4. Helmet Testing Standards

Most helmet tests in the past have been done with blunt force injury and bone fracture in mind. Vertical drop tests are commonly used, wherein the helmet is fitted onto a test head model and dropped from a fixed height onto a stiff mat (Ouckama and Pearsall, 2014). This testing method offers the advantages of being easily repeatable with minimal setup or equipment required, and adjusting the drop height allows impacts of different severities to be tested. This type of test is the one currently in use by the NOCSAE: "test standard involves mounting a helmet on a synthetic head model and dropping it a total of 16 times onto a firm rubber pad" (NOCSAE, n.d.).

Unfortunately, this method of testing offers little to no insight into the potential for brain injuries; the main data gathered from it is simply the damage done to the helmet, which has little relation to the prevalence of concussions. Current methods for estimating concussion incidence and severity in the NFL, NOCSAE, and several other athletic organizations are based on the Head Injury Criteria (HIC) and Gadd Severity Index (GSI), mathematical reference values derived from the linear acceleration experienced by the head and the amount of time for which it is experienced. This would require collecting acceleration data, something increasingly being implemented in football matches, but not often done in testing helmets.

Even if accelerometers were attached to the test helmet / head, a drop test would not provide accurate data, as it does not properly simulate the acceleration profile of an impact to the head. To fulfill this purpose, linear pneumatic accelerators or weighted pendulum setups are usually used, which provide a robust way to provide an impact with specified linear momentum and impulse. While this serves to simulate the impact on the projectile side, realistic acceleration data also requires the head model use to closely resemble the head conditions of a user.

2.3.5 Pitching Machine Method

The pitching machine method was given thought as a possible solution to creating the necessary impacts. One study that focused on baseball catcher masks, impact locations, and ball trajectory on head acceleration used a pitching machine as its preferred approach to gathering data (Siu, Okonek and Schot, n.d.). Figure 10 shows an example of a pitching machine testing rig.

Figure 10: Pitching Machine for Baseball Tests (Siu, Okonek and Schot, n.d.)

The baseball used, with a weight of 0.146 kilograms, could be fired at 28.2 meters per second at the full power of the pitching machine. The pitching machine was fully adjustable and was fired at two different trajectories in the ten trials presented. However, the study presents the possibility that a main source of error in the trials may have been that the maximum speed of the pitching machine was not adequate for a simulation of real baseball travel speeds in the given scenario and so the pitching machine was moved closer to the masks tested. Therefore, the tested scenario was not accurate to the real-world counterpart situation. The necessary velocity tests were also found inadequate by a study that tested whether pitching machines could be used as a replacement method to display impact performance of cricket helmets using a standard 1.56 kilogram cricket ball (Pang, Subic and Takla, 2013).

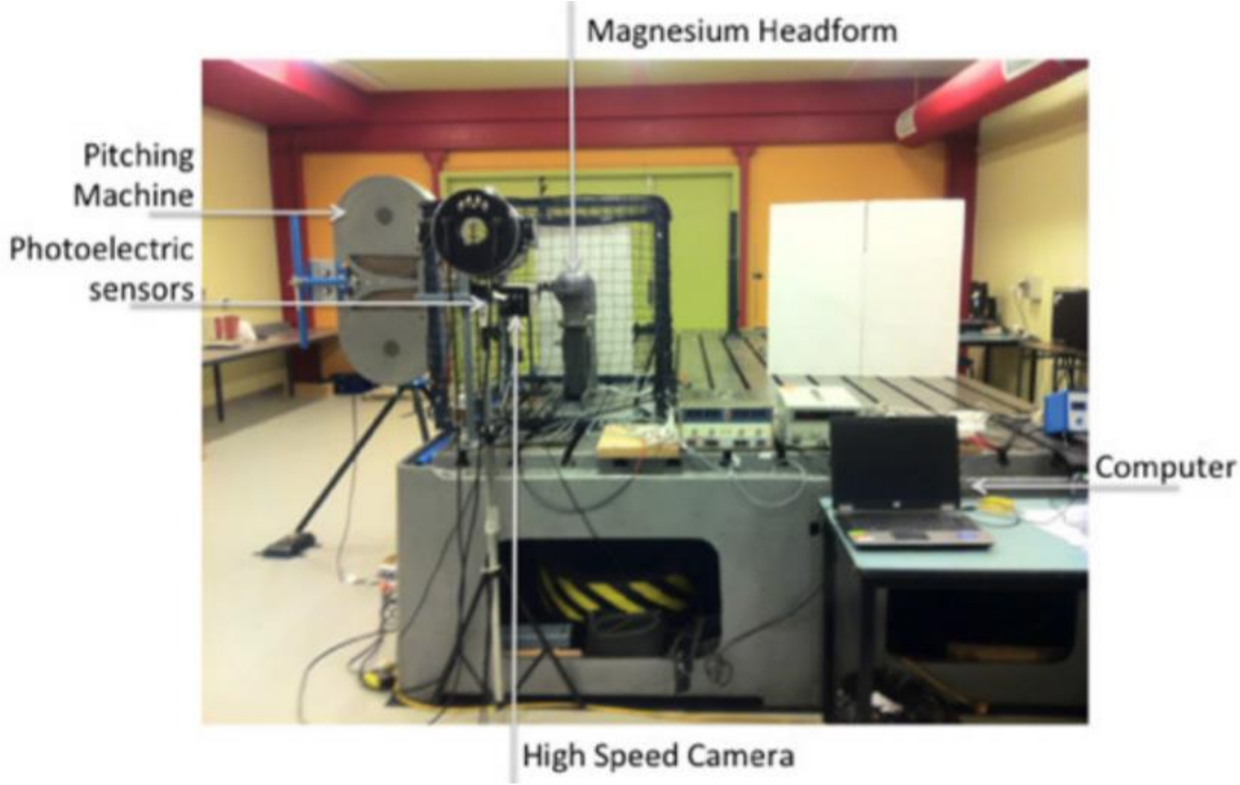


Figure 11: Pitching Machine for Cricket Tests (Pang, Subic, and Takla, 2013)

Ball-to-head impact velocities in cricket can reach up to 32 to 45 meters per second and the designed pitching machine rig presented in Figure 11 that was built was expected to perform as such. While it did reach the necessary range of velocities, it was found that the results of the tests degraded due to the repeatability being affected by consistent performing high velocity impacts by the rig. It is worth noting that the baseball-related study used a production grade pitching machine, while the cricket related device was designed from the ground up.

2.3.6 Air Cannon Method

Another path worth noting is the air cannon setup. While it was not the main focus of the study, the group involved in the cricket impact performance tests Figure 11 also described how air cannon tests have performed previously. It stated that an air cannon could fire the cricket ball at speeds of over 45 meters per second as required. However, the air cannon rig designed was quite complex and did not allow for much flexibility in regard to test repetition and replication; this leads to even less repeatability over the course of trials. Despite the flaws, the air cannon method was stated to be the standard test for cricket helmet impact performance.

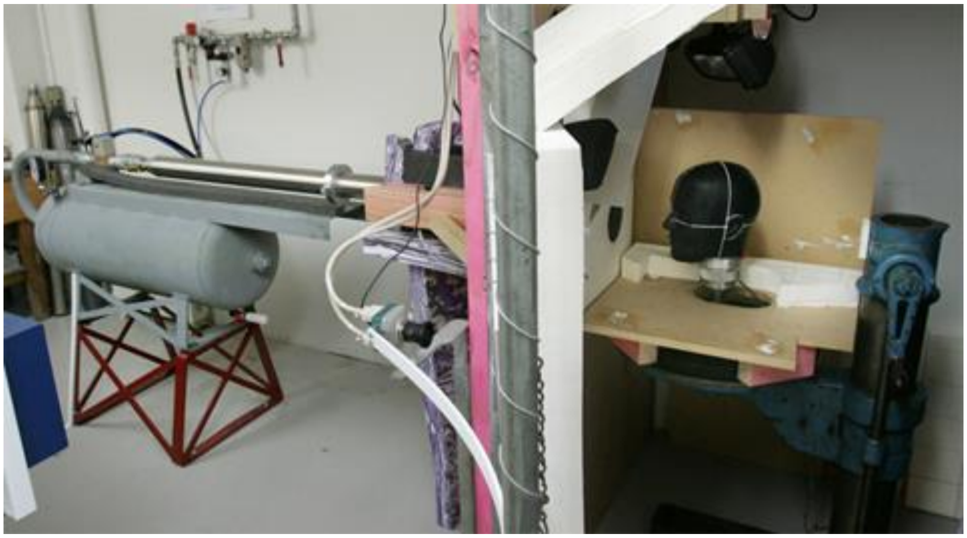


Figure 12: Air Cannon for Cricket Tests (Pang, Subic, and Takla, 2013)

Air cannons are commonly used throughout several different industries. This can been seen in the automotive, protective gear, and aeronautic feilds. HP White Laboratory Incorporated utilized air cannons for research on the performance of ballistic eyewear and face protection. The cannons are capable of shooting lacrosse balls, baseballs, softballs, hockey pucks, et cetera at speeds of upwards 62 meters per second (Hpwhite.com, n.d.). However, these air cannon setups are often quite complex and very large.

2.3.7 Pendulum Method

A pendulum provides a testing environment that closely simulates a real-world impact. It produces similar momentum as an actual impact which utilizes momentum, gravity, et cetera to deliver similar results to its real-world counterpart. In a study that performs impact-based pendulum experiments on several different forms of athletic headgear, the pendulum was designed with a rigid aluminum frame that stood 9 feet tall, shown in Figure 13 (Thorne, 2016).

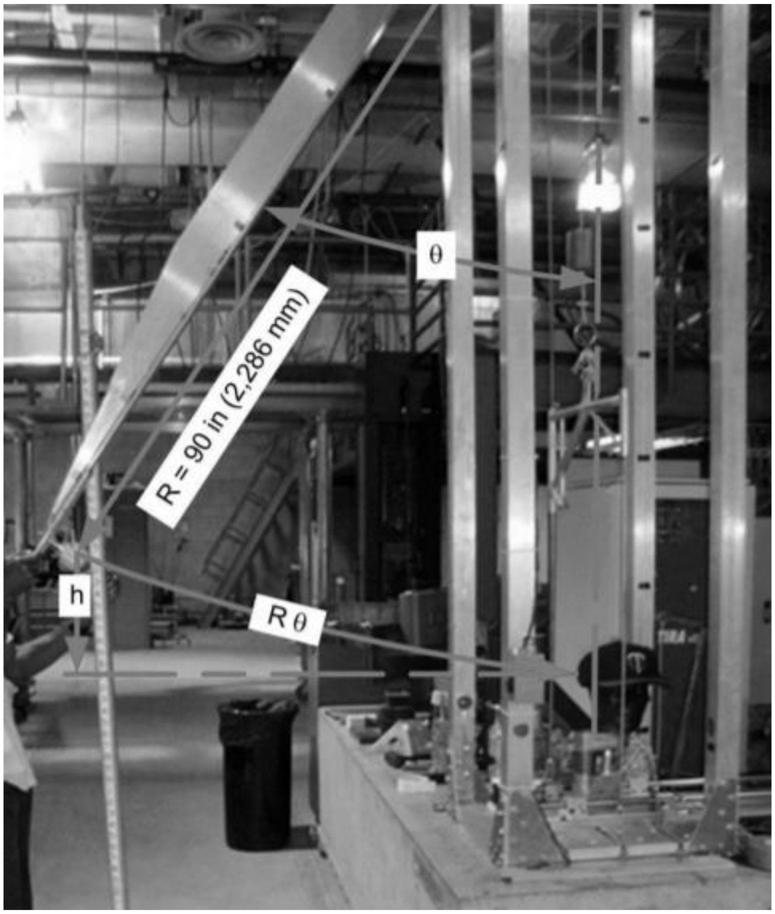


Figure 13: Pendulum for Various Sports Testing (Thorne, 2016)

The swinging pendulum arm had a length of 7.5 feet and including mounting points for the varying sizes in sports equipment, ranging from a baseball to a soccer ball. The trials here were conducted at speeds of up to 29 meters per second and the results were stated to have agreed with the velocities and measurements expected. However, sources of error came from the operator either accidentally pushing the ball slightly, thus introducing a force during a trial, leading to the tests being completely automated. The speeds utilized here are affected by gravity's interaction with the pendulum arm, something that was addressed by another study dealing with concussions caused by football helmet collisions (Pellman et al., 2006).

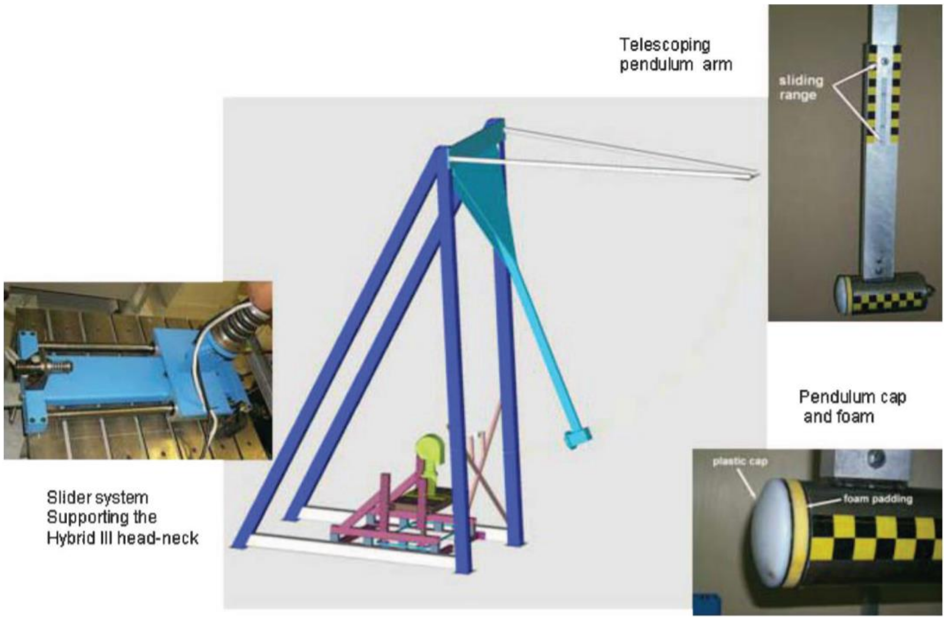


Figure 14: Pendulum for Football Testing (Pellman et al., 2006)

When a velocity of 9.5 m/s was needed to accurately simulate a typical NFL concussion, the pendulum arm seen in Figure 14 that had been designed proved inadequate for reaching that target. In order to keep the design at its current stature, the principle of momentum transfer was utilized and the head of the pendulum was made more massive to counteract the lower pendulum speed and still produce realistic results.

2.3.8 Atwood Machine Method

Variations of the pendulum concept have also gotten past the regular pendulum's shortcomings. The Atwood machine surpassed size and weight issues, which was used in a study on measuring impact performance of field hockey sticks. It utilized a field hockey stick for a swinging arm and had realistic results similar to what would be found in a field hockey match. It could reach speeds of 19 meters per second (Allen et al., 2012).

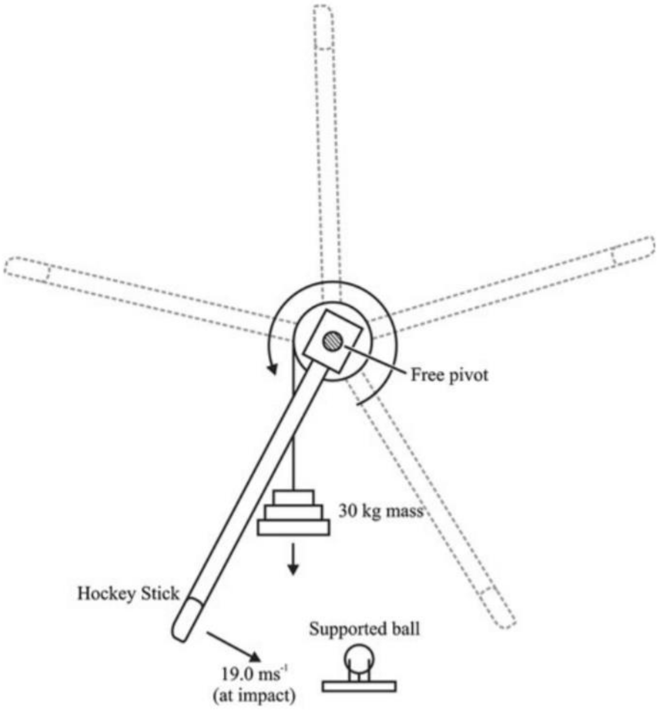


Figure 15: Atwood Machine for Field Hockey Testing (Allen et al., 2012)

The field hockey stick tested had a length of 3.3 feet. This type of variation may be a possible avenue for future reference.

2.3.9. Physical Head Models

Helmet testing usually involves using a standardized model head as a stand-in. These standardized models usually approximate the shape, size, and weight of an average (50th percentile) individual's head; the NOCSAE has one such model they use for their testing. Perhaps the most widespread model is the Hybrid III crash test dummy; a full-body model developed for use in the automotive industry. It has gained popularity for simulating many aspects of the human form, including body-part specific weights and dimensions, joint configurations, and physical stand-ins for key anatomical features. This includes a ribbed chest structure to approximate human chest force deflection characteristics and a rubber cylindrical lumbar spine to provide human-like slouch (as an automotive dummy, it was primarily created for use in seated positions) (NHTSA, n.d.).

Of particular interest to concussion testing is the Hybrid III's neck model; made from rubber and aluminum segmented molding; it has anthropomorphic dynamic moment / rotation, flexion, and extension response characteristics, with a cable through the axis to limit stretching (Humanetics ATD, n.d.). The neck is understandably a major factor in determining head motion, and so simulating its dynamic characteristics is essential to acquiring realistic head acceleration data in testing. Since the neck effectively functions like a spring in such impacts, it is sometimes modeled as such, where the linear and torsional spring constants are chosen close to biological values to provide biomimetic dynamic response.

2.3.10. Simulation

Computerized simulation allows one to test how an impact will affect someone or something while not putting the subject into any actual danger. Finite element analysis (FEA) analysis involves creating geometrical models of objects that computers can use to mathematically simulate real world problems. FEA is commonly used by people creating safety equipment to see if their product will actually reduce the amount of impact a person receives if they were using the equipment. Additionally, it is used to check if their product can withstand certain forces computationally, so that the company does not have to build multiple prototypes just to break them. FEA tests different forces and stresses against the product and checks for points of weakness before the product is even manufactured.

An example of FEA in a practical setting is shown in Figure 16, which shows the modeling of a helmet and showing the stresses on the skull with and without a helmet if a person were to fall on their head. The red colored portion of the figure indicates higher stress levels to the skull.

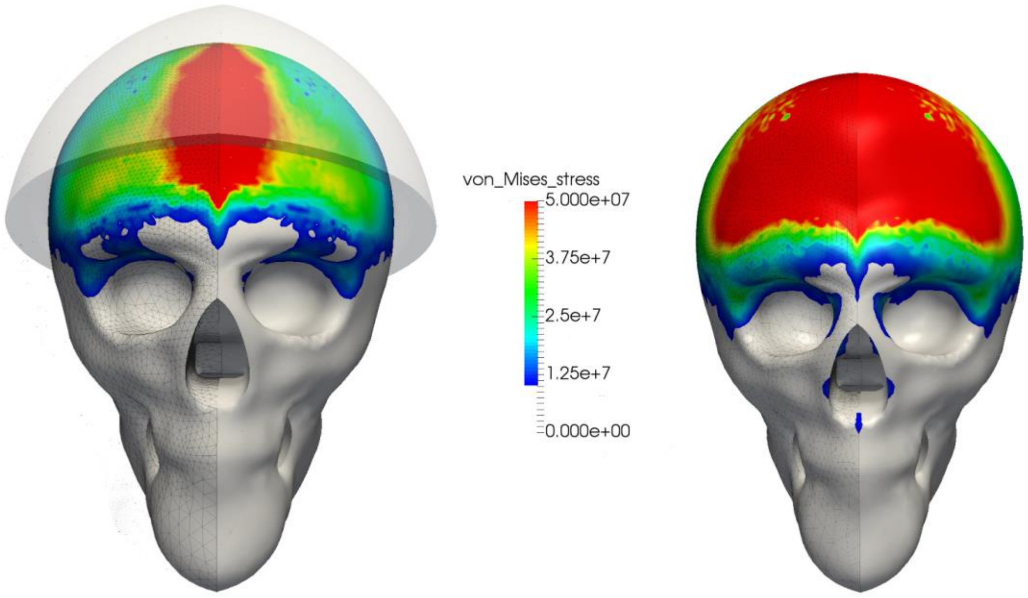


Figure 16: Stress Analysis of a Person Falling on their Head With + Without a Helmet (Hussain, 2015)

2.3.11. Bone properties

There are two main types of bone, cortical (compact) bone and cancellous (spongy) bone. Cortical bone is defined as the dense outer layer of bone that protects the internal cavity (SPINE-health, n.d.). Cancellous bone is the spongy inner layer of the bone that contains red bone marrow (Study.com, n.d.). The material properties for each of these types of bone are shown in Table 1 below.

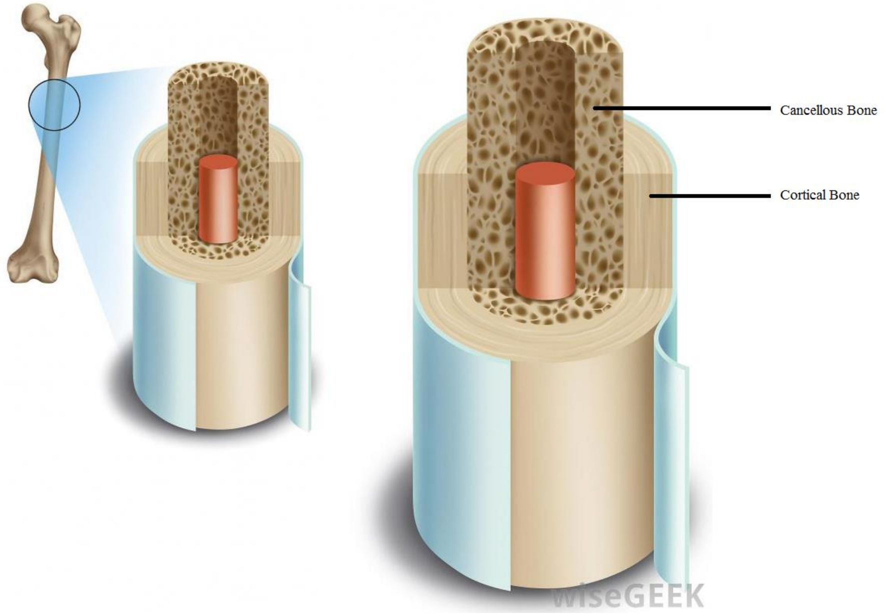


Figure 17: Bone Composition Breakdown (Foster, n.d.)

Table 1: Bone Material Properties (CES EduPack 2017)

	Cortical Bone, Transverse	Cortical Bone, Longitudinal	Cancellous Bone, Low Density	Cancellous Bone, High Density
Density (kg/m^3)	1800 - 2080	1800 - 2080	300 - 550	700 - 975
Young's Modulus (GPa)	10 - 13	18 - 26	0.07 - 0.4	0.8 - 1.5
Shear Modulus (GPa)	3.3 - 4	4.5 - 6.7	0.03 - 0.15	0.3 - 0.5
Poisson's Ratio	0.13 - 0.3	0.13 - 0.3	0.28 - 0.3	0.28 - 0.3
Yield Strength (MPa)	45 - 55	90 - 144	2 - 3	5 - 10

Tensile Strength (MPa)	49 - 60	135 - 167	2 - 3	6 - 12
Compressive Strength (MPa)	130 - 150	130 - 250	2 - 3	9 - 15
Fracture Toughness (MPa*m$^{(½)}$)	3.3 - 4.1	3.5 - 6.1	0.11 - 0.22	0.5 - 0.8
Toughness (kJ/m^{2})	1.6 - 1.8	4 - 4.6	0.06 - 0.2	0.5 - 0.75

2.3.12. Acceleration Data from Physical Testing

As mentioned previously, current understanding of concussions relies on head acceleration data to predict brain injury. While the widespread HIC and GSI criteria use a single, linear acceleration data stream as the basis for their calculations, these models are a bit outdated in academia, having been surpassed by simulation-based computational models in accuracy of predicting injury (Knowles and Dennison, 2017). HIC and GSI are still widely used in practice because of their relative simplicity. Current simulation models, such as the Simulated Injury Monitor (SIMon), are highly complex. It requires linear and angular acceleration data in all dimensions,usually acquired using an orthogonal array of 9 linear accelerometers (Ouckama and Pearsall, 2014), as input and takes considerable computational time to produce results. This makes them not yet feasible for real-time monitoring, applications for which HIC and GSI are popular. However, that HIC/GSI are calibrated for single impacts, and provide little to no information on the effect of multiple, recurring, smaller impacts.

Helmet testing does not typically feature such stringent time constraints, and can much more realistically accommodate additional accelerometers for data collection. As such, collection of additional acceleration data and usage of computational brain models have the potential to vastly improve our evaluation of the effectiveness of helmets. This may result in better understanding of favorable design practices and better, safer standards.

3. Project Strategy

3.1 Initial Client Statement

In field hockey, as in most athletic competitions, there is an inherent risk of injury to the players. Field hockey players are required to wear a form of facial protection while in high school play but the NCAA does not require it (this policy is in the process of being changed). The “face masks” most commonly used are more like goggles, covering little more than the eyes, restricting the vision of the player, and can even divert the force of an impact into the player’s nose causing a fracture. The goal of this Major Qualifying Project was to produce a mask capable of absorbing the impact of a direct strike to the player’s face, protecting the player from broken bones in the covered region, reducing the impairment of the player’s vision, and costing about the same as a standard field hockey face mask. By achieving these goals, we provided the possibility of an alternative design for field hockey athletes in both high school, college, and preferably professional leagues later on.

3.2 Design Requirements - Technical

Based on the research into existing designs of the protective headgear used in field hockey and other sports in which a risk of head injury is present the following features have been established.

The overarching objective of the design was to increase protection of the player from head injuries while minimizing the impairment of the player’s ability to perform in the game.
In terms of functionality, the mask had to successfully protect from impacts to front of the head – temple to temple, chin to forehead – by spreading and absorbing impact force, reducing injury to skin, bone, and cartilage, as well as reducing peak impact-induced acceleration experienced by the head, established to be a dominant factor in causing concussions. The mask had to avoid appreciably interfere in the athlete’s performance; namely, impact on visibility, mobility, and comfort had to be minimal.

In fulfilling these functions, the mask was required to abide by certain constraints. The material strength of the mask had to be sufficient such that impacts from field hockey balls at speeds of 20-40 m/s did not cause significant structural damage or distortion. The guard for the face had to be metal wire-framed cage or solid clear plate for maximum visibility. The cage had to have a gap for the eyes in order to maximize the player’s forward vision. The padding of the mask had to connect to the player’s head in at least two locations (the top of the forehead and the base of the chin) but no more than four (the previous two plus one on each side); the idea was to minimize the thickness of the padding so that the player’s ability to look in the direction of the pad is not hindered. The mask had to be attached to the head using an adjustable fabric or elastic harness that either vary in size or are adjustable for the different sizes of the players’ heads; a simple strap in this case would have been insufficient to keep the mask on the head and stabilized.

More technical specifications were derived from these constraints as guidelines to inform our design process. All materials used were non-toxic and resistant to temperatures in the range of -10 to 40 °C. They must be water resistant and not prone to corrosion by sweat. The adjustable harness was capable of being comfortably adjusted to head diameters between 50 and 60 cm (Bushby et al., 1992). Maximum deformation of mask under peak recorded forces was less than 2mm and below material yield stress.

3.3 Design Requirements - Standards

Standards for athletic equipment and their testing are primarily maintained by the NOCSAE. While field hockey helmets or masks do not have established standards due to their optional and infrequent use, standards from football and lacrosse protective equipment were relevant. Notably, any damage during testing that compromised the fit of the protective headgear signified a failure of the design. In addition, Head Injury Criterion registered during testing could not exceed a rating value of 1200, with an average less than 300 (nocsae.org, 2017). However, these thresholds were for the NOCSAE's standard drop test; when using a pendulum and model-head based impact simulation, which more closely resembles real impacts, we found it more useful to set our maximum to an HIC rating value of 700, which correlates to a 5% risk of severe injury (iihs.org, 2014), and averaging less than 250, the average threshold found to cause concussions in most athletes (Viano, 2005).

3.4 Revised Client Statement

In field hockey, as in most athletic competitions, there is an inherent risk of injury to the players. Field hockey players are required to wear a form of facial protection while in high school play but the NCAA does not require it (this policy is in the process of being changed). The "face masks" most commonly used are more like goggles, covering little more than the eyes, restricting the vision of the player, and can even divert the force of an impact into the player's nose causing a fracture. The objective of this project was to produce a mask capable of absorbing the impact of a direct strike to the player's face, protecting the player from broken bones in the covered region, reducing the impairment of the player's vision, and costing about the same as a standard field hockey face mask. By achieving these goals, we provided the possibility of an alternative design for field hockey athletes in both high school, college, and preferably professional leagues later on.

3.5 Management Approach

The general project schedule followed throughout the three project periods designated August to October 2017 (Term A) for background research and literature review, October to December 2017 (Term B) for first prototype manufacturing and preliminary testing, and January to March 2018 (Term C) for design verification, testing, and validation. The budget allocation used during the course of the project can be found in the table below.

Table 2: Budget

Task	**Cost (Total Budget = $1250)**
Poron Microcellular Urethane Foam (12” x 12” x ½”) x2	$51.70
Shock Absorbing Sorbothane (12” x 12” x ⅛”) x2	$57.90
NEULOG Force Plate Logger Sensor, 16 Bit ADC Resolution	$206.38
NEULOG USB Module	$59.29
Compression Spring (2.844” Overall Length, 6-pack)	$7.18
Sensor Force Load Cell (100lbs)	$66.88
Shock Absorbing Sorbothane (12” x 12” x ⅛”) x2	$57.90
Acceleration Sensor Development Tools Digital Accelerometer x3	$14.85
Acceleration Sensor Development Tools Analog Accelerometer x3	$74.95
Total Cost	$541.78

4. Design Process

4.1 Potential Designs

The first potential design was a solid face mask, similar to what is currently used in NCAA field hockey for corner plays. The main advantage of these is their small profile, making them easy to put on and remove, in addition to having minimal effect on visibility.

The second design considered was a full-head helmet with a clear, solid faceplate. This was investigated as an extension of the faceplate idea as it offers protection for the entire head, rather than only against frontal impacts, and allows for greater contact with the head, which leads to greater distribution of the impact and lower overall stresses / accelerations.

The third design was inspired by the masks worn by catchers in baseball, and involves a metallic mesh for stopping frontal ball impact while minimally affecting visibility (no distortion from clear solid materials). This mesh is attached to supportive pads on the chin and forehead, made of some impact-absorbing material to reduce the impulse transferred and large enough to prevent concentrated stresses.

The final design was a mix of the second and third designs: a full-head helmet with a wire mesh face guard, which has the potential to maximize protection while minimizing impact on visibility, with the tradeoff of being heavier, more intrusive, and potentially more expensive.

4.2 Decision Matrix

Table 3: Decision Matrix for Design Ideas

	Visibility	Protection	Manufacturability	Likelihood of Acceptance	Total
Weight	25	35	15	25	100
Style	10	15	9	25	59
Helmet with Face plate	12	30	12	11	65

Full Face Wire Mesh	22	26	12	21	81
Helmet with Full Face Wire Mesh	22	30	12	11	75

Each category in the design matrix served as an important factor to consider. Visibility referred to the likelihood of the design to allow for a reasonable amount of visibility for the player. Protection referred to the projected ability of the design to reduce impacts. Manufacturability was the ease with which the design could be produced. Likelihood of acceptance covered both situations of whether it was probable that the players would want to wear the design and whether the league would accept it as approved headgear. The main conceptual sketch brought about by the face mask is shown in Figure 18.

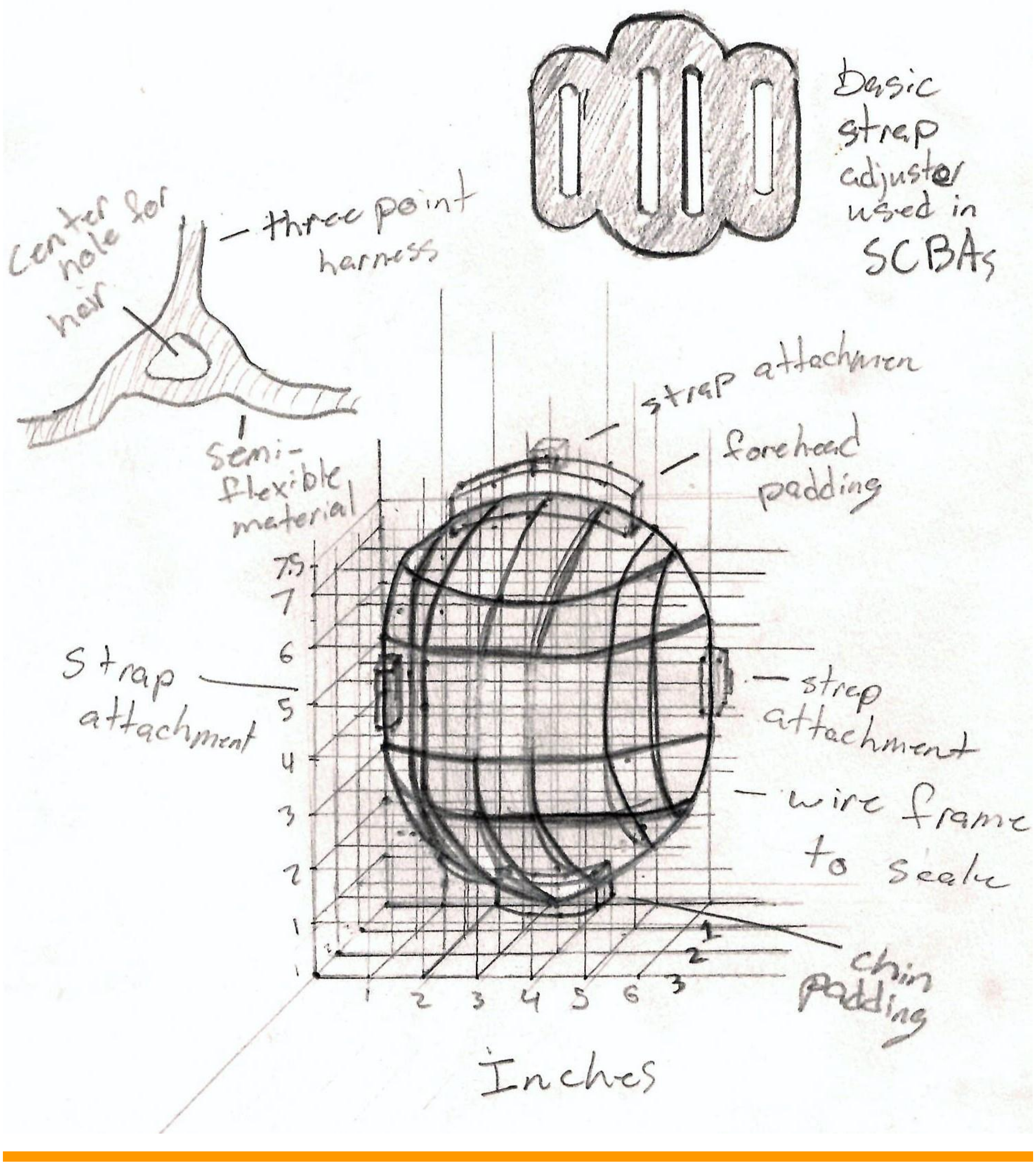


Figure 18: Concept Drawing of Chosen Design

4.3 Materials

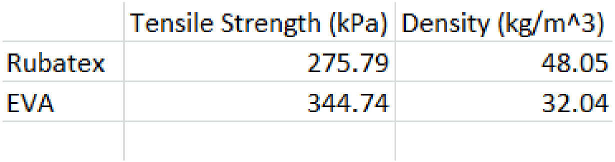
Several different materials were considered for the construction of the prototype. Our team looked at different metals and a polymer. The polymer was the first to be ruled out because most affordable polymers have a fracture strength below the minimum requirements for the impacts expected to be experienced. Both Stainless and Mild Steels were considered for their high strength, durability, and corrosion resistance. Steel was ruled out due to its higher weight and the fact that it is an excess safety factor for the present application. The team settled on aluminum as the decided metal but it then came down to selecting an alloy. The first alloy reviewed was Al 6063, this was an optimal material offering a reasonably high strength and durability in addition to good workability. Workability did not factor into mass production as much due to the likelihood of different means of production (as described in the construction subsection). The other aluminum alloy researched was Al 2017, this offered the similar levels of strength, durability and workability with the added benefit of being cheaper in mass quantities. For our prototype the chosen material was Al 6063 due to its workability, accessibility in small quantities, and its low cost.

For impact reduction, one of the major focuses of our field hockey mask prototype was the foam lining component. This foam lining can be seen on many field hockey masks used for facial protection during corner kick plays.

Figure 19: Field Hockey Corner Kick Mask

The mask seen in Figure 19 had been used by a field hockey player at Worcester Polytechnic Institute. The white cushion that outlined the face of the mask was the attached protective foam. The foam was actually double-layered, with the layer that made contact with the face being softer and the foam attached to the mask being firmer. Unfortunately, the exact specifications of these foams were not standard. Viscoelastic properties of these materials are situationally dependent and although they were considered they could not be quantified due to lack of standardized documentation. Mask manufacturers have brought differing masks to the market that have foams of deviating properties, densities, and even changing the double layering to just be a single layer based on the foam choice. To find a standard to base our foam choices off of, we turned to the preferred foams utilized regularly among field hockey players in their masks found on product pages, discussion boards, and forums. The two foams we found were Rubatex Vinyl Nitrile 310V and EVA foams. As mentioned previously, finding properties and performance statistics of the foams can be difficult, but the density and tensile strength of these two particular foams were found. They have been placed in the Table 4 below.

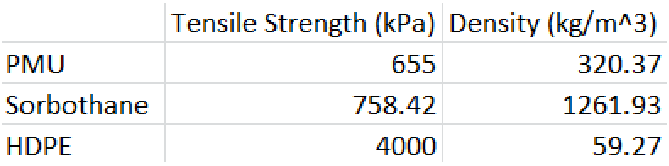
Table 4: Rubatex and EVA Foam Properties



	Tensile Strength (kPa)	Density (kg/m^3)
Rubatex	275.79	48.05
EVA	344.74	32.04

Since both of these foams have been approved for use in consumer purchasable mask designs, the decision to research foams was made to find those that surpassed the properties here while still being structurally similar and situationally relevant in order to surpass the protective ability of field hockey face masks that currently exist. Like with our choice of material for the mask grille, it was important to keep in mind the realistic limits of what we could purchase and build with using the faculties available. Poron Microcellular Urethane, Sorbothane, and High Density Polyethylene became our top choices. Their tensile strength and density have been placed in Table 5 below.

Table 5: PMU, Sorbothane, and HDPE Foam Properties



	Tensile Strength (kPa)	Density (kg/m^3)
PMU	655	320.37
Sorbothane	758.42	1261.93
HDPE	4000	59.27

Of these choices, the HDPE was ruled out. It went far beyond the abilities of any of the other foams and was found to be both the most expensive and least flexible for everyday construction and application. That left PMU and Sorbothane which both exceeded our expectations on standard foam properties (i.e. Rubatex and EVA) as well as being malleable enough to be cut and shaped by average tools. PMU has already been used in modern day ice hockey helmets and Sorbothane in baseball glove inserts. Both have been used in bicycle helmet designs. We decided to proceed with the double layered foam approach as Sorbothane was found to be much firmer and PMU comparably softer with both materials being within a reasonable price. The Poron and Sorbothane foams were ordered at thicknesses ⅛” and ½”, respectively.

4.4 Preliminary Impact Testing

Preliminary testing was done to check for material, design, and procedural integrity. This included an initial prototype mask design, a model head to place the mask on, and a variation of the pendulum designed for the actual testing process. The model head was rested at the pendulum strike point with the mask attached to the face with tape. The pendulum head, which was attached to a field hockey ball and several weights, was raised until it was .7 meters above the model head and released, striking the mask. The model head was raised or lowered each time so that each strike occurred at a different point on the mask.

Figure 20: Preliminary Test Setup

4.5. Material Testing

To determine the effectiveness for shock absorption and force dampening of the two foam paddings (Poron and Sorbothane), a simple impact test was performed. The pendulum struck a load cell with variations of the two foams placed on top to register the peak forces experienced during the impact. The pendulum was released from a fixed height of five inches above our load cell. The table below summarizes the results, with the peak force displayed being the average of five trials; full graphs of the recorded data can be found in Appendix A.

Table 6: Peak Forces of Foam Testing

Test conditions	Peak force (lbf)
No Foam	78.4
Sorbothane	38.7
Poron	11.0
Both Foams, Poron on Top	6.4
Both Foams, Sorbothane on Top	8.8
No Foam (repeatability test)	80.9

These tests corroborated the hypothesis that the foams would significantly reduce peak force loads from impact, an important goal of our design. It is important to note that this was only a feasibility study though; the forces involved in actual impacts are typically in the range of 200 lbf, twice our sensor's maximum, hence our lower drop height for these.

4.6 Construction of Mask Design

There are numerous methods with which aluminum bars can be transformed into a mask. If a manufacturer is intending to create a large scale production, then the economic choice is to do either a standard casting or an injection molding. While these forms of production do tend to have an effect on the material properties of the aluminum it is the effect is smaller than with iron or steel. If the manufacturer were to be concerned with the material properties it is possible to heat treat the final product in order to restore the entirety of the product to a specified set of properties.

The team decided that the most efficient method of production for a single prototype was to weld the mask. When working with aluminum there are three main methods with which to fuse the metal: brazing, soldering, or arc welding. Brazing is a process in which a filler metal of a high melting point is used to join two base metals. This involves the filler metal flowing into miniscule capillaries of the base metals and creating a very strong joint. Soldering is essentially the same process but the filler metal tends to have a lower melting point; soldering produces a significantly weaker bond than brazing. Arc welding is the process of using a flow of electricity to melt the base metals together; arc welding can use a filler metal but it is not necessary and will mix with the melted base.

Arc welding aluminum requires a specific procedure in order to have the weld turn out properly. For this a TIG (Tungsten Inert Gas) welder was used. The electrode of the arc welder is specified for each metal type but not for each alloy, meaning Aluminum 6063 and 2017 both use the same lead but iron would use a different metal. The lead for aluminum is pure tungsten in order to ensure no reaction between the lead and the base metal. Aluminum has a lower melting point than most metals which applies when welded and therefore the electrical energy input must be adjusted to be lower.

The original design required some design modifications. The original design was a series of simple "T" welds; these welds are easy to complete but not necessarily applicable for a functioning product. For most marketable products the proper weld to use is a "cross" or "X" weld. This type of weld involves the two pieces of stock being laid across each other and being fused together. The problem with "cross" welds is that the two pieces of stock must be melted completely. Anytime when working with molten metal there is a great deal of variability; the metal can fuse to the workstation, the liquid metal will change shape, and the properties of the piece are altered by the drastic change in shape and structure. For design purposes, "cross" welds would be more harmful than anything else. The simple solution to the issue of either over-simplifying the design to use "T" welds or damaging the structure by using "cross" welds was to utilize two techniques called Piecing and double "T" welding. Piecing is cutting down the bars to component parts such that there are no bars in a certain orientation that stretch more than one fourth the length of the structure. Double "T" welding is the process of laying two normal "T" welds to the same point, giving the appearance of a "cross" weld without the potential for structural damage.

Figure 21: "Cross" Weld

Figure 22. "T" Weld

Foams were cut with scissors and fitted to the outline of the welded face grille as a base in four areas including the resting place of the mask on an individual's chin, forehead, and both cheekbones. In Figure 23, the Poron Microcellular Urethane in on the left and the Sorbothane is on the right.

Figure 23: Foam Examples

4.7 Mask Structure

When we first started designing the mask we first started with a design similar to goggles, we looked for an outside source that designed a typical goggle structure. Figure 24 shows a design we found below that shows a pair of ski goggles. This design would do a great job of protecting the eyes but does not necessarily protect the nose. This led to us revising our design objective from protecting the eyes to protecting the whole face from an impact.

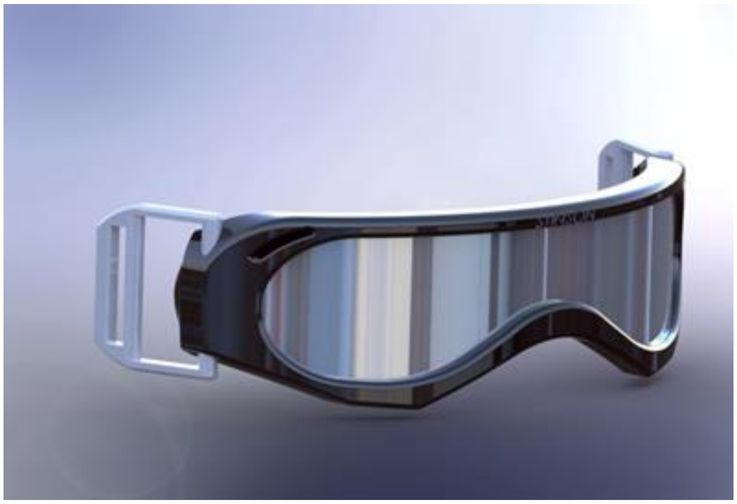


Figure 24: GRABCAD Goggle Example for Inspiration (Stinson, n.d.)

We realized that the face could be protected better by the development of a lightweight facemask for field hockey. A catcher’s mask from baseball provided the inspiration for our following designs. A network of rods made of a lightweight metal could achieve a safe, and durable facemask. These rods connected in a wire mesh fashion would be very useful from an impact reduction standpoint. This is because when a ball hits the wire mesh, it is very likely to hit more than one bar which will split the force between all of the impacted rods. Additionally we decided to research different foams to be attached to the mask to absorb the impact instead of redirecting most of the force into the user. The initial design for the wire mesh face mask was created in SolidWorks by sketching the outline of a face onto the front plane as shown below in Figure 25 and then sweeping that outline with a circular profile. The bars for the wire mesh were created by sketching a series of three to nine point splines across various intersecting planes and then sweeping a circular profile on each as shown in Figure 26. The completed design can be seen in Figure 27 and 28.

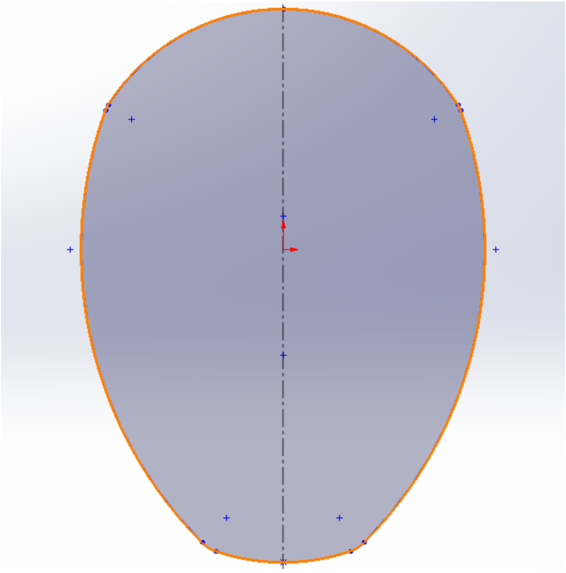


Figure 25: Face Outline Sketch Design One

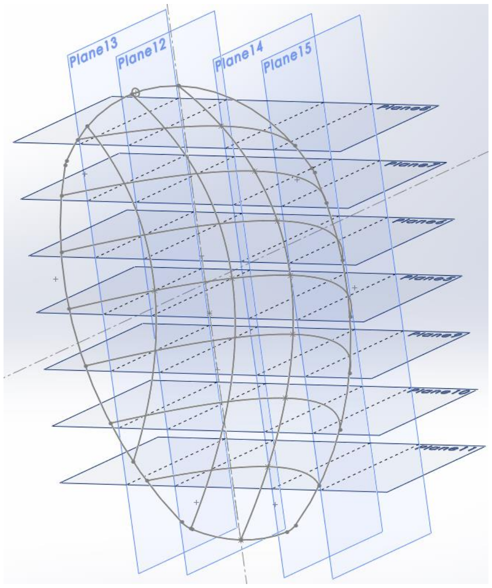


Figure 26: Spline Wire Mesh Design One

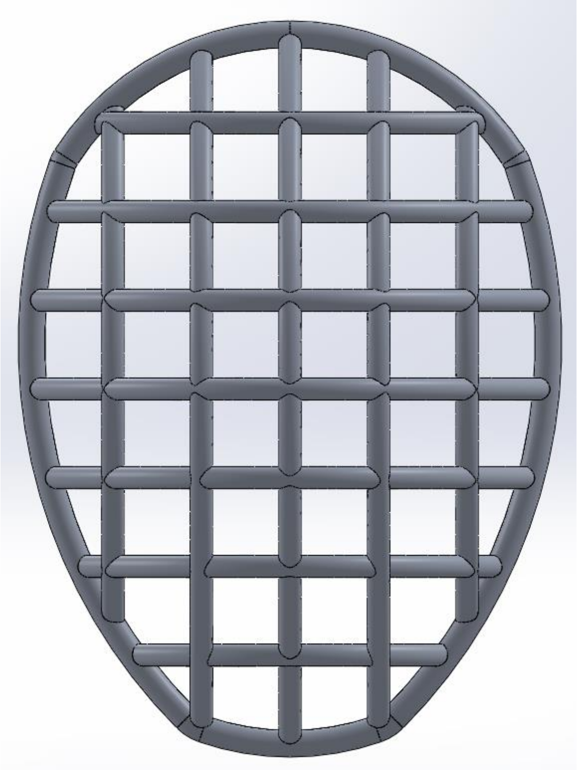


Figure 27: Mask Design One (Front View)

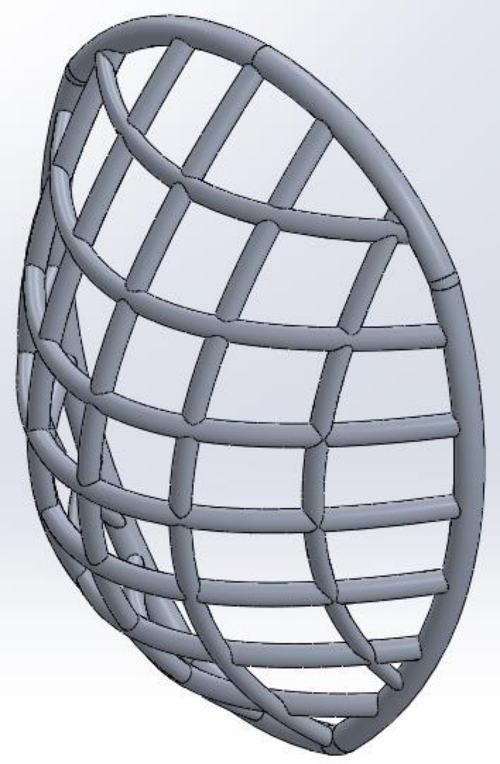


Figure 28: Mask Design One (Isometric View)

After a single iteration, we decided that there could be less bars vertically and horizontally in order to improve visibility while wearing the mask. When the mask was redesigned, it bars had much more space between them while still keeping the spaces in the bars smaller than the size of the ball to ensure it does not fit in between. This newer model was designed in a similar fashion starting with sketching the face shaped outline on the front plane as shown in Figure 29 then sweeping a circular profile along the outline. Similarly the bars were created on separate planes with splines and were swept with circular profiles as shown in Figure 30. The SolidWorks model for this newer design is shown below in Figure 31 and 32.

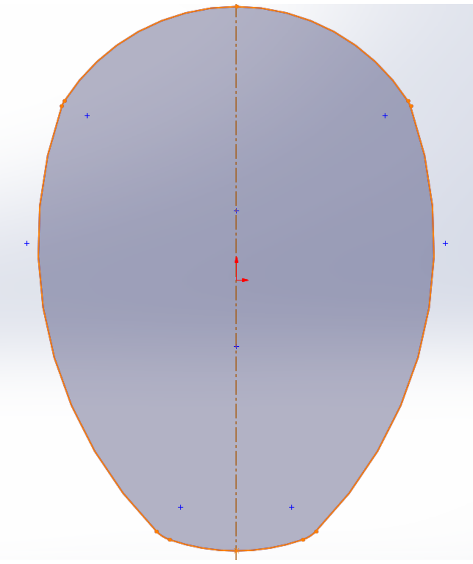


Figure 29: Face Outline Sketch Design Two

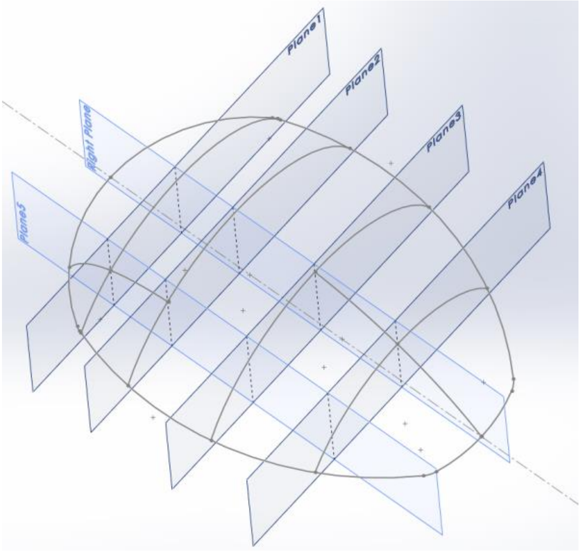


Figure 30: Spline Wire Mesh Design Two

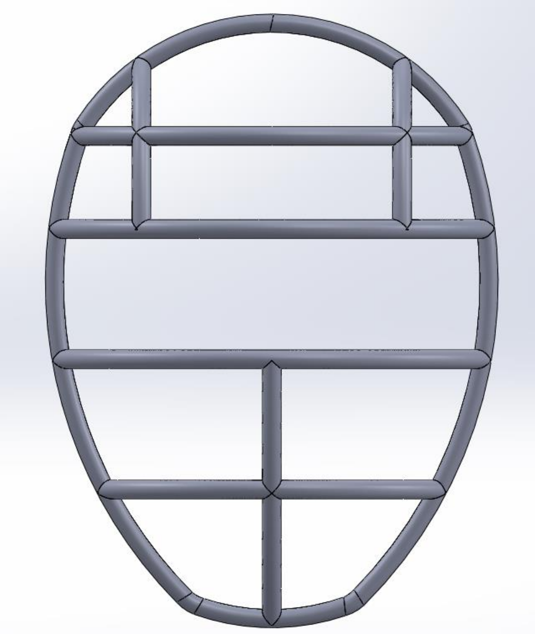


Figure 31: Mask Design Two (Front View)

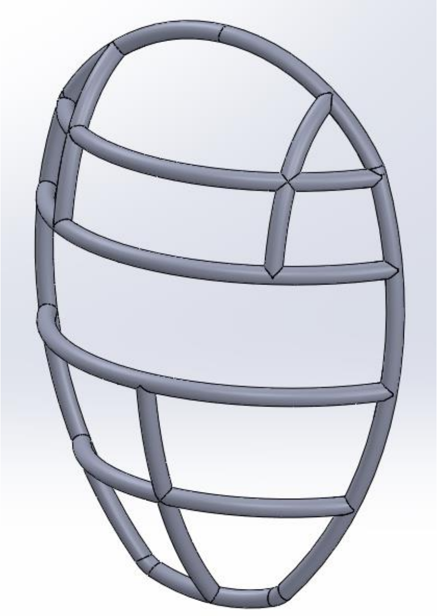


Figure 32: Mask Design Two (Isometric View)

After some preliminary testing with the actual welded mask, we realized there was a huge stress concentration near the eye slot shown in Figure 33, leading to the face mask deforming in a bending fashion whenever impacted. This led us to add an extra support bars at each end in order to reduce the concentration at the indicated locations. This led to the new second design shown below in Figure 34 and 35.

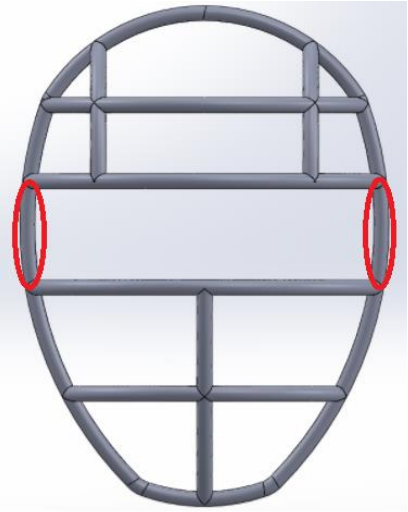


Figure 33: Stress Concentration Location Circled in Red

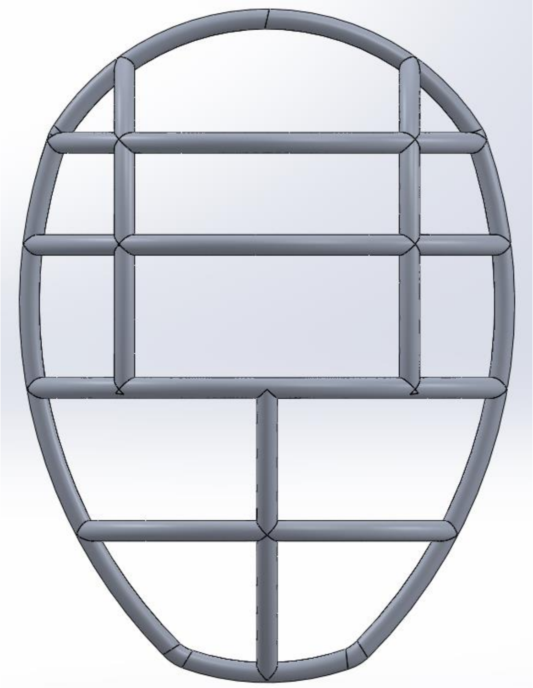


Figure 34: Mask Design Two Revised (Front View)

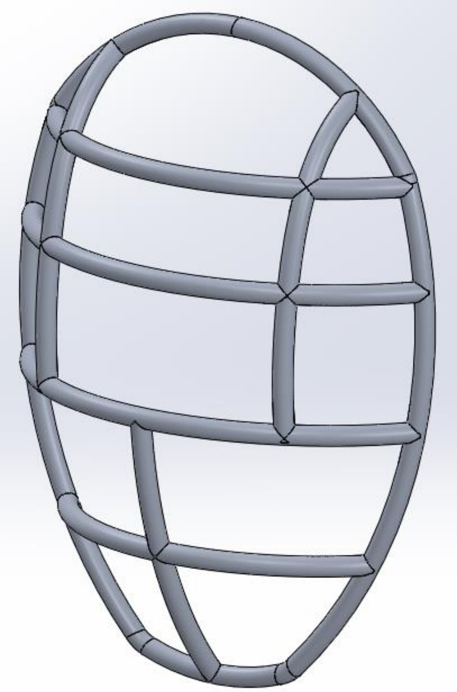


Figure 35: Mask Design Two Revised (Isometric View)

After some thoughts were shared about the current state of the design were shared, we decided to switch to a curved design for the back of the face mask. This is because it would make it much easier to attach to the face of a user. Additionally, we feel that it would make it look much better in general. This design was created in SolidWorks much differently than the other mask designs. This is because the initial sketch for the back of the mask had to be a 3D sketch using a spline that was then swept with a circular profile as shown in Figure 36. The wire mesh was created using splines on angled planes as well as the right plane as shown in Figure 37. The completely modeled curved face mask can be seen below in Figures 38 and 39.

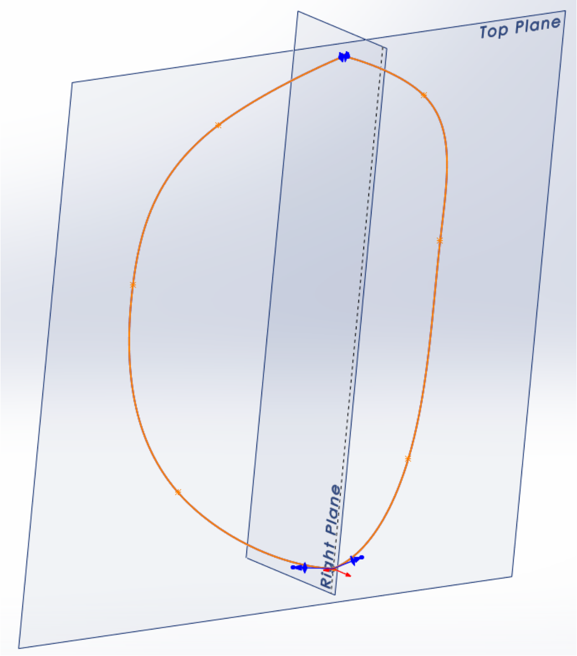


Figure 36: Face Outline Sketch Design Three

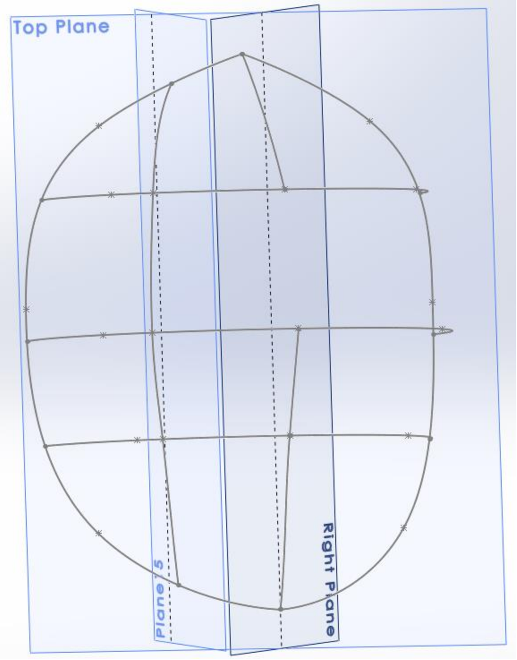


Figure 37: Spline Wire Mesh Design Three

Figure 38. Curved Face Mask Design Three (Front View)

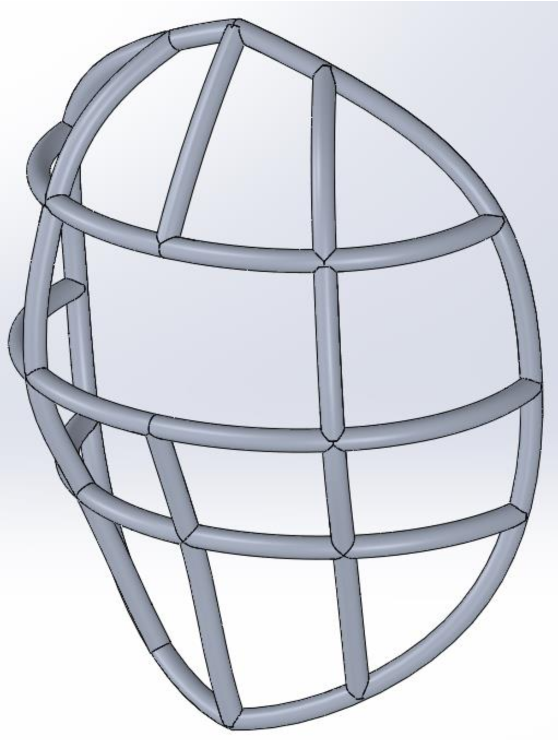


Figure 39: Curved Face Mask Design Three (Isometric View)

Since the above curved face mask is our final design, we decided to run some preliminary stress analysis calculations on this model in SolidWorks. Assuming a force of 700N based on preliminary testing data and the mask gets hit from multiple different angles the von Mises Stresses, Displacements and Strains are shown below in Figures 40 to 51 for each hit. Since the mask is perfectly symmetrical, the simulations were only done on the left side of the mask since the results would be mirrored on the right side of the mask.

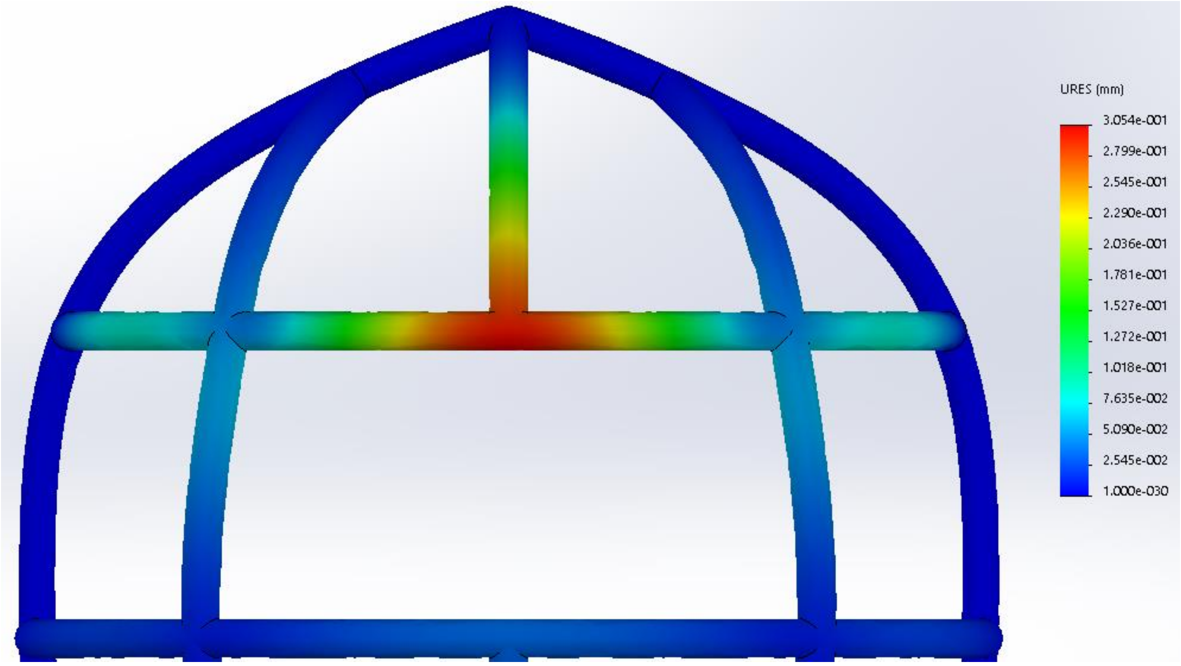


Figure 40: Center Top Hit Displacement

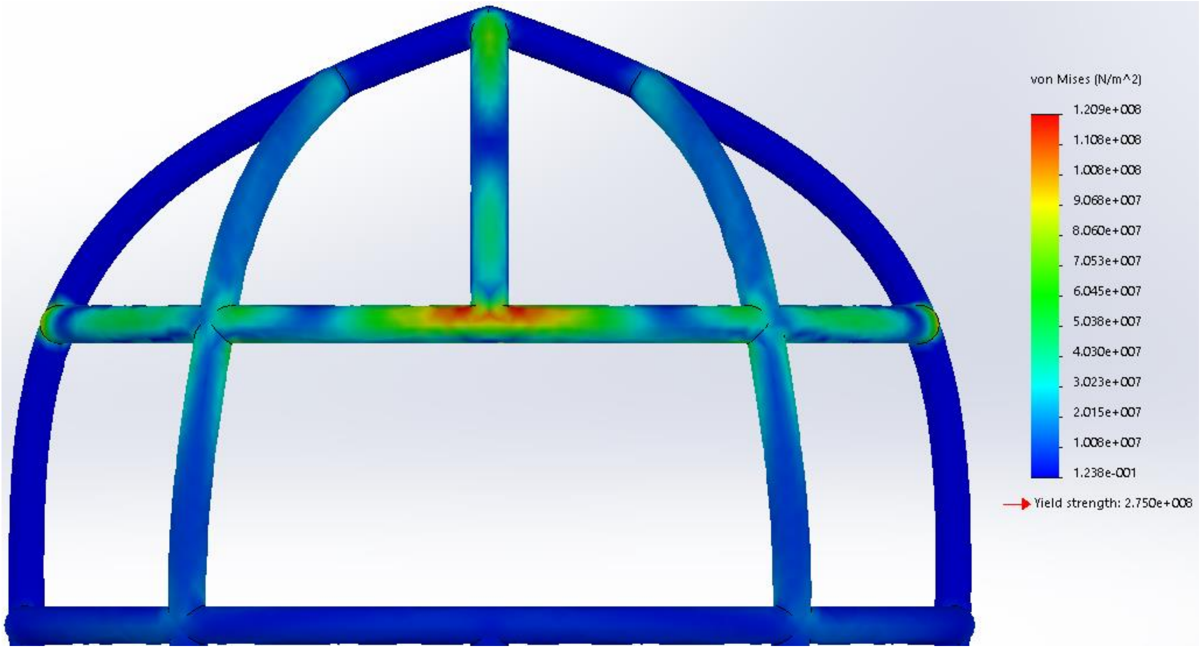


Figure 41: Center Top Hit von Mises Stress

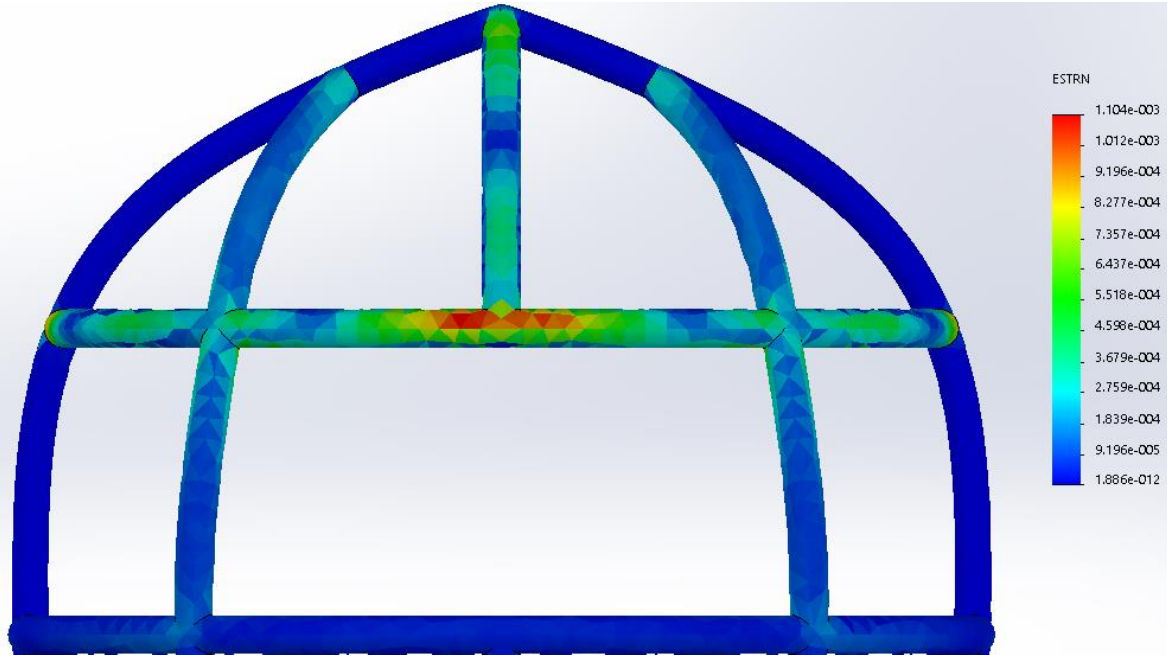


Figure 42: Center Top Hit Strain

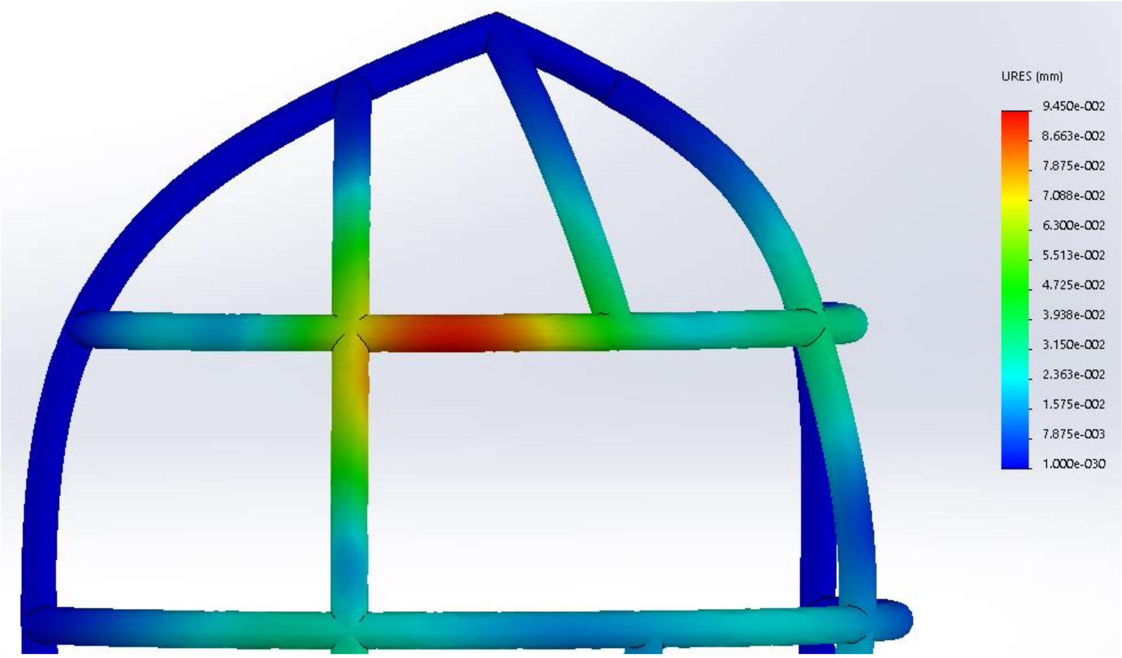


Figure 43: Left Top Hit Displacement

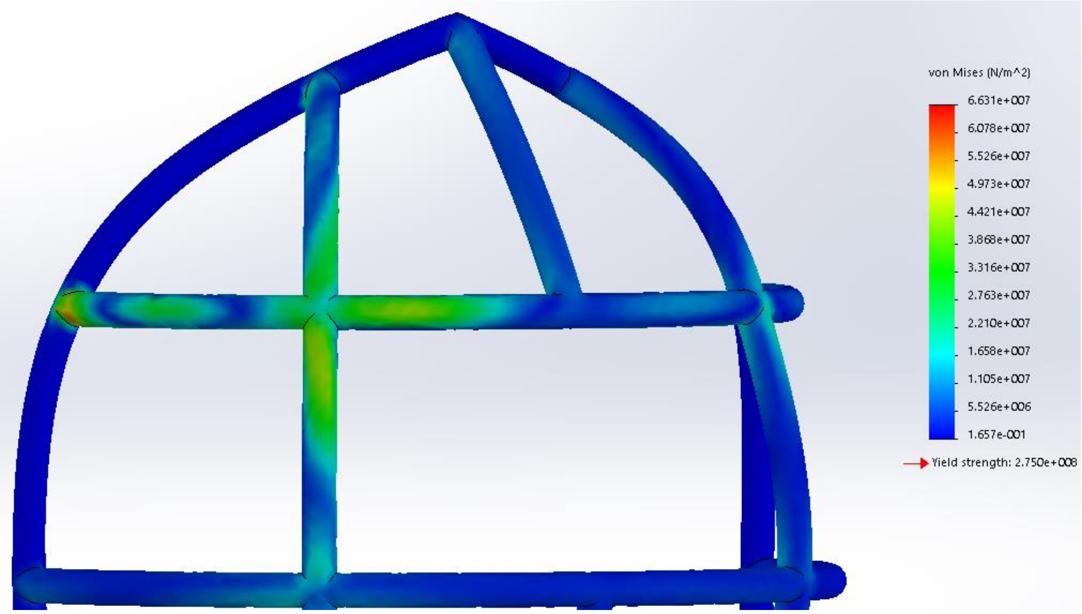


Figure 44: Left Top Hit von Mises Stress

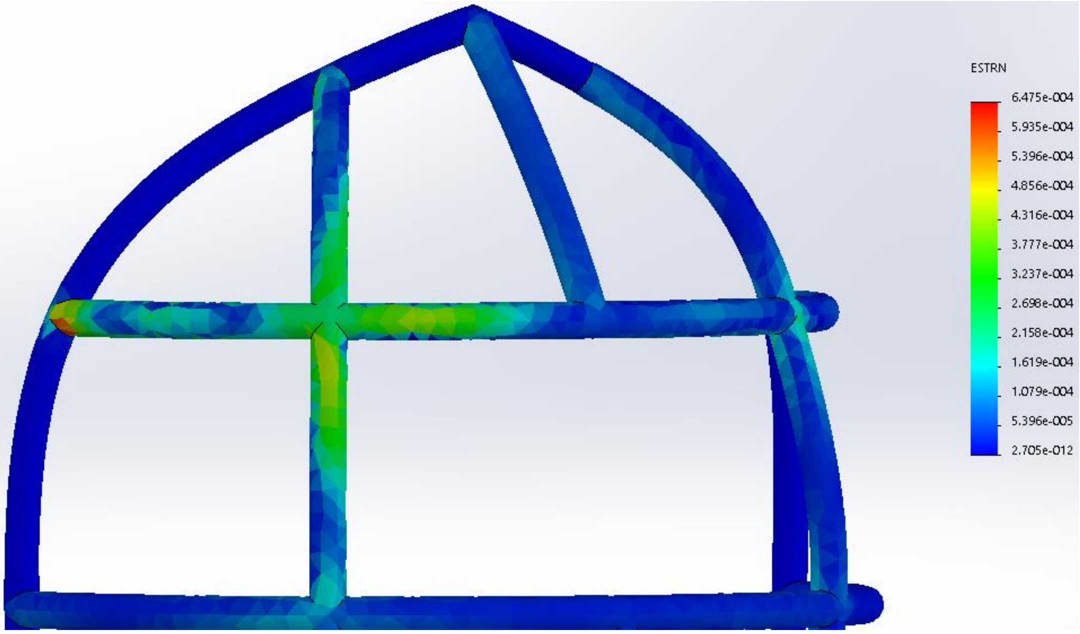


Figure 45. Left Top Hit Strain

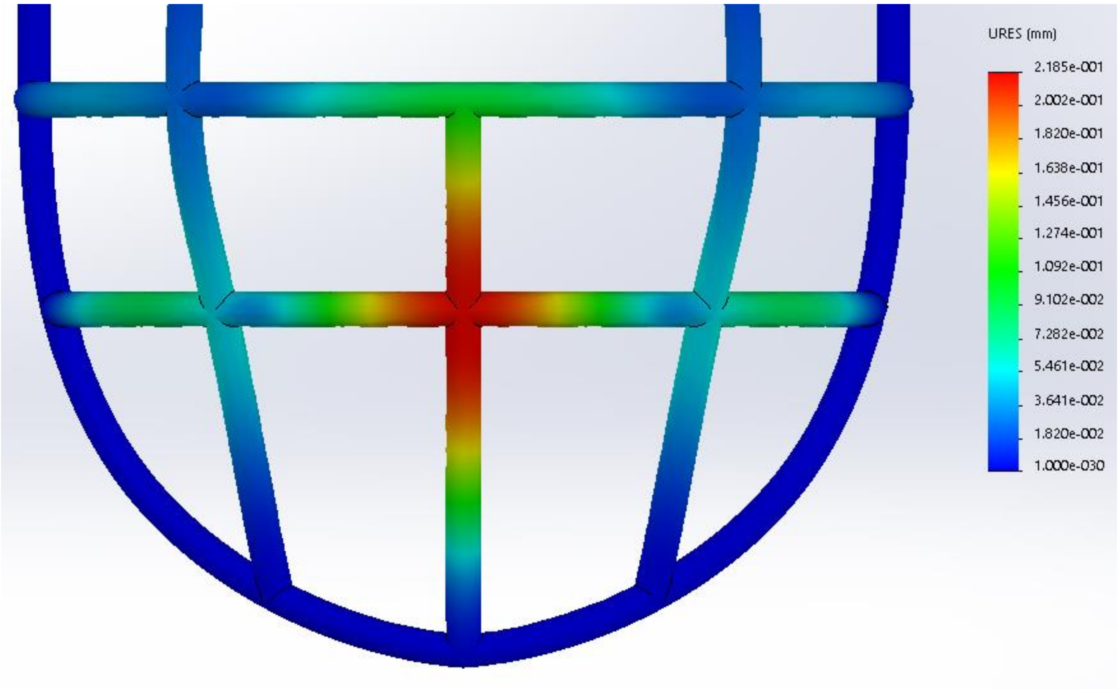


Figure 46: Center Bottom Hit Displacement

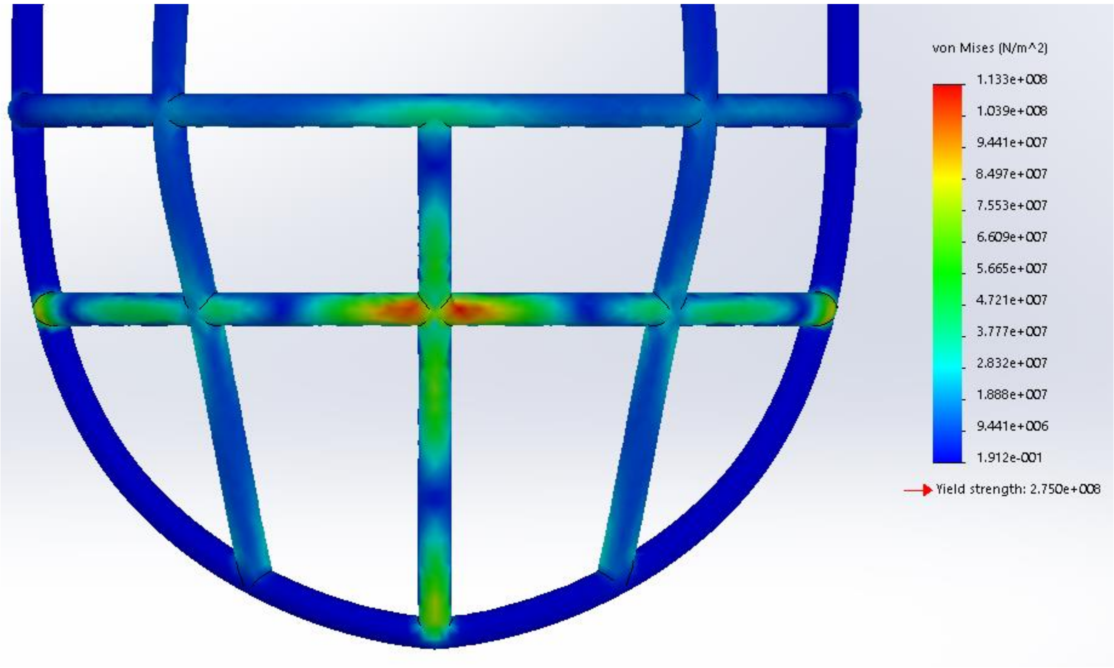


Figure 47: Center Bottom Hit von Mises Stress

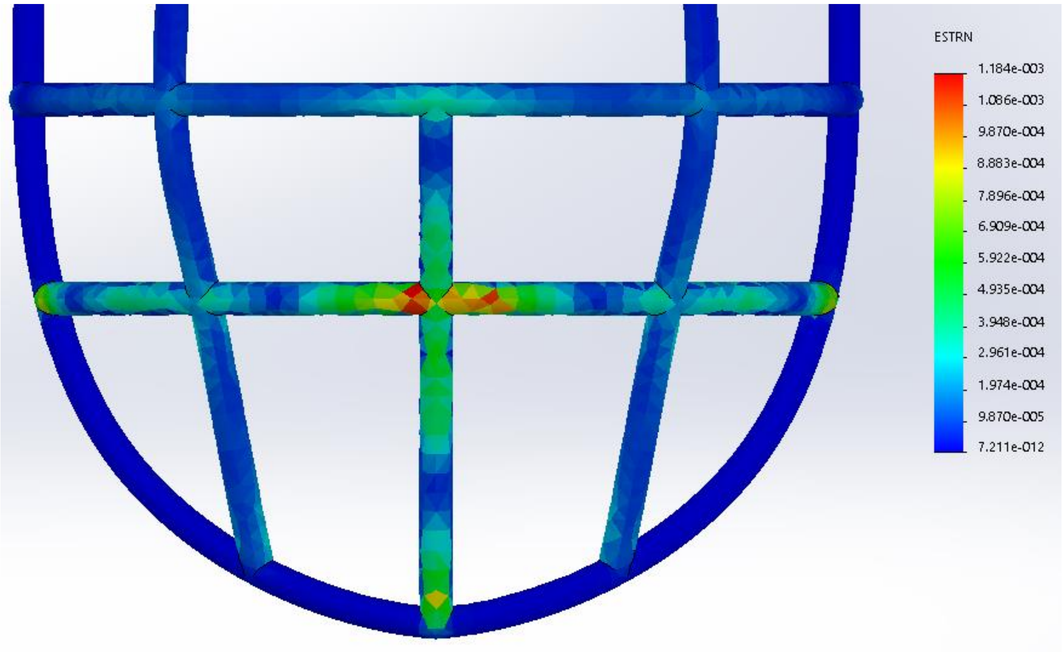


Figure 48. Center Bottom Hit Strain

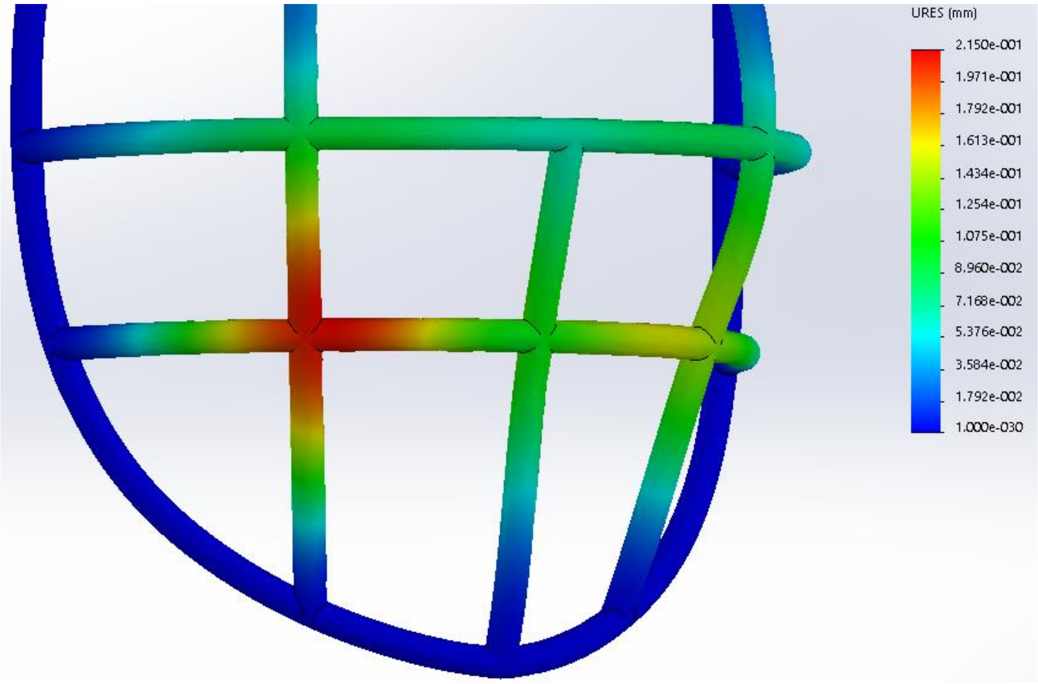


Figure 49. Left Bottom Hit Displacement

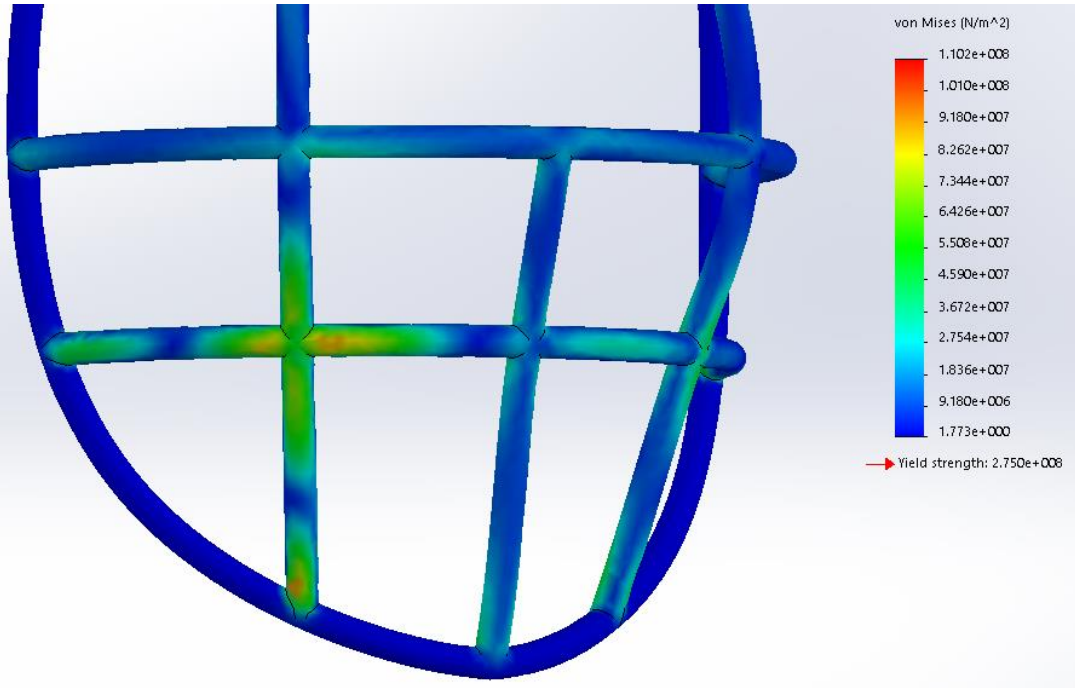


Figure 50. Left Bottom Hit von Mises Stress

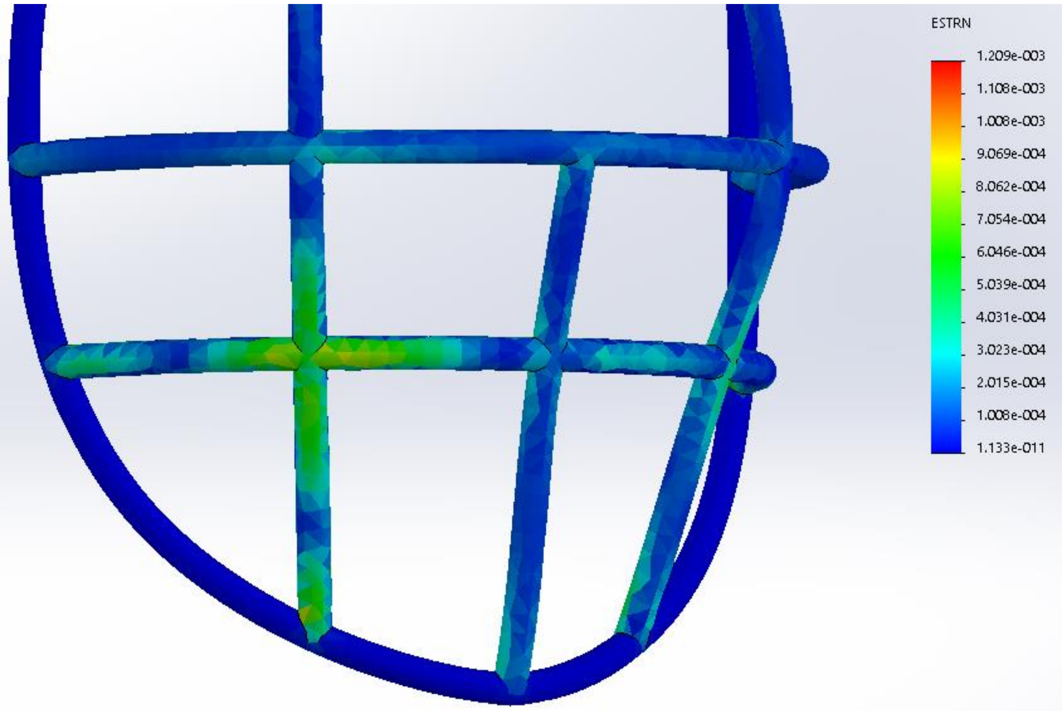


Figure 51. Left Bottom Hit Strain

As a general synopsis from the above Figures, the mask does deform by about 0.3 mm in the worst location to be hit (top center). This displacement is not significant enough to cause injury to the user because the foams will keep the mask significantly more than 0.3 mm from their face. Additionally, since the maximum von Mises stress in the material of 1.2x10^8 Pa is less than the yield strength of the Aluminum (2.75x10^8 Pa), the material is not permanently displacing. This means that the face mask will return to its original shape after impact. There is approximately a safety factor of 2.29 for the yielding of the mask when the face mask is impacted with a 700N hit. However, repeated strikes in the same location could cause the mask to fatigue and thus becoming less helpful to the user. This problem could be delayed by changing the material of the mask to a stronger metal while still keeping most of the mask's lightweight feature (current mask mass = 0.31 pounds).

One possible stronger material is a titanium alloy, which has a higher yield strength but will have a larger mass. Since the largest displacement and highest stresses were located at the center top hit, the titanium alloy mask was tested similarly. This titanium alloy would lower displacement to 0.18 mm while increasing the mass to 0.55 pounds. With this stronger material, the diameter of the face mask wires can be reduced to 3/16 inch to increase visibility and reduce the mass of the mask to make it comparable to the Al 6061 1/4 inch mask. Figure 52 to 55 show the 3/16 inch mask displacement, von Mises stress and strain when a force of 700N is applied to it.

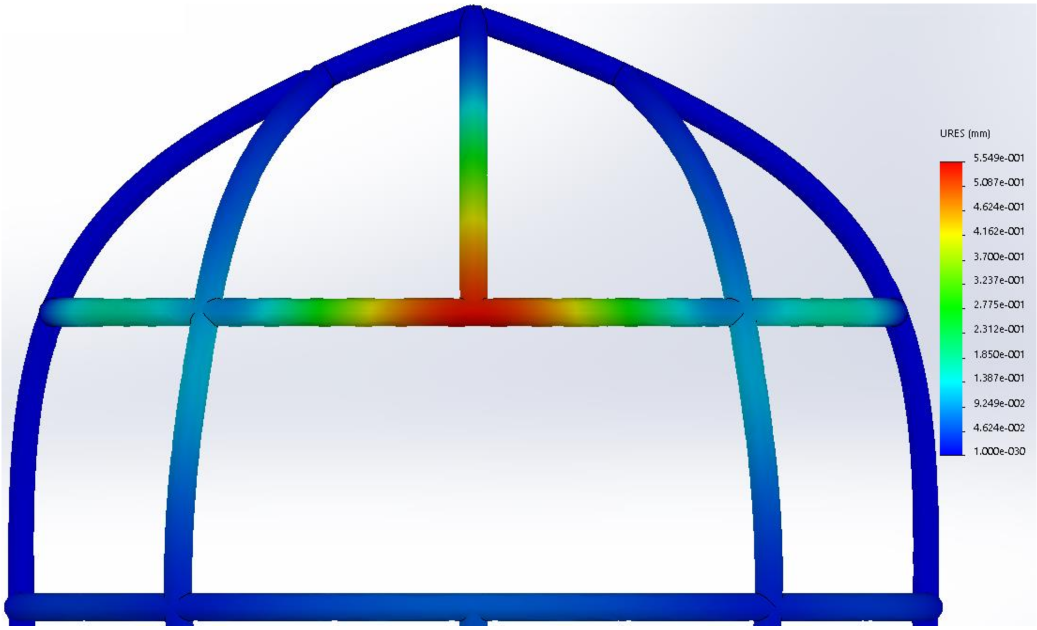


Figure 52: Center Top Hit Displacement Titanium Alloy

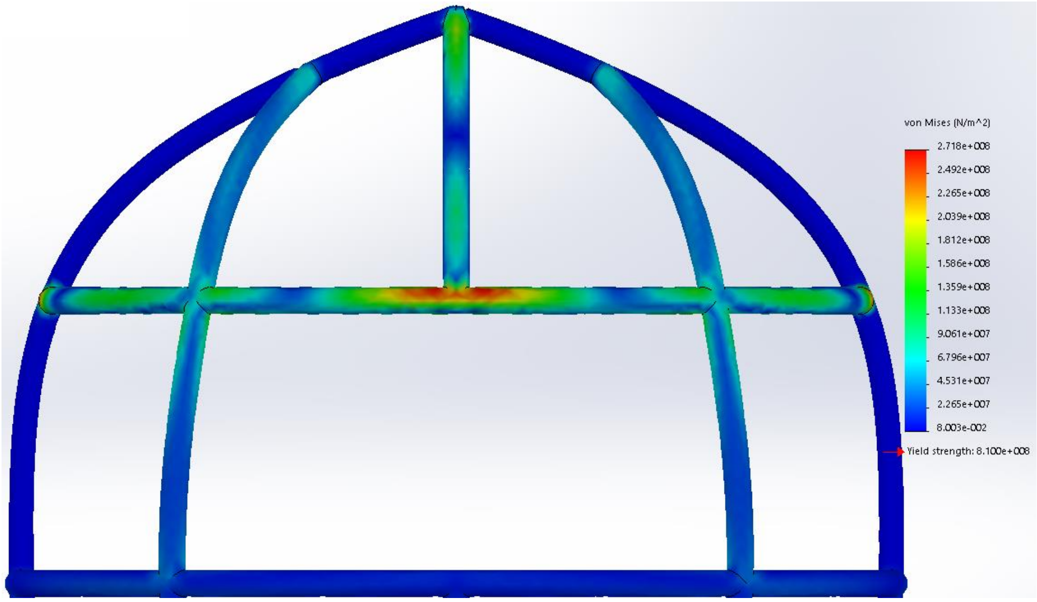


Figure 53: Center Top Hit von Mises Stress Titanium Alloy

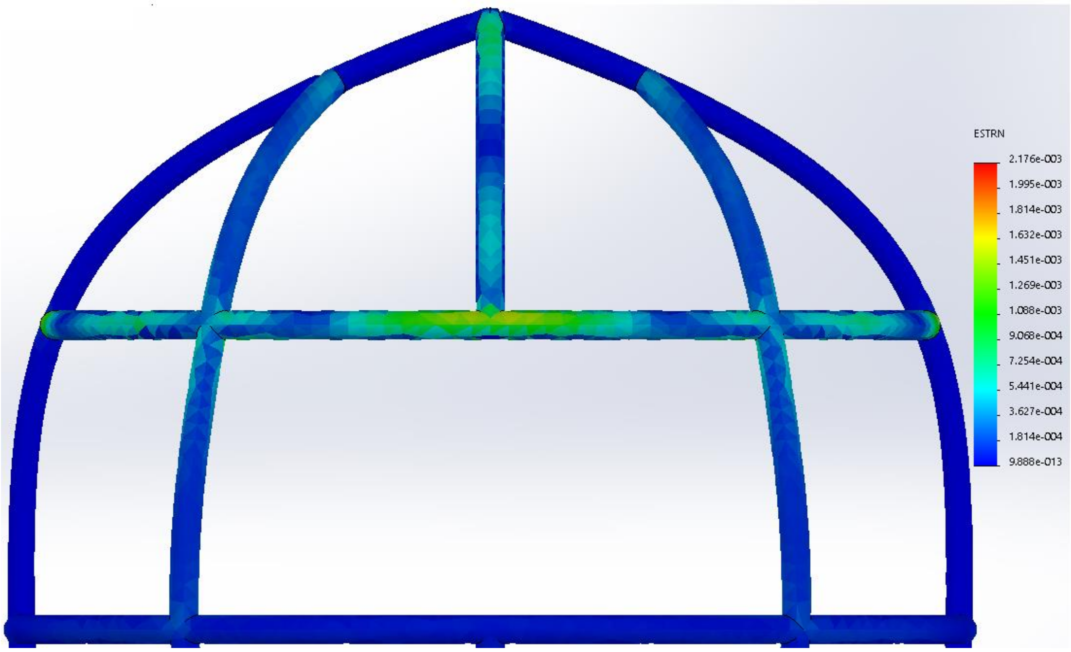


Figure 54: Center Top Hit Strain Titanium Alloy

The 3/16 inch mask has a maximum von Mises stress of 2.72×10^8 Pa and a yield strength of 8.1×10^8 Pa, meaning that the mask will return to its original shape after impact and has a safety factor of about 3. This mask displaces a total of 0.5 mm; the foam will safely keep the user’s face more than 0.5 mm from the impact. Additionally, this mask has a mass of 0.31 pounds which is exactly the same as the 1/4 inch aluminum mask.

5. Design Verification

5.1 Compression Testing of Foams

Although the energy-absorbing properties of the padding materials in the mask (sorbothane and poron) are affected by the high strain rates of impacts, static compression tests were performed to evaluate the forces at which sorbothane and poron compress. When both compression force and compression distance are known, the total energy absorbed by crushing the foam may then be calculated, as well as the force at which no more energy can be absorbed, called the crush force, usually 25% strain. (BHSI, 2017). For viscoelastic foams, forces required for deformation depend on the strain rate and impact performance may be different.

Procedure Steps

1. Cut foam into 4 squares, each 1 inch across, and measure their dimensions with a caliper.
2. Place each square under a corner of a flat, light, rigid pine board.
3. Set the board onto a flat level surface capable a bearing weight
4. Verify the setup is perfectly level.
5. Measure the height from the top of the board to the surface of the table three times. Mark where on the board this baseline measurement was made.
6. Gently place a weight atop the pine board and verify that the board is still level.
7. Measure the distance from the top of the board to the surface of the table with the caliper three times.
8. Gradually increase the weight and continue taking measurements until the compression of the foam is less than the repeatability of the caliper.
9. Repeat with other foams.
10. Calculate the compression of the foam for each weight, which is the difference in height compared to the previous measurement.
11. Graph the median compression of the foam with respect to force applied.
12. Calculate impulse of the weights on the foam, which is the integral of force with respect to distance, using a Riemann Sum or Trapezoidal method. Discard any data points showing negative distances.

Detailed testing notes and formulas, including testing equipment, are included in Appendix A. The results shown below are repeatable to a tenth of a millimeter, limited by the difficulty using the caliper and time-based plastic strain of the foam.

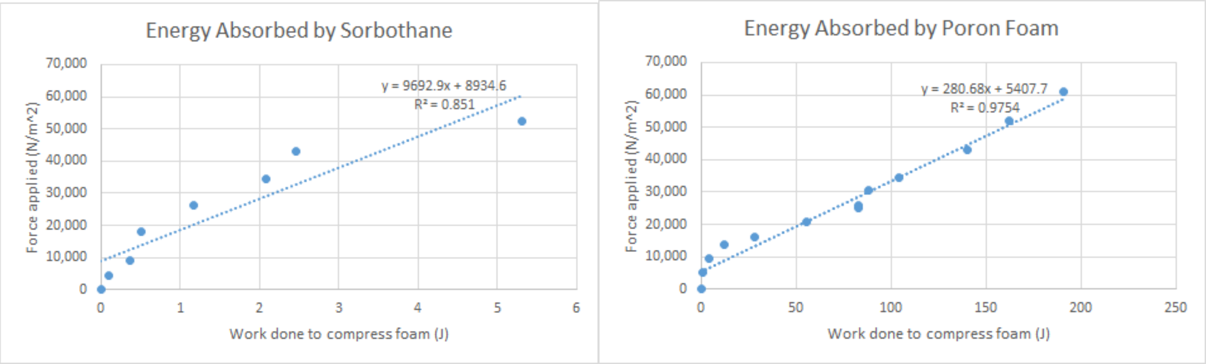


Figure 55. Energy Absorbed by Compressing Padding

The Poron foam absorbed significantly more energy than the sorbothane, primarily because it compressed a larger distance. The sorbothane is viscoelastic, meaning it absorbs energy differently during fast impacts, so the compression test merely supplements the results of the impact testing which was performed on the foam and mask. This means that the energy absorbed from the impact will be adapted to the intensity of the force/pressure applied; in this case the force applied from an average impact was roughly 700 N and the energy was roughly 18 J. Based on this approximately one third of the energy was absorbed by foam.

5.2 Impact Testing Apparatus - Head, Neck, and Pendulum

In order to achieve the same impact characteristics of a field hockey ball striking a face of a player at an injury-causing speed, a model head was struck with a field hockey ball on a pendulum. The model head was secured in front of the pendulum strike point at the end of its arc (90 degrees from the release point). It was locked in by the spring that simulates the neck so that when the head receives an impact, it can move as freely as a human neck when the head is rocked back by an impact from a ball. Videos of field hockey injuries show a healthy athlete normally attempts to move out of the way, lessening the severity of the ball's impact, but in order to maximize the safety factor the worst-case was assumed. The spring support was designed to achieve a bending stiffness of 5500 N/m, established as an approximation of the neck (Tavernelli et al., 2016). To accomplish this, the bending stiffness of a length of spring was calculated by measuring the displacement when a weight was placed on its free end as in Figure 53 below:

Figure 56: Measurements for bending stiffness calculation

We then used the bending stiffness equation ($k = 3EI/L^3$) to calculate the required length of the spring.

A plastic head-shaped form was filled with plaster and mounted to springs to simulate a human neck. Accelerometers were installed on the rear of the model head along the geometric center for each test. The head featured in Figure 54 is a plastic shell filled with plaster to match the 10-pound weight of a human head (about 4.5 kg). A wooden stand holds the head, which is glued to springs simulating the flexing of the human neck.

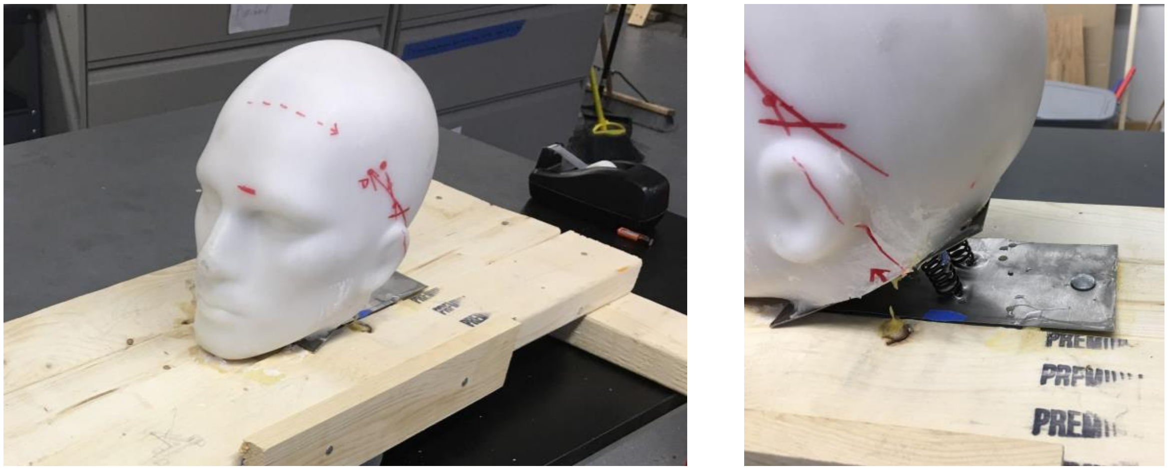


Figure 57: Mounted Model Head and Neck

A PVC pipe pendulum with a 0.7 meter (about 26 inches) arm is set up above a wooden stand with a plastic and plaster head. The pendulum weight consists of one field hockey ball with plumb bobs and a small steel weight duct-taped to it for a total weight of 0.6 kg, which is equivalent to four field hockey balls. When the weight falls 0.7, (the length of the pendulum arm) it has a speed of 3.7 m/s (8 mph) but the same momentum as a field hockey ball moving at 15 m/s (34 mph).

Materials: Wood stand, Pine blocks and planks, Hand saw, Wood glue, Nails, Duct tape, DAQ box and cords, Laptop with LabVIEW and Excel, PVC pendulum, Facemasks to test, Facemasks for comparison, Measuring tools, Bullet Level

Figure 58: Full Testing Rig

5.3 Impact Testing Process

Procedure Steps

1. Attach three-axis accelerometer to head.
2. Connect the accelerometers to the arduino and open LabVIEW.
3. Set up Arduino program.
4. Verify the LabVIEW program works.
5. Save data to excel file using an informative file name.
6. Start recording.
7. Lift the pendulum to horizontal and check with bullet level.
8. Drop the pendulum without pushing it, allowing it to strike the plastic head.
9. Lift the pendulum and drop it for a total of 10 impacts.
10. Stop recording.
11. Save data to excel using an informative file name including the date, time, and test conditions.
12. Open the data in Microsoft Excel and save it as an excel file
13. Conditional Format the data so high values are red and find the local maximums for each impact.
14. Graph the data in Excel

15. Save the Excel file
16. Repeat steps 2-13 for each variation tested, including each durometer of foam and all permutations of stacking the foam. Remember Neulog returns to default settings after each test.

Detailed testing of the foam with a load cell, with a force plate, and using manual measurement, are included in Appendix A, as are procedures for impact testing of the mask on the head, which is described here. The mask was tested by striking it with the pendulum 10 times, mimicking a 15 meter per second impact by a field hockey ball. Afterwards the face and the mask were examined for deformation, and acceleration data was taken to verify the effectiveness of the final mask. These results were then incorporated into the design of the final mask.
The accelerometer used was an analog sensor with sensitivity of 8.2 mV/G; the DAQ box's 16-bit ADC had sufficient resolution to be very accurate. However, natural noise and imperfections result in other inaccuracies; the manufacturer-given accuracy is approximately +/- 1 G.

5.4 Impact Testing Results

The collected acceleration data was used to calculate the HIC-15 of each impact. The formula for HIC is defined as the maximum value of the integral:

Equation 2: HIC Formula

$$HIC = \left\{ \left[\frac{1}{t_2 - t_1} \int_{t_1}^{t_2} a(t)dt \right]^{2.5} (t_2 - t_1) \right\}_{max}$$

For all possible t1 < t2 which bound a time interval up to the maximum interval size. t1 and t2 are measured in seconds and acceleration is measured in Gs. The maximum time interval specified was 15 milliseconds (hence HIC-15), which at our collected data rate of 8000 Hertz corresponded to a span of 120 data points. The HIC from each impact was calculated using trapezoidal integration; the Matlab script used for processing the data is located in Appendix D. The results are summarized below, with the full data available in Appendix C.

Table 7: Summary of HIC From Test Results

	Bottom Hit	Side Hit	Top Hit
No Foam	8.28 +/- 1.41	7.48 +/- 0.35	20.72 +/- 4.74
Sorbothane	6.58 +/- 0.97	4.56 +/- 0.68	9.36 +/- 3.38
Poron	3.67 +/- 4.78	3.46 +/- 0.85	22.88 +/- 30.77
Both Foams	2.33 +/- 0.43	2.73 +/- 0.29	3.14 +/- 0.16

Table 7 represents the average of 10 impacts for each scenario, with the associated standard deviation as the uncertainty. The general trend is a clear decrease in HIC with the foams in each situation. The one value which escapes this trend, the Poron-only top hit test, was notably the most irregular, with a high standard deviation. Referencing the full data indicates this was primarily due to a small number of excessive outliers; it is likely this was due to some error during data collection (e.g. faulty wiring). Larger scale testing or more better testing equipment could potentially smooth out these hiccups. The graphs below, Figures 59-61, show all calculated HIC values. All of the HIC values present here are much lower than the average value at which athletes receive concussions based on NOCSAE standards, 250. We had set this limit as one of our design requirements, seen in Section 3.3. This means that all of our configurations are effective at protecting an athlete from internal head trauma, with both foams being the most effective, based on these tests.

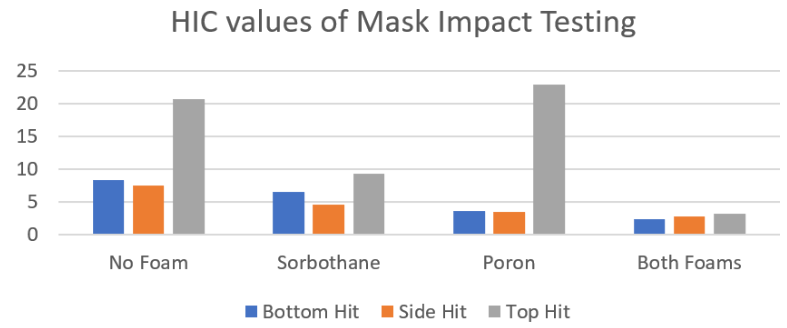


Figure 59: Summary Graph of HIC Values From Impact Testing

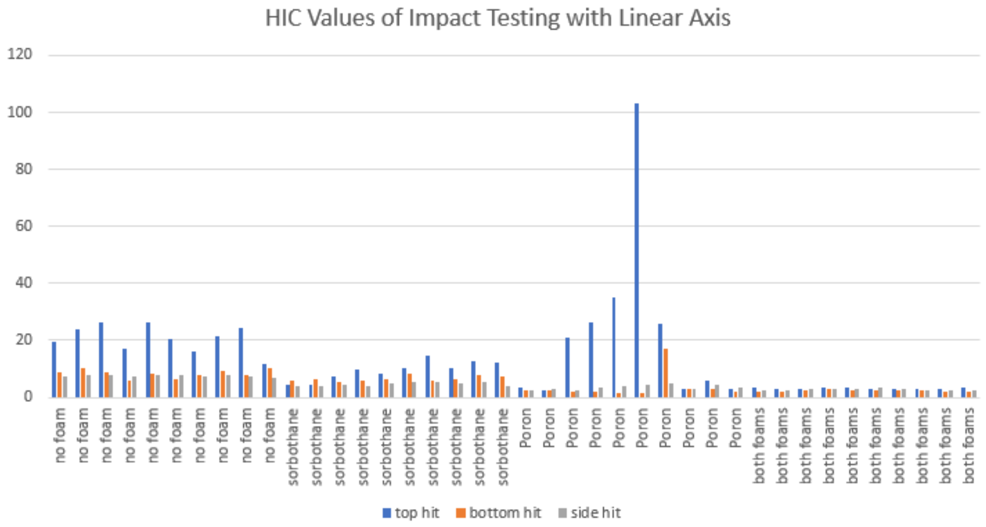


Figure 60: Graph of HIC Values From Impact Testing with Linear Axis

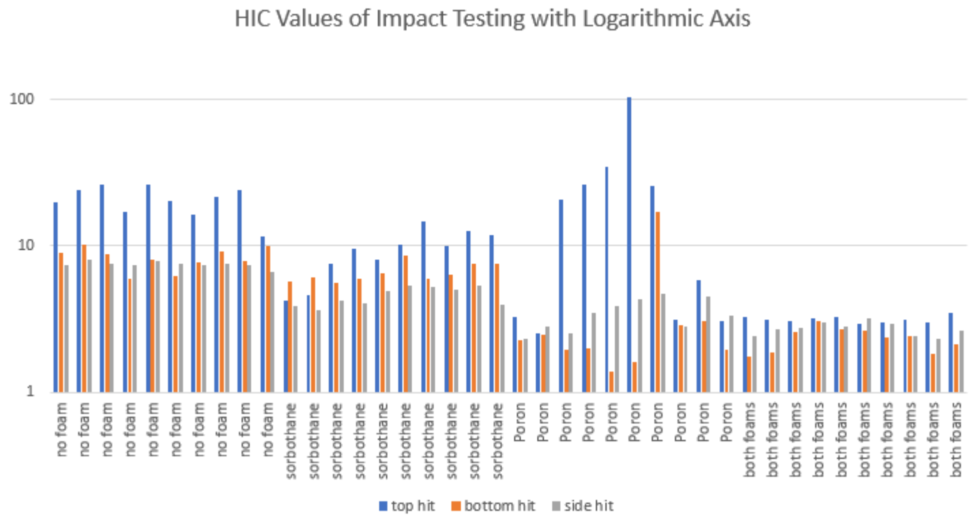


Figure 61: Graph of HIC Values From Impact Testing with Linear Axis

5.5 Player Survey

To evaluate some of the more qualitative aspects of our mask, such as aesthetic appeal, consumer perception, comfort, and general athletic performance, we opted to administer a survey to a focus-testing group of student athletes. A survey instrument was developed as a series of Likert Scale questions (e.g. “On a scale of 1-10, is the mask comfortable for you to wear?”) and an open-ended general comments / feedback section. Subjects were individually recruited, give a prototype of our mask for hands-on exploration, and prompted to answer our survey questions to the best of their abilities. The survey instrument and a summary of responses given can be found in Appendix D.

6. Final Design and Validation

6.1 Achievement of Final Goal

At the start of this project, the final objective that was set involved creating protective headgear that can protect against impact-related injuries effectively. This brought about an idea for a facemask that that not only absorbs impact to prevent severe damage but also has very little restriction of field of vision so playing ability is not limited when worn. In order to not restrict vision the majority of the facemask was designed to be a solid grille. The gaps between the bars would block incoming hits from the field hockey ball while still allowing the player to see well enough to perform competitively. Retaining the general form from other field hockey masks on the market, a foam lining was attached to the outside of the grille for the mask to rest comfortably on a player's face. Based on budget and time constraints, the materials that were bought and tested consisted of Aluminum 6063 and two foams, Sorbothane and Poron Microcellular Urethane. These materials were found to be effective, so the aluminum was welded to a proper shape and the foam was cut out from ordered sheets. When combined, this facemask was tested on with a pendulum to simulate the facial impacts that may be received during the game by a ball. Several tests proved the mask to be effective as well. The final design is pictured below.

Figure 62: Final Design

The final design does satisfy the objectives that had been set in the beginning of the project. It blocked impacts from a field hockey ball effectively at all points on the mask without deformation or failure. It also maintains the field of vision necessary for field hockey players when worn. There are, however, several criticisms that can be made; while being effective, the ability of the mask to absorb impact was less impressive than was theoretically planned. This may be due to the time and budget constraints measured above as those factors were one of the major deciding areas for picking materials, Aluminum 6063, Sorbothane, and PMU being desirable on a ratio of value to performance standpoint. Consideration also had to be given to the tools available for shaping, forming, and changing the raw materials for what was required. The materials chosen had to be manufactured by hand or with academic-level power tools that did not require a large time commitment. This is the same for the model head and the testing rig materials, such as the plaster and the PVC pipes. This hand-crafted approach also does not lead to ideal comfort in wearing the mask due to limited accuracy in sculpting to faces. However, the mask reduced the severity of impact-related head injuries on the head while not reducing vision; this device would provide safety benefits to the average field hockey player.

Based on the surveys conducted (found in Appendix D), players find the mask to be appealing in both function and form. They appreciate the improved visibility over existing mask and the improved airflow compared with that from a solid plastic faceplate. The mask was a reasonable weight, yet made the user feel as though their whole face was protected. The only area of criticism was the clips and strap that held the mask to the player's face; it was described as feeling loose and difficult to adjust. An elastic band was recommended over the current sewn strap, an easy replacement given more time. Given these statements and opinions, this alternative to the current protective headgear on the market for field hockey players likely would be widely adopted if given to a manufacturer who can provide for a wider audience and eventually increase the safety of field hockey as a whole.

6.2 Economics

If this product were introduced to the market and rebuilt with corporate manufacturing-grade materials and methods similar to other sports headgear and face masks, the economic ramifications would involve a new choice for consumers. There are several different types and brands of protective sports gear on the market today, even for field hockey alone. With the goal of creating a face mask that performs better than other face masks current available, the trajectory of this mask design will put it on track as an item that most field hockey players would want to purchase as their protective gear of choice. Although the mask in its current state does not exceed the competition in leaps in bounds, this is with, as previously stated, corporate manufacturing-grade materials and methods for constructing this design as a mass-produced, consumer product which would eliminate the constraints that were present during this project.

The field hockey headgear in today's market comes from several different, each priced similarly. The more commonly used the design, goggles that only protect the eyes, are provided by companies like Bangerz, Debeer, and STX who price between $20.99 to $49.99, with an outlier from Bangerz priced at $68.97. While this is an outlier price for goggles design brands, it is standard for full face masks for field hockey to be priced around $70. These masks come from brands such as Kookaburra, GRAYS, and Gryphon. A player may choose the goggles format for play as it is the least restrictive on the face, being both lightweight and easier to breath or see through. A player may choose the full mask format as it provides the most overall protection of the two. Since the mask design produced by this project strikes at the in between, it would theoretically be the most preferable choice and therefore the most purchased choice between all of these brand’s options. It provides full face protection while being open-air, utilizing a grille of aluminum bars over a solid plastic shape, so that the player can still have a good amount of visibility without sacrificing too much on weight. The aluminum, foams, and other materials purchased for this mask were all a the lower-end of price, so if mass produced, this mask design should be able to edge out a lower price than current full face masks and be able to compete with the pricing of higher end goggles. Overall, this project’s mask design should perform quite well in the consumer market.

6.3 Environmental Impact

The environmental impact of this design was not taken into account in terms of materials choice and construction, apart from the choice to build a multiple-impact mask instead of a disposable one. As it stands right now, neither the Aluminum 6063, Sorbothane, PMU, or overall construction provide any sort of significant environmental impact. However, when economically mass-produced, more efficient manufacturing may allow for less material to be used when each face mask is built but with no compromise to the safety standard of the original design. The resources required would not be wasted as much in turn as an output alongside the final line of products. In this day and age, many companies are encouraged by consumers to “go green” in power consumption, waste disposal, sustainable practices, ethical procedures, and so on. Manufacturers can reap the benefits of good marketing by displaying to the public how they produce their products and in turn drawing more consumers for product purchases. Finding a manufacturer that uses these environmentally-friendly practices would benefit this mask design greatly in the market as well as lowering its impact on the world’s ecosystem.

6.4 Societal Influence

This desired social impact of this mask design is to actually get field hockey player to wear protective gear while playing for the majority of the time. Currently, field hockey players do not want to wear the gear that is proven to offer adequate protection from impact-related injuries since they find that headgear restrictive or heavy. The designs that are on the opposite spectrum, being small and light like protective sports goggles, offer little to no protection to most of the face. While more frequently used, field hockey players would rather wear nothing at all since there are no middle ground devices. The only time masks are required is during corner kick plays. With the final design of this project, those issues have been attempted to be fully addressed. The face mask is not particularly light, but is much lighter in comparison to heavy helmets and other face masks. The majority of the mask being a metal grille made up of a limited amount of aluminum bars allows for very little compromise on visibility. The aluminum grille and the impact-absorbing foam still offer injury prevention here as it is was the highest priority for the mask despite the need for weight and visibility improvements. If this were offered as an alternative to field hockey players, it would hopefully offer enough for them to utilize them throughout their games.

6.5 Political Ramifications

The current legal climate of the United States of America makes preventing concussions more difficult because of liability laws and scientific uncertainty, although standards have been established for several other aspects of field hockey safety. The Consumer Product Safety Commission (CPSC) has the legal authority to set standards for helmet safety, and the National Operating Committee on Standards for Athletic Equipment (NOSCAE) established testing standards. American Society for Testing and Materials (ASTM) also has a voluntary standard (ASTM F2713). These standards all focus on preventing eye injury by preventing projectiles or the mask itself from touching the ocular region during impact testing (the ocular region does not include the nose, which is frequently broken in field hockey). As eye injuries are a major concern in field hockey, the existence of these standards is necessary but not sufficient. These standards require accelerometers to verify impacts to the skull are non-fatal, and forbid the mask from being permanently damaged by impact tests or penetration tests.

There are also optical distortion standards, coverage requirements, and similar expectations. The lifelong consequences of head trauma for athletes are well documented, yet there are no legally binding standards on concussion-preventing field hockey gear in the USA. There are standards for skull protection and for eye damage, but standards for concussion protection in the are relatively non-existent. Furthermore, because of liability laws, athletic equipment manufacturers do not advertise concussion prevention. Concussions are difficult to define and quantify, and scientists and doctors do not agree on safe levels of impact for adults, much less for children and adolescents. Concussions are not merely a function of maximum linear acceleration, but also of angular acceleration and duration of acceleration, as well as lifetime number of impacts. Further complicating the matter, concussion victims are susceptible to further concussions while healing, and athletes do not always rest long enough to fully recover, creating a vicious cycle in which each concussion leaves the athlete more concussion-prone until even trivial impacts yield serious concussions.

Without definitive guidelines from the scientific community, manufacturers dare not market their products as concussion-preventing, lest an athlete wearing their helmet gets a concussion and sues them for medical costs, or worse a death (in the USA death cases award a theoretically infinite amount of money). As equipment manufacturers will not market the concussion-preventing abilities of their helmets, they rarely invest in designing for concussion prevention, and the typical consumer cannot easily compare different helmets safety performance. The ramifications this project will have on politics are unlikely to be dramatic, as it is narrowly focused on field hockey, although the facemask design and testing methodology may be effective for other athletics, such as similar sports like baseball or lacrosse. Conversely, the political and legal climate of the USA notably hinders the practical use of our project, and significantly hinders national efforts to prevent concussions in sports.

6.6 Ethical Concerns

Due to the severe and potentially lifelong damage head injuries can cause field hockey athletes, our product endeavors to prevent concussions among field hockey players. Conducted honestly and reported accurately, this is an ethical pursuit. Our product aims to prevent mental and physical damage and to offer peace of mind to the player and the family, friends, and fans of that player through the design of a safer field hockey mask. Engineering and testing the product is meant to inspire trust in the safety that the product can provide without impacting field hockey's fast-paced gameplay. This should mean less time injured, less time worrying about injury, and more time enjoying the game. Additionally, concussion prevention should improve the quality of life for these athletes both while they play field hockey and in the years after they retire from the game.

To avoid unethical activities during the design and testing process, this project complied with all WPI guidelines and policies during the MQP process, including stringent interviewing protocols by WPI's Internal Review Board (IRB). The students who conducted the interviews completed a web-based National Institute of Health (NIH) training course, "Protecting Human Research Participants", obtained written informed consent from all interviewed students, and protected the privacy and identities of all interviewed students through anonymity. All activities were held to the ethical standards of our university, as well as the professional ethical standards expected of engineers and personal moral standards.

6.7 Health and Safety

The main purpose of this facemask is to improve the health and safety of field hockey players through concussion prevention, reducing injuries and improving their quality of life both while they play the sport and in the years after they have retired from the game. Historically, field hockey players have experienced a wide variety of injuries, particularly concussions, nasal fractures, eye injury, and irreversible damage to the mouth, usually caused by impact of the ball. To keep players healthy and safe during field hockey games and practices, athletes must wear effective headgear. Protective goggles and face masks do not provide adequate protection, and are particularly insufficient for concussion prevention, partly because they are rarely designed for concussion prevention (see Political Ramifications).

This project's facemask is designed and tested to decrease in those types of head injuries to which field hockey players are prone. It is difficult to evaluate the potential for poorly understood injuries such as concussions, making test criteria difficult to select, but in terms of a general factor of safety this product is designed and tested to exceed currently the existing facemasks which are commonplace in field hockey leagues. More broadly, engineered facemask designs such as this one may inspire current providers of equipment for field hockey and sports in general to revisit or redesign the protective gear they currently produce in order to provide a healthier and safer way for players to compete without the rate of injuries and damage that exists today. Our design focused on the ball causing injuries because this mechanism of injury is the most commonly occurring in field hockey. We have not tested the effectiveness of the mask in impacts created by a human elbow or a field hockey stick. Field hockey is an inherently risky activity and no equipment can make it entirely safe, but all ethically developed designs aim to improve the health and safety of the sport.

The facemask must be manufactured in a safe and environmentally conscious manner. Mask paints must be safe for prolonged skin contact even under hot sweaty conditions. The mask, including all attachments and coatings, must be free of lead and other substances harmful to children and/or forbidden in the USA. The mask and its prototypes may not have sharp edges, sharp points, or catch points which may cause injury, nor may it be prone to break and create such edges or points under normal use. No part of the mask or harness may be detachable in such a way as to pose a choking hazard. The harness must be assembled to prevent strangulation hazards even under unusual circumstances, such as getting stuck in a tree, because children do these things with helmets on, although it is not possible to protect against deliberate self-harm. In summary, this product is intended to be worn on young people’s faces and must comply with all regulations for such devices, as well as ethical engineering standards, common sense, and due caution.

During the project, our group followed WPI’s established health and safety policies, the lab policies, and group-specific expectations. There were no injuries, and near misses were reported to the group. For details, see Appendix A.

6.8 Manufacturability

The Aluminum 6063 was bent, cut, and formed to shape by hand with basic tools and was welded together to form a grille with a simple welding torch available to base users on an academic campus. The Poron Microcellular Urethane and the Sorbothane was malleable enough to be cut with office scissors and Exacto knives in order to properly outline the solid structure. The tools and conveyer belt methods that are available to manufacturers today should cut down on the production time considerably as well as constructing each item more accurately and precisely. In terms of the cost to manufacture the product, the materials that were chosen for this product with consideration not only to the ease of utilization for building, but for the price points at well. Manufacturers who purchase supplies in bulk for mass-production will no doubt acquire the necessary materials at an even greater overall value than what was available for designing a prototype. To summarize, theoretically neither the construction nor the cost of a mass-production model variant of this project’s face mask blueprint should cause any issues for manufacturing processes.

The grill of the mask can be produced through a number of manufacturing processes. The two most cost and effort efficient methods are to spot weld the masks or to injection mold them. In industrial manufacturing, the ability to control all processes through computer models and robotic procedures allows for much greater accuracy when making a product. Robotically controlled welding is both rapid and can be set to user specifications through calculation as opposed to the trial and error approach necessary for the utilization of a manual spot welder. Injection molding is another fast and accurate process. The ability to reuse a mold well over one hundred times prior to its retirement allows for low overall cost and extremely high repeatability. The molds can be produced to have extremely tight tolerances which allows the manufacturer to select the level of perfection of the final product. Both of these processes allow the manufacturer to have greater control over the final product and the final pricing.

The foams would most likely be applied in a similar way to the method that was used for this prototype. This means attaching with adhesive but the only difference being that it would be computer controlled such that the repeatability would be increased. Additionally, there may be an applied outer layer to increase the durability of the foam and to increase the lifespan of the foam. This outer layer would simply be a leather or water-resistant polyester lining.

6.9 Sustainability

As this mask is designed for multiple impacts, it is more sustainable than a single-use mask. The non-impact absorbing covering could be made of biodegradable or recyclable wrappings, and the final responsibility to recycle the mask would rest with the player, as the metal itself is recyclable. However, the mask design has minimal effect on the environment as a whole.

The ecological footprint of this mask would depend primarily upon the ecological responsibility of those who manufactured it, but manufacturing of the mask was not examined in great detail within this project. Environmentally conscious energy sourcing, manufacturing waste management, and recycling should all be practiced but were beyond the scope of this project. Socially conscious business practices are again recommended but beyond the scope of this project.

7. Discussion

The choices made to design and create the face mask were inspired from technology and products proven to be effective in a variety of different studies. We built on existing technology and methodologies, particularly for the functional appearance of the mask, the choice of materials, and the approach for testing the mask's performance.

The effectiveness of a baseball catcher's mask was excellent, protecting against projectile speeds up to 90 miles per hour, and therefore was the main model for our designs. The grille that covers the face accommodated the wide visibility needs of field hockey players in games. However, the baseball catcher's mask is not made for motion on the field, as baseball catchers are expected to remain stationary, so for this project the design and straps were altered. Research on viscoelastic materials indicated that their impact absorption performance exceed average foam paddings and were found to be quite effective in preventing brain injuries. Sorbothane was found to be reasonably priced and was used as a major component to the face mask designed for this project. The testing apparatus was selected among several different designs to balance lead time, space, and material requirements. The test rig was able to mimic a field hockey ball moving at 3.7 meters per second. A model head and neck was designed and built to serve as a realistic target, providing the general standards of a human head weight and shape and an average neck involving a bending thickness of 5500 N/m.

The HIC calculations from our testing showed a marked impact reduction with the foam padding. Notably, the mask itself resulted in HIC values well below those established by the NOCSAE as limits even without padding. This likely indicates that impacts that occur in field hockey are relatively safe even without head protection - which anecdotally seems to be corroborated by the lower number of concussions observed in the sport (only one to two yearly for WPI's team). That being said, the decrease in HIC values was significant - in the range of a 60-70% reduction. Forehead-height impacts generally caused higher accelerations and HIC values, likely due to the greater rotational acceleration about the neck.

As is common in impact testing, the standard deviation of our tests was fairly high, in some cases even surpassing the mean value. In most cases, this was caused by one or two strong outliers, as can be seen in Appendix B. While increasing the number of trials might have mitigated this, the very unpredictable, chaotic nature of impact testing means reproducibility is almost always problematic. We consider our pendulum testing method generally more reproducible and accurate than the drop tests which are industry standard.

8. Conclusions and Recommendations

When discussing these results, it is important to consider recommendations for further improvement beyond this project. In terms of manufacturing, our fabrication of the mask achieved the overall goal but was labor-intensive and somewhat imprecise, mostly because the metal was hand-shaped freehand with tools such as welding torches, files, and mallets, yielding an imperfect fit. If the mask is mass-produced, other methods of manufacture will be needed, and it is likely that automation and dedicated machinery will greatly improve reliability.

Some potential improvements were also identified during our surveys with the field hockey players. Players surveyed complained about impairment of their peripheral vision. This poses a difficult problem, as the bars in the mask are necessary for structural integrity but impair the players' peripheral vision, compared to wearing no mask. One improvement on this could be made by changing materials to a titanium alloy in manufacturing; as mentioned in Section 4.7, usage of a titanium alloy would allow for thinner bars. Additionally, the players were asked if the visibility was comparable to that of the current masks they used. They consistently answered that this design was superior to the current existing masks and one player stated, in reference to the polycarbonate mask, "when you're breathing heavily and the [mask] fogs up you can't see anything". This indicates that although visibility remains an issue, this design is still an improvement on the existing options in terms of comfort and vision, as well as impact reduction. They also remarked on the need to quickly don and doff the mask, and recommended the strap be made of an elastic blend instead of the polyester strap used in the prototype, a recommendation we endorse.

With that said, while there are definitely more improvements to be made, we were successful in creating a working prototype that reduces HIC of typical field hockey impacts by 60-80% while offering better visibility than existing designs, which should dramatically decrease brain injuries while improving player satisfaction and gameplay. It is our hope that continual development and improvement of such designs will result in widespread use of protective equipment that reduces injuries and keeps athletes safe.

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Appendix A - Detailed Procedures

Safety Rules and Guidelines for Impact Reduction Major Qualifying Project

Our Group's Safety Culture:

- Use caution, common sense, and good housekeeping to prevent injury to yourself and others.
- Always have a buddy whenever working in the lab.
- Follow the safety rules of the lab space you are in.
- As prospective engineers, think about what you're doing.
- Treat others with the respect and kindness you would like to receive. If the person performing an operation (especially welding or impact testing) needs Personal Protective Equipment (PPE), everyone else in the vicinity should be wearing PPE as well. (Does not apply to gloves.)
- Avoid distractions or horseplay. Be aware of your surroundings, including the activities of non-group members in the laboratory.
- Report unsafe conditions to other people in the lab spaces and to relevant authorities.
- Always wear appropriate safety equipment for the task being performed, even if it is not officially required.
- Report near misses and lessons learned to the entire group as a learning experience.
- Throw out broken equipment if it cannot be fixed. Clean up your own messes.
- If you don't know how to do something like use a machine, ask someone who does.

Other group-specific safety notes:

- Do not weld coiled springs. They arc and explode.
- If you smell gas or chemicals, even if you are not the person using them, open windows to create a cross-breeze, and notify other people in the vicinity of your observations (odors, dizziness, etc.). Also report this to relevant authorities.
- When using glues, cements, and epoxies, wear gloves. Mixing with brushes and sticks is recommended. If you get them on your skin immediately wash with soap and lots of water. Do not allow it to dry, cure, or harden.
- Do not eat in the lab. Wash your hands between leaving the lab and eating.
- Lock the door when you leave the lab empty.

WPI-wide Laboratory Safety Rules:
(https://www.wpi.edu/offices/environmental-health-safety/laboratory/rules)

- All personnel working in labs must be trained in safe work practices by the lab supervisor.
- An accurate hazardous materials inventory must be maintained. Order chemicals in quantities for short-term use. An MSDS should be available for each hazardous material in the lab. Call x5216 for copies.
- Each container must have a proper label with the chemical name. Manufacturers labels may not be removed or defaced on primary containers.

- Segregate incompatible hazardous materials and place in a safe storage location. For assistance call x5216.
- Use fume hoods when using or producing flammable, toxic or odorous vapors. Know where emergency equipment is located and how to use it.
- Wear the appropriate protective equipment, such as gloves, safety goggles and respiratory protection. Choose equipment compatible with the hazard.
- Use non-hazardous or less-hazardous materials whenever possible. Design procedures to minimize the production of hazardous wastes.
- Obtain authorization from EH&S Office prior to using explosives, radioisotopes, carcinogens or infectious agents.
- Any spills or accidents which result in exposure to individuals or a release outside the lab must be reported to EH&S. Call Campus Police, x5555.
- Hazardous materials to be discarded must be clearly labeled, and placed in sealed, secure containers. Call x5216 for assistance.

WPI Machine Shop safety rules:

- All students must complete the safety quiz and associated training.
- Lab monitor must be present at all times. Follow the instructions of the lab monitor.
- Dress appropriately for the task. Safety glasses and close-toed shoes are required at all times. Avoid loose clothing and remove jewelry and neckties.
- Long hair must be pulled back, preferably a bun.
- Obey all posted signs and WPI procedures.
- Individuals performing tasks must be trained on those tasks. Otherwise, ask the Lab Monitor for assistance and follow his/her guidance.
- Welding is a potentially hazardous activity to be performed only by the group members trained in doing so safely, and additional safety requirements apply.

Procedure for Foam Compression Test:

Setup: A board with 1" square foam pieces under each corner is placed on a level table. The height from the tabletop to the top of the board is measured with a caliper held flush to the edge of the board. Plate weights are added atop the board and the change in height is measured.

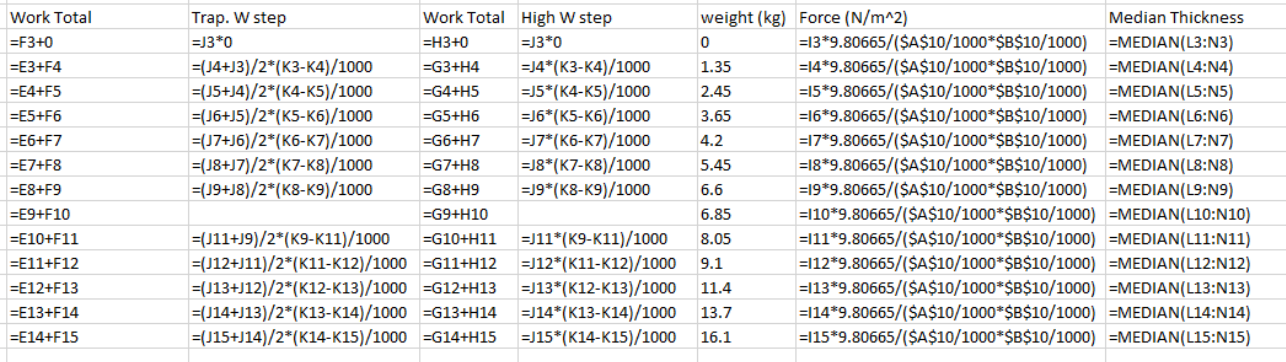
Materials: 16 lbs. Of plate weights from 0.5 lbs to 2 lbs, sturdy level surface, bullet level, caliper with depth gauge, rigid flat lightweight smooth pine plank, foams, knife/scissors,

Procedure steps

1. Cut foam into 4 squares, each 1 inch across, and measure their dimensions with a caliper.
2. Place each square under a corner of a flat, light, rigid pine board.
3. Set the board onto a flat level surface capable a bearing weight
4. Verify the setup is perfectly level.
5. Measure the height from the top of the board to the surface of the table three times. Mark where on the board this baseline measurement was made.
6. Gently place a weight atop the pine board and verify that the board is still level.

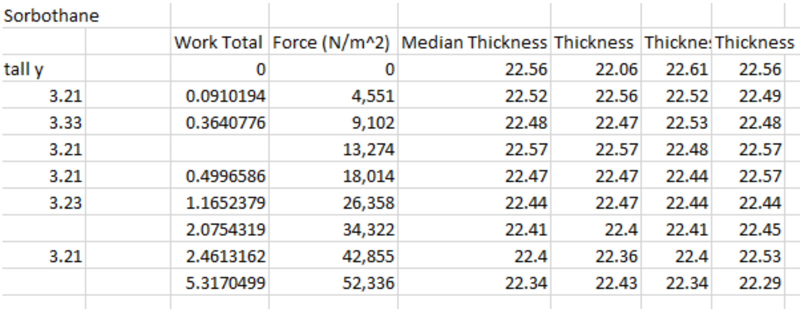
7. Measure the distance from the top of the board to the surface of the table with the caliper three times.
8. Gradually increase the weight and continue taking measurements until the compression of the foam is less than the repeatability of the caliper.
9. Repeat with other foams.
10. Calculate the compression of the foam for each weight, which is the difference in height compared to the previous measurement.
11. Graph the median compression of the foam with respect to force applied.
12. Calculate impulse of the weights on the foam, which is the integral of force with respect to distance, using a Riemann Sum or Trapezoidal method. Discard any data points showing negative distances.

Data Analysis:

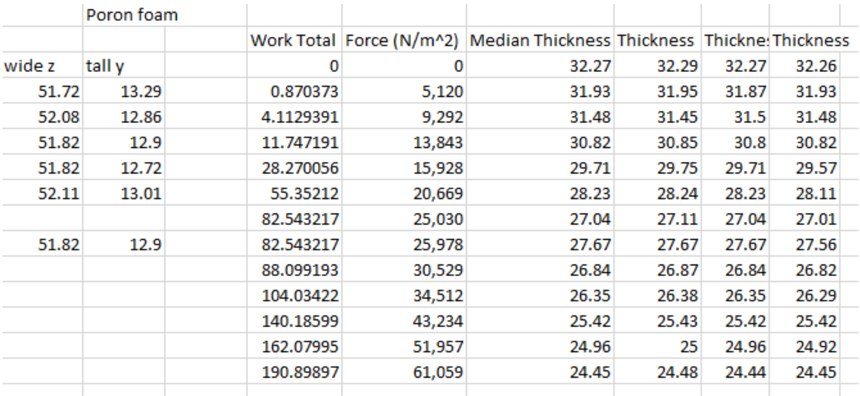


Work Total	Trap. W step	Work Total	High W step	weight (kg)	Force (N/m^2)	Median Thickness
=F3+0	=J3*0	=H3+0	=J3*0	0	=I3*9.80665/($A$10/1000*$B$10/1000)	=MEDIAN(L3:N3)
=E3+F4	=(J4+J3)/2*(K3-K4)/1000	=G3+H4	=J4*(K3-K4)/1000	1.35	=I4*9.80665/($A$10/1000*$B$10/1000)	=MEDIAN(L4:N4)
=E4+F5	=(J5+J4)/2*(K4-K5)/1000	=G4+H5	=J5*(K4-K5)/1000	2.45	=I5*9.80665/($A$10/1000*$B$10/1000)	=MEDIAN(L5:N5)
=E5+F6	=(J6+J5)/2*(K5-K6)/1000	=G5+H6	=J6*(K5-K6)/1000	3.65	=I6*9.80665/($A$10/1000*$B$10/1000)	=MEDIAN(L6:N6)
=E6+F7	=(J7+J6)/2*(K6-K7)/1000	=G6+H7	=J7*(K6-K7)/1000	4.2	=I7*9.80665/($A$10/1000*$B$10/1000)	=MEDIAN(L7:N7)
=E7+F8	=(J8+J7)/2*(K7-K8)/1000	=G7+H8	=J8*(K7-K8)/1000	5.45	=I8*9.80665/($A$10/1000*$B$10/1000)	=MEDIAN(L8:N8)
=E8+F9	=(J9+J8)/2*(K8-K9)/1000	=G8+H9	=J9*(K8-K9)/1000	6.6	=I9*9.80665/($A$10/1000*$B$10/1000)	=MEDIAN(L9:N9)
=E9+F10		=G9+H10		6.85	=I10*9.80665/($A$10/1000*$B$10/1000)	=MEDIAN(L10:N10)
=E10+F11	=(J11+J9)/2*(K9-K11)/1000	=G10+H11	=J11*(K9-K11)/1000	8.05	=I11*9.80665/($A$10/1000*$B$10/1000)	=MEDIAN(L11:N11)
=E11+F12	=(J12+J11)/2*(K11-K12)/1000	=G11+H12	=J12*(K11-K12)/1000	9.1	=I12*9.80665/($A$10/1000*$B$10/1000)	=MEDIAN(L12:N12)
=E12+F13	=(J13+J12)/2*(K12-K13)/1000	=G12+H13	=J13*(K12-K13)/1000	11.4	=I13*9.80665/($A$10/1000*$B$10/1000)	=MEDIAN(L13:N13)
=E13+F14	=(J14+J13)/2*(K13-K14)/1000	=G13+H14	=J14*(K13-K14)/1000	13.7	=I14*9.80665/($A$10/1000*$B$10/1000)	=MEDIAN(L14:N14)
=E14+F15	=(J15+J14)/2*(K14-K15)/1000	=G14+H15	=J15*(K14-K15)/1000	16.1	=I15*9.80665/($A$10/1000*$B$10/1000)	=MEDIAN(L15:N15)

Raw Data:



Sorbothane							
		Work Total	Force (N/m^2)	Median Thickness	Thickness	Thickne:	Thickness
tall y		0	0	22.56	22.06	22.61	22.56
3.21		0.0910194	4,551	22.52	22.56	22.52	22.49
3.33		0.3640776	9,102	22.48	22.47	22.53	22.48
3.21			13,274	22.57	22.57	22.48	22.57
3.21		0.4996586	18,014	22.47	22.47	22.44	22.57
3.23		1.1652379	26,358	22.44	22.47	22.44	22.44
		2.0754319	34,322	22.41	22.4	22.41	22.45
3.21		2.4613162	42,855	22.4	22.36	22.4	22.53
		5.3170499	52,336	22.34	22.43	22.34	22.29



	Poron foam							
			Work Total	Force (N/m^2)	Median Thickness	Thickness	Thickne:	Thickness
wide z	tall y		0	0	32.27	32.29	32.27	32.26
51.72	13.29		0.870373	5,120	31.93	31.95	31.87	31.93
52.08	12.86		4.1129391	9,292	31.48	31.45	31.5	31.48
51.82	12.9		11.747191	13,843	30.82	30.85	30.8	30.82
51.82	12.72		28.270056	15,928	29.71	29.75	29.71	29.57
52.11	13.01		55.35212	20,669	28.23	28.24	28.23	28.11
			82.543217	25,030	27.04	27.11	27.04	27.01
51.82	12.9		82.543217	25,978	27.67	27.67	27.67	27.56
			88.099193	30,529	26.84	26.87	26.84	26.82
			104.03422	34,512	26.35	26.38	26.35	26.29
			140.18599	43,234	25.42	25.43	25.42	25.42
			162.07995	51,957	24.96	25	24.96	24.92
			190.89897	61,059	24.45	24.48	24.44	24.45

Procedure for Head Impact Test:
Setup: A PVC pipe pendulum with a 0.7 meter (about 26 inches) arm is set up above a wooden stand with a plastic and plaster head. The pendulum weight consists of one field hockey ball with plumb bobs and a small steel weight duct-taped to it for a total weight of 0.6 kg, which is equivalent to four field hockey balls. When the weight falls 0.7, (the length of the pendulum arm) it has a speed of 3.7 m/s (8 mph) but the same momentum as a field hockey ball moving at 15 m/s (34 mph). The head is a plastic shell filled with plaster to match the 10-pound weight of a human head (about 4.5 kg). Inside the plaster are 3 high-resolution accelerometers connected to a data acquisition box (DAQ box). A wooden stand holds the head, which is glued to springs simulating the flexing of the human neck. Make sure the setup is aligned so the pendulum strikes the head when the pendulum arm is vertical. Take care that the head does not fall to the ground.

Materials: Wood stand, Pine blocks and planks, Hand saw, Wood glue, Nails, Duct tape, DAQ box and cords, Laptop with LabVIEW and Excel, PVC pendulum, Facemasks to test, Facemasks for comparison, Measuring tools, Bullet Level

Procedure Steps
1. Attach three-axis accelerometer to head.
2. Connect the accelerometers to the arduino and open LabVIEW.
3. Set up aurdino program.
4. Verify the LabVIEW program works.
5. Save data to excel file using an informative file name.

6. Start recording.
7. Lift the pendulum to horizontal and check with bullet level.
8. Drop the pendulum without pushing it, allowing it to strike the plastic head.
9. Lift the pendulum and drop it for a total of 10 impacts.
10. Stop recording.
11. Save data to excel using an informative file name including the date, time, and test conditions.
12. Open the data in Microsoft Excel and save it as an excel file
13. Conditional Format the data so high values are red and find the local maximums for each impact.
14. Graph the data in Excel
15. Save the Excel file
16. Repeat steps 2-13 for each variation tested, including each durometer of foam and all permutations of stacking the foam. Remember Nulog returns to default settings after each test.

Procedure for Impact Testing Foam Using Load Cell:
Setup: A PVC pipe pendulum with a 26-inch arm (pivot point to weight) is set up above a wooden stand with a plastic and plaster head. The pendulum weight consists of one field hockey ball with plumb bobs and a small steel weight duct-taped to it for a total weight of 0.6 kg, which is equivalent to four field hockey balls. The load cell is taped to a stand on the table so that it is perfectly level with the pivot of the pendulum arm, causing the field hockey ball on the pendulum to strike the load cell vertically. Align and shim the setup is aligned so the pendulum strikes the load cell when the pendulum arm is horizontal. The load cell is less than a square centimeter but striking it repeatably is achievable.

Materials: Sturdy table and stand, Metal shims, tape, DAQ box and cords, computer with LabVIEW and Excel, PVC pendulum, Foams to test, Tape measure, Bullet Level

Procedure steps
1. Connect the load cell to the laptop and open LabVIEW.
2. Set up LabVIEW program.
3. Verify the LabVIEW program works.
4. Save data to notebook file.
5. Start recording.
6. Lift the pendulum one above horizontal.
7. Drop the pendulum without pushing it, allowing it to strike the load cell.
8. Repeat at that height for a total of five impacts.
9. Repeat steps 6-8, increasing height by one inch at a time, until limit of load cell is exceeded.
10. Stop recording.
11. Save data to excel using an informative file name including the date, time, and test conditions.
12. Open the data in Microsoft Excel and save it as an excel file

13. Repeat steps 3-12 with each combination of foam to be tested (high durometer foam, low durometer foam, both foams with high durometer foam on top, and both foams with high durometer foam on the bottom).
14. Repeat steps 3-12 without foam over the load cell to check for drift over the course of the experiment.

Procedure for Testing Foam using Horizontal Force Plate:
Setup: A PVC pipe pendulum with a 26-inch arm (pivot point to weight) is set up above a wooden stand with a plastic and plaster head. The pendulum weight consists of one field hockey ball with plumb bobs and a small steel weight duct-taped to it for a total weight of 0.6 kg, which is equivalent to four field hockey balls. When the weight falls 26 inches, (the length of the pendulum arm) it has a speed of 3.7 m/s (8 mph) but the same momentum as a field hockey ball moving at 15 m/s (34 mph). A pine cradle made of pine blocks and 2-by-4 planks is built on the table, and the force plate is laid horizontally so it cannot fall off but is not taped down. Make sure the setup is aligned so the pendulum strikes the force plate horizontally. Measure 26 inches above the surface of the force plate and mark this location for the release of the pendulum.

Materials: Wood stand, Pine blocks and planks, Hand saw, Sturdy table, Duct tape, Laptop with Nulog and Excel, PVC pendulum, Foams to test, Facemasks to test, Measuring tools, Marker, Bullet Level

Procedure Steps:
1. Connect the force plate to the laptop and open Nulog.
2. Align force plate so the when the pendulum strikes it, the pendulum’s arm is perfectly horizontal. Check with bullet level.
3. Set up Nulog for maximum sample rate and sufficiently long recording time
4. Make sure nothing is resting on the force plate and zero the force plate.
5. Verify that Nulog settings have not reverted.
6. Start recording.
7. Lift the pendulum to 13 inches above the force plate so the pendulum is at a 45 degree angle.
8. Drop the pendulum without pushing it, allowing it to strike the force plate.
9. Rapidly lift the pendulum and drop it for a total of 10 impacts.
10. Stop recording if necessary.
11. Save data to excel using an informative file name including the date, time, and test conditions.
12. Open the data in Microsoft Excel and save it as an excel file
13. Conditional Format the data so high values are red and find the local maximums for each impact and graph the data in Excel.
14. Save the Excel file
15. Repeat steps 2-13 for each variation tested, including each durometer of foam and all permutations of stacking the foam, as well as all versions of the mask to be tested. Remember Nulog returns to default settings after each test.
16. Find peak forces for all impacts using excel files and compare results.

Appendix B - Impact Test Data

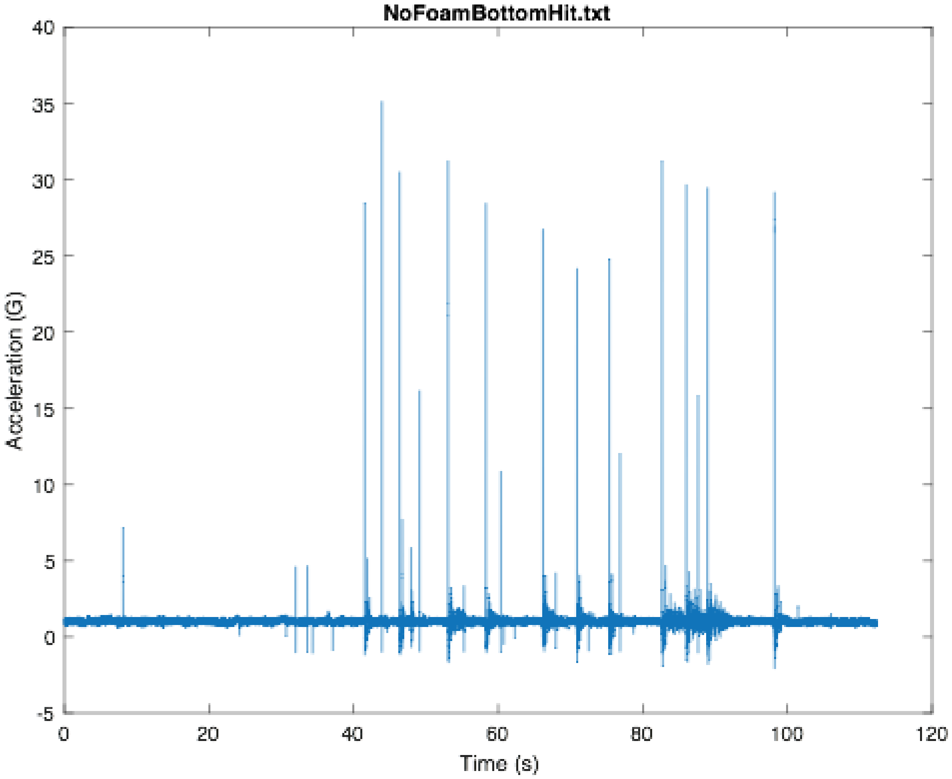


Figure 31: No Foam Bottom Hit Graph

Table 4: No Foam Bottom Hit Data

Impact	Peak Acceleration (G)	15ms Average Acceleration (G)	HIC-15
1	28.4687	7.5795	8.8898
2	30.5106	7.6129	10.1077
3	31.2672	7.0132	8.7153
4	28.4411	5.9747	6.0138
5	26.7406	6.7495	8.0835
6	24.8160	6.1190	6.1989
7	31.2312	6.3930	7.6410
8	29.6944	7.0692	9.1880

9	29.4730	6.3326	7.8809
10	29.1849	7.2020	10.0703
Average	**28.9828**	**6.8046**	**8.2789**
STD	2.0095	0.5849	1.4144

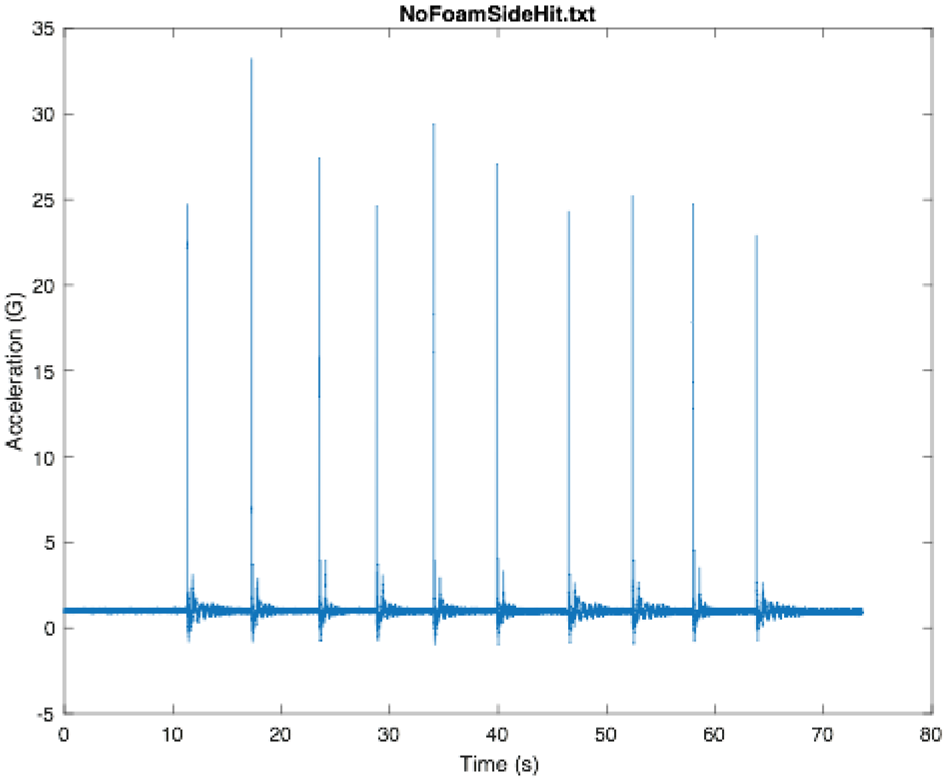


Figure 32: No Foam Side Hit Graph

Table 5: No Foam Side Hit Data

Impact	Peak Acceleration (G)	15ms Average Acceleration (G)	HIC-15
1	24.7222	8.1415	7.4018
2	33.2367	8.5283	7.9653
3	27.4413	8.6465	7.558
4	24.6343	8.4293	7.3631
5	29.4364	8.4683	7.8333

6	27.0961	8.5015	7.5684
7	24.3254	8.3911	7.4228
8	25.2530	8.4234	7.5887
9	24.7521	8.3007	7.4454
10	22.9235	7.6514	6.6375
Average	**26.3821**	**8.3482**	**7.4784**
STD	3.0529	0.2797	0.3528

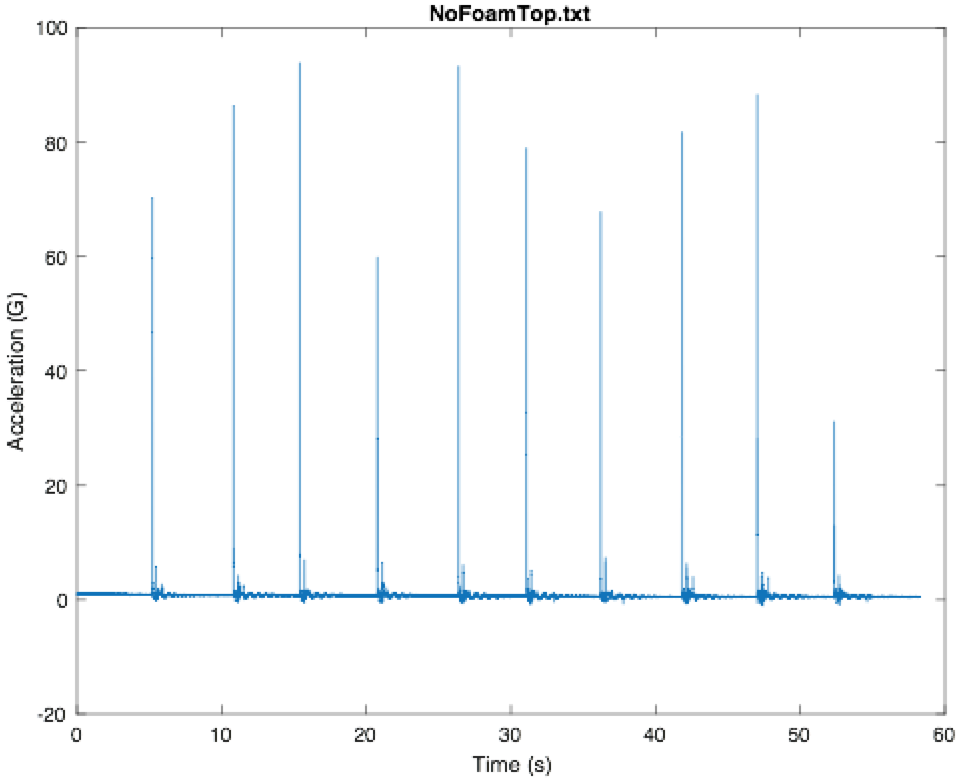


Figure 33: No Foam Top Hit Graph

Table 6: No Foam Top Hit Data

Impact	Peak Acceleration (G)	15ms Average Acceleration (G)	HIC-15
1	70.3215	10.0531	19.6703
2	86.4129	10.4073	24.0305

3	93.9365	9.798	26.3475
4	59.9173	11.3367	17.0593
5	93.3183	9.9673	26.2057
6	78.967	11.542	20.438
7	67.7915	11.6312	16.2784
8	81.777	12.8134	21.4271
9	88.3595	13.4075	24.1504
10	31.2177	10.0826	11.6379
Average	**75.2019**	**11.1039**	**20.7245**
STD	19.0973	1.2641	4.735

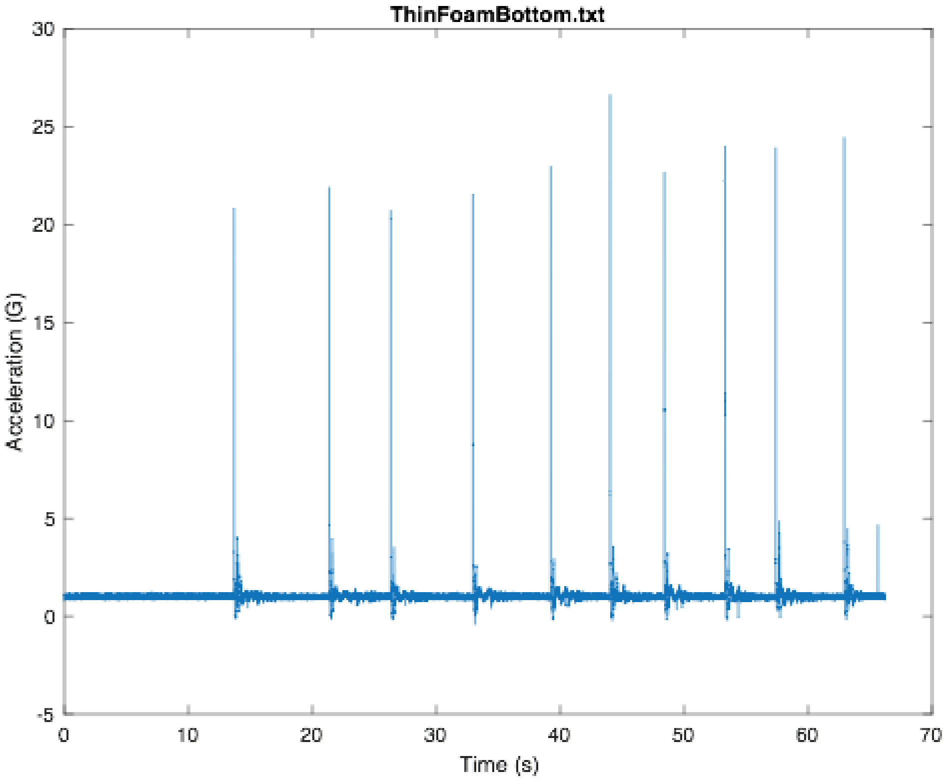


Figure 34: Sorbothane Bottom Hit Graph

Table 7: Sorbothane Bottom Hit Data

Impact	Peak Acceleration (G)	15ms Average Acceleration (G)	HIC-15

1	20.8233	8.7667	5.7525
2	21.9058	8.96	6.12
3	20.7069	8.8731	5.5422
4	21.5396	7.9766	5.89
5	22.9587	8.714	6.512
6	26.6288	9.1751	8.4967
7	22.6977	8.8716	5.9878
8	23.9855	9.2044	6.4168
9	23.9381	9.5057	7.602
10	24.4653	9.2845	7.5035
Average	**22.965**	**8.9332**	**6.5823**
STD	1.8431	0.4193	0.9662

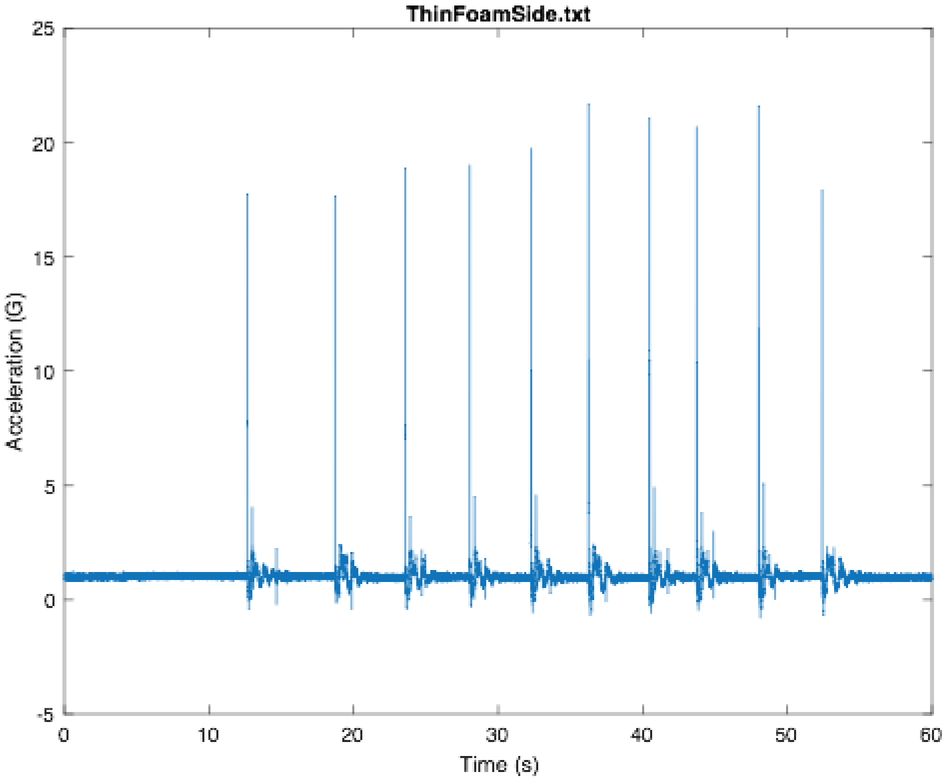


Figure 35: Sorbothane Side Hit Graph
Table 8: Sorbothane Side Hit Data

Impact	Peak Acceleration (G)	15ms Average Acceleration (G)	HIC-15
1	17.765	7.2391	3.9096
2	17.6794	6.6801	3.6695
3	18.8968	7.0286	4.2144
4	19.0221	6.8545	4.0171
5	19.7452	7.3167	4.8613
6	21.702	7.5835	5.3975
7	21.083	7.6594	5.2604
8	20.6968	7.3495	5.0604
9	21.6211	7.5932	5.3026
10	17.9223	6.7991	3.9393
Average	**19.6134**	**7.2104**	**4.5632**
STD	1.5855	0.3542	0.675

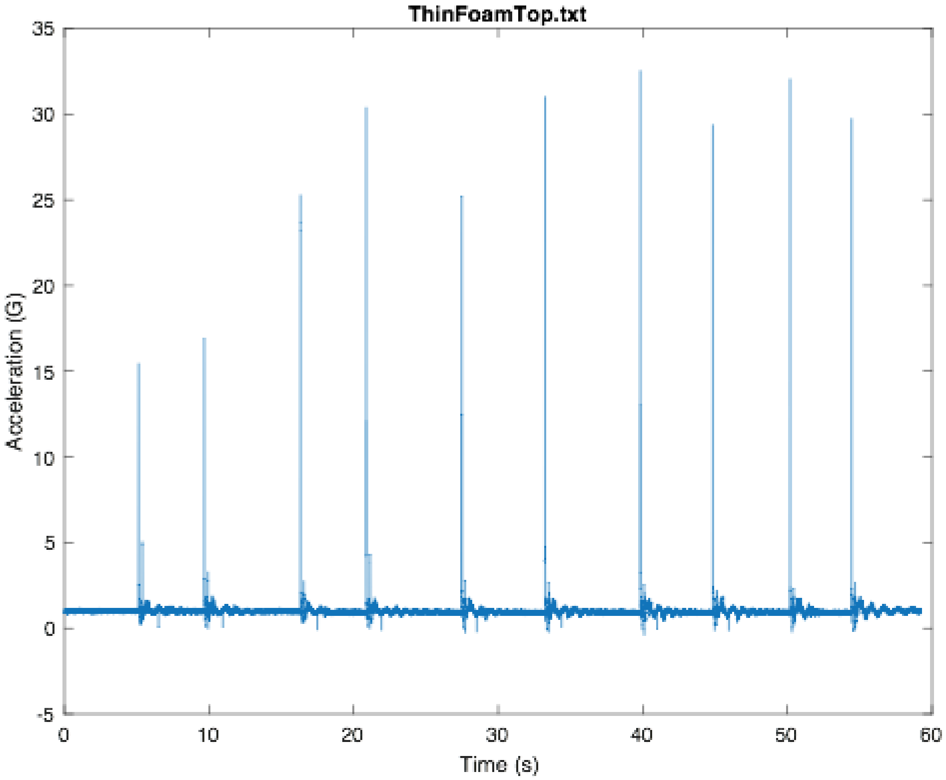


Figure 36: Sorbothane Top Hit Graph

Table 9: Sorbothane Top Hit Data

Impact	Peak Acceleration (G)	15ms Average Acceleration (G)	HIC-15
1	15.4617	7.4616	4.178
2	16.9215	7.5267	4.5635
3	25.2845	8.0947	7.5008
4	30.404	8.9468	9.542
5	25.2364	8.2711	8.0904
6	31.0208	8.8435	10.2703
7	32.5367	10.0724	14.7027
8	29.3819	9.2959	10.0749
9	32.0602	9.5246	12.7204
10	29.7377	9.3757	11.9582

Average	**26.8045**	**8.7413**	**9.3601**
STD	6.1243	0.8756	3.3811

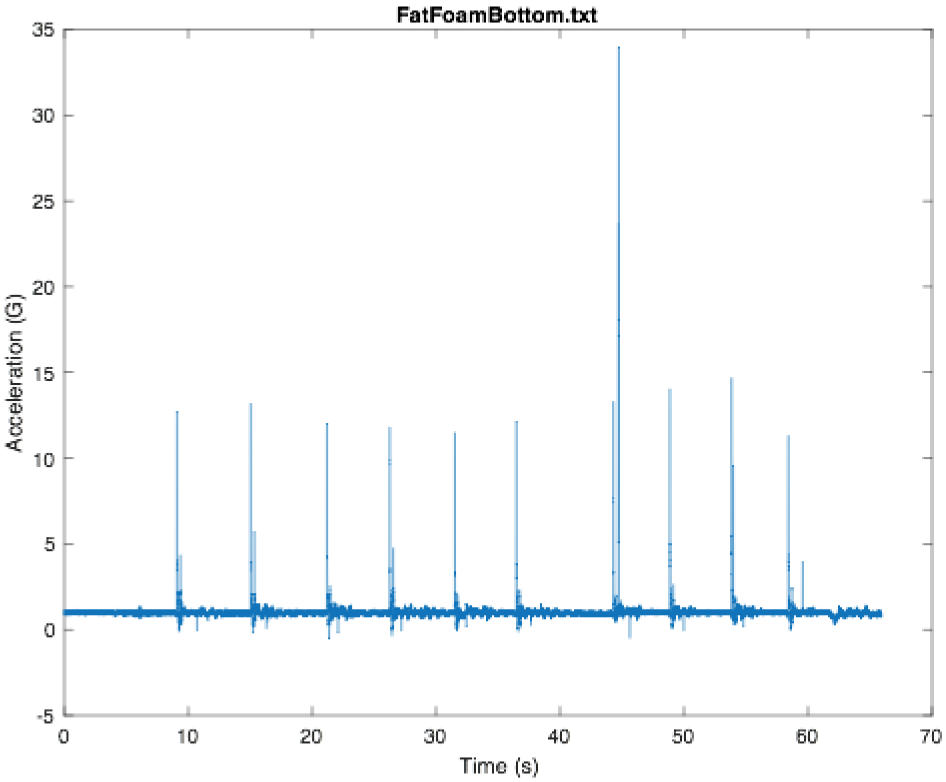


Figure 37: Poron Bottom Hit Graph

Table 10: Poron Bottom Hit Data

Impact	Peak Acceleration (G)	15ms Average Acceleration (G)	HIC-15
1	12.7385	6.8049	2.2678
2	13.1736	6.9378	2.4566
3	12.0449	6.4127	1.9512
4	11.8249	6.6456	1.969
5	11.496	5.4605	1.3824
6	12.1528	5.8331	1.5973
7	34.0011	12.5169	17.2
8	14.0486	6.6123	2.8368

9	14.6759	6.7067	3.0599
10	11.2978	5.7505	1.9344
Average	**14.7454**	**6.9681**	**3.6655**
STD	6.8537	2.013	4.7837

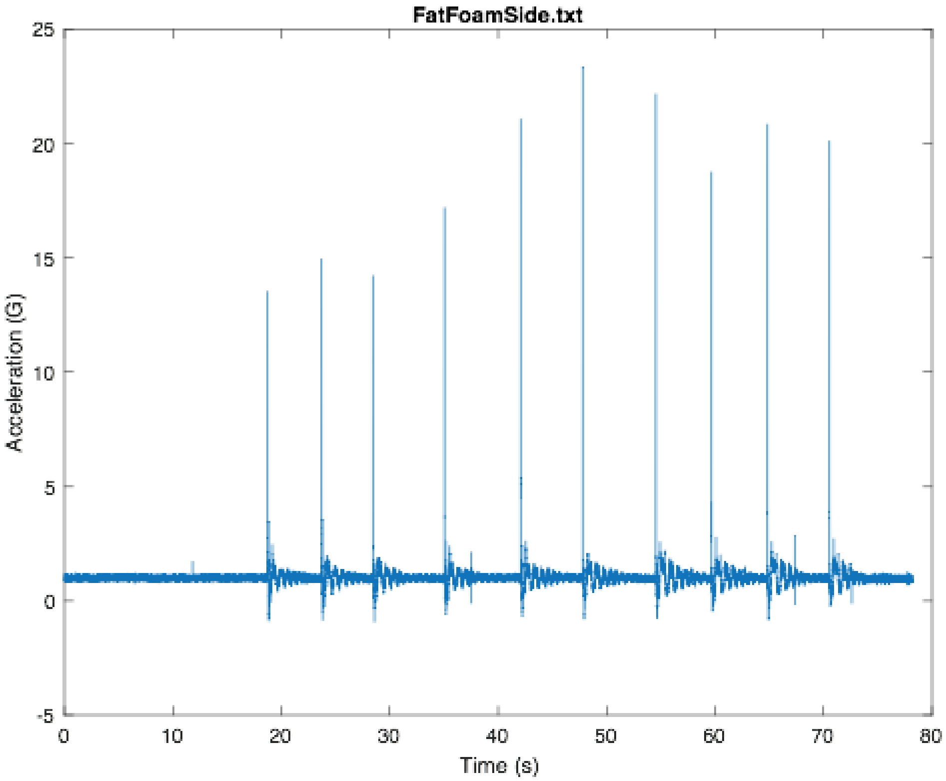


Figure 38: Poron Side Hit Graph

Table 11: Poron Side Hit Data

Impact	Peak Acceleration (G)	15ms Average Acceleration (G)	HIC-15
1	13.5224	6.267	2.3005
2	14.9363	6.6604	2.8151
3	14.2129	6.4923	2.4953
4	17.1919	7.3231	3.4511
5	21.0642	7.0423	3.8773
6	23.3745	6.407	4.323

7	22.1768	6.8097	4.6545
8	18.7586	5.5788	2.8192
9	20.8545	6.8329	4.4634
10	20.1027	6.013	3.3535
Average	**18.6195**	**6.5426**	**3.4553**
STD	3.4874	0.5093	0.8476

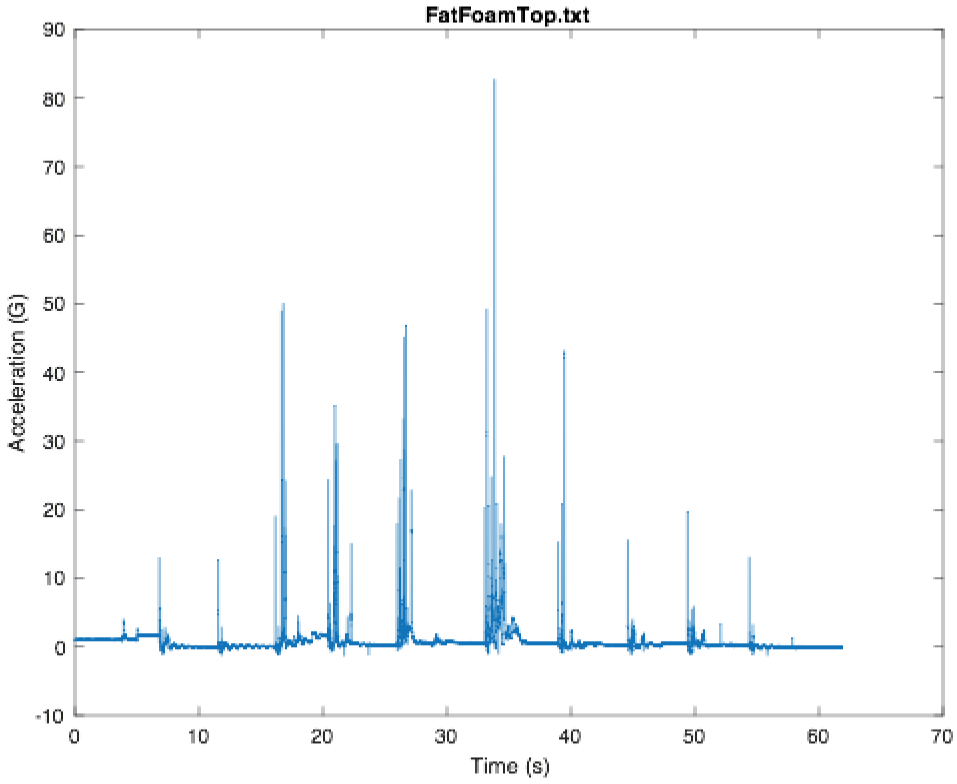


Figure 39: Poron Top Hit Graph

Table 12: Poron Top Hit Data

Impact	Peak Acceleration (G)	15ms Average Acceleration (G)	HIC-15
1	12.9589	7.9507	3.2382
2	12.7633	6.0893	2.4996
3	50.0306	8.9638	20.6956
4	35.2435	18.5066	26.4968

5	46.9131	14.9585	34.8375
6	82.7099	19.1562	103.3852
7	43.2205	14.7708	25.5639
8	15.555	6.9445	3.1495
9	19.7657	7.7762	5.8809
10	13.0975	7.0721	3.0375
Average	**33.2258**	**11.2189**	**22.8785**
STD	22.9744	5.0784	30.7721

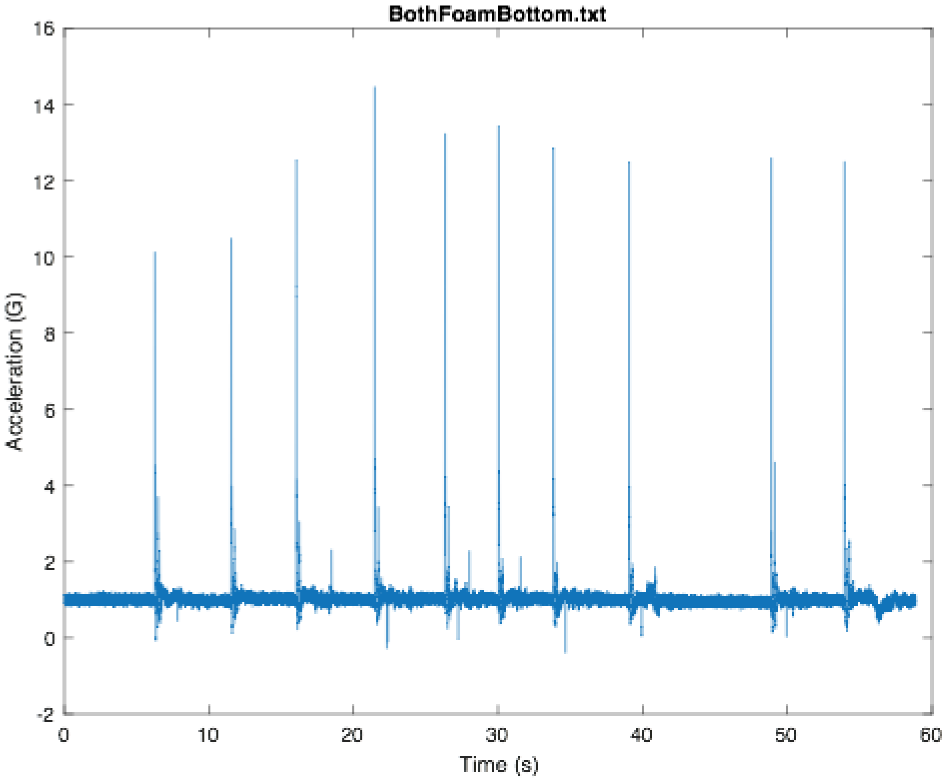


Figure 40: Both Foams Bottom Hit Graph

Table 13: Both Foams Bottom Hit Data

Impact	Peak Acceleration (G)	15ms Average Acceleration (G)	HIC-15
1	10.1186	5.934	1.7557
2	10.4817	6.071	1.8571

3	12.5443	6.7147	2.5687
4	14.4664	6.999	3.0464
5	13.2438	6.5963	2.6634
6	13.4376	6.3875	2.6444
7	12.8711	6.2864	2.3641
8	12.4947	6.3766	2.4136
9	12.6108	5.6739	1.8303
10	12.5082	6.1347	2.106
Average	**12.4777**	**6.3174**	**2.325**
STD	1.2992	0.3894	0.4271

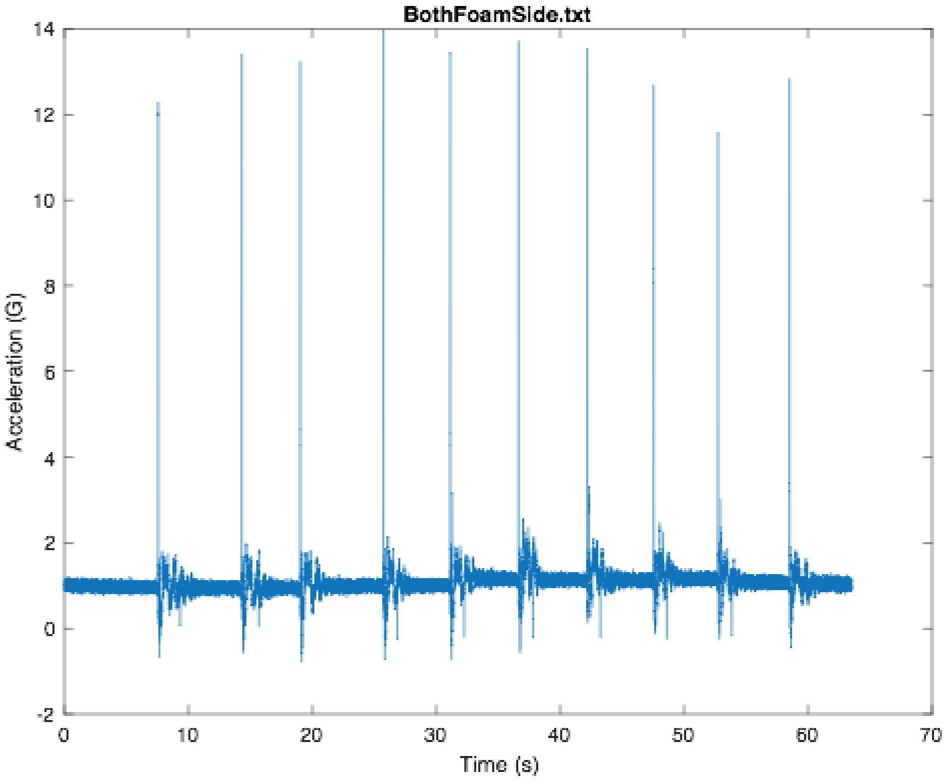


Figure 41: Both Foams Side Hit Graph

Table 14: Both Foams Side Hit Data

Impact	Peak Acceleration (G)	15ms Average Acceleration (G)	HIC-15

1	12.2791	6.4505	2.4386
2	13.4046	6.5945	2.6779
3	13.2426	6.6731	2.7551
4	13.9635	6.8351	3.0221
5	13.4577	6.761	2.8322
6	13.717	7.0792	3.2172
7	13.5578	7.0145	2.9377
8	12.6862	6.4718	2.4062
9	11.5947	6.5961	2.3014
10	12.8317	6.7697	2.6463
Average	**13.0735**	**6.7246**	**2.7235**
STD	0.7267	0.211	0.2905

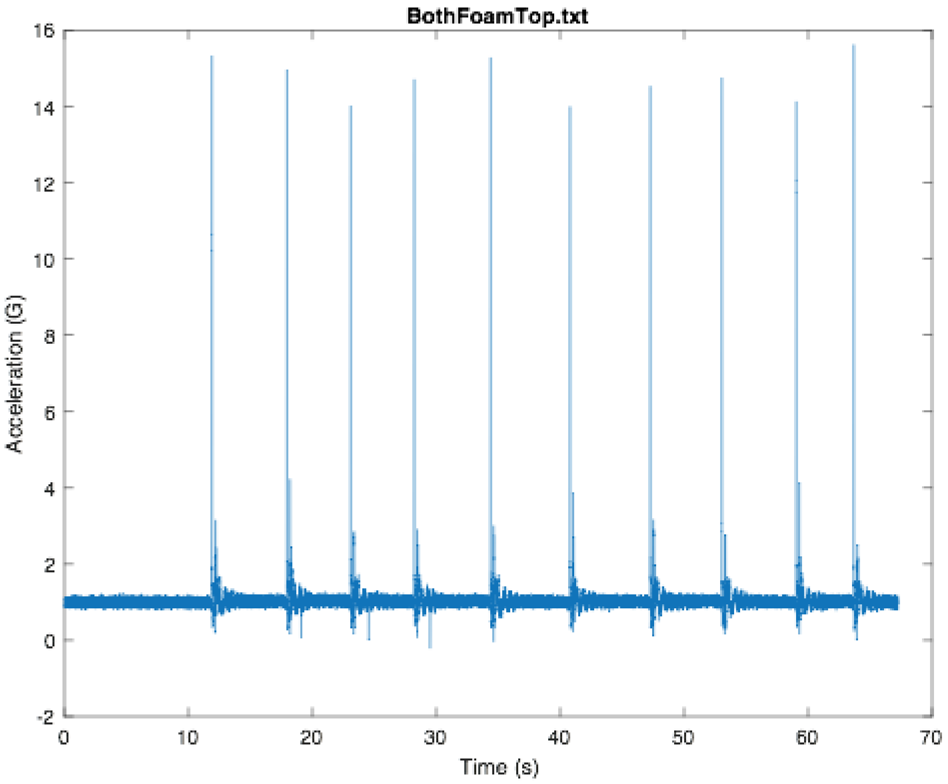


Figure 42: Both Foams Top Hit Graph
Table 15: Both Foams Top Hit Data

Impact	Peak Acceleration (G)	15ms Average Acceleration (G)	HIC-15
1	15.3235	7.3805	3.2578
2	14.9592	7.256	3.1145
3	14.0299	7.0087	3.0339
4	14.7179	7.2358	3.1838
5	15.2935	7.283	3.2618
6	13.9968	7.1232	2.9195
7	14.5303	7.1379	3.0095
8	14.7654	7.235	3.1087
9	14.138	7.2009	2.9901
10	15.6241	7.4528	3.4708
Average	**14.7379**	**7.2314**	**3.1351**
STD	0.5716	0.1272	0.1636

Appendix C - Matlab Code for Acceleration Data Processing

Script for analyzing files

```
clear variables; close all; clc; fclose('all');

%% Read in the data

[fileName, filePath, ~] = uigetfile('*.txt'); %UI window to find data file
filePath = strcat(filePath,fileName);
dataRate = 8e3; % Set this to the data rate you were using
zeroG = 1.65; % zero point in Volts
scaling = (200-(-200))/3.3; % Voltage to Gs conversion factor

accels = csvread(filePath); % Parse in data columns

fclose('all');

%% Processing
accels = (accels - zeroG).*scaling; % Sensor voltage-to-G scaling

linAccel = hypot(hypot(accels(:,1),accels(:,2)),accels(:,3)); % Linear Acceleration from 3 axis

calibOffset = mean(linAccel(1:dataRate)) - 1; % Use first second for calibrating with gravity
linAccel = linAccel - calibOffset;

timePoints = linspace(0,(length(linAccel)-1)/dataRate,length(linAccel)); %Time Vector

[Peaks(1,:),Peaks(2,:)] =
findpeaks(linAccel,'MinPeakDistance',2*dataRate,'MinPeakHeight',8,'MinPeakWidth',floor(0.0005*dataRate));
numPeaks = length(Peaks);

i15ms = floor(0.015*dataRate); % Number of points corresponding to a 15 ms interval
i15ms = i15ms + mod(i15ms,2); % Make it even

avgGs = zeros([1,numPeaks]);
for i = 1:numPeaks %% Calculate 15ms-average for each peak
   avgGs(i) = mean(linAccel(Peaks(2,i)-i15ms/2:Peaks(2,i)+i15ms/2));
end
```

```
%% HIC Calculations
HIC = zeros([1,length(numPeaks)]);
for i = 1:numPeaks
   HIC(i) = HIC15(linAccel(Peaks(2,i)-i15ms:Peaks(2,i)+i15ms),dataRate);
end

%% Plotting
plot(timePoints,linAccel);
title(fileName);
xlabel("Time (s)");
ylabel("Acceleration (G)");
```

HIC Calculation Function

```
function [ HIC ] = HIC15( acceleration, dataRate )
%HIC15 Calculates 15 ms Head Injury Criteria given acceleration data

i15ms = floor(0.015*dataRate); % maximum interval between t1 and t2, determined as 15 ms

integrands = (1/dataRate)*cumtrapz(acceleration); % calculate all cumulative integrals for efficiency using trapezoid rule

t1 = linspace(0,(length(acceleration)-1)/dataRate,length(acceleration)); % all possible values of t1

HICs = zeros([length(t1),i15ms]); % matrix to store all HIC values
for i = 1:length(t1) % for loop scrolls through each possible t1 value
   for j = 1:min(i15ms,length(t1)-i) % second for loop scrolls through each possible t2 value
      t2 = t1(i)+j/dataRate; % calculate current t2
      HICs(i,j) = ((1/(t2-t1(i)))*(integrands(i+j)-integrands(i))).^2.5 *(t2-t1(i)); % calculate HIC
   end
end

HIC = max(max(HICs)); % Find max HIC value stored to return

End
```

Appendix D - Survey Data

Average Results

Improved Field Hockey Mask Design Please consider each question on a scale of 1 - 10, 10 being most positive and 1 being most negative	Score 1-10
1. Do you like the look of this mask?	6.7
2) If this were in stores do you feel that you would be likely to buy it?	5
3) Do you feel that this mask provides adequate protection?	9.3
4) Is there clear visibility while wearing the mask?	7.9
5) Can you see well out of your peripherals?	7.2
6) Is the mask comfortable for you to wear?	8.2
7) Do you feel as if the mask will stay put while running?	5.7
8) Would you consider this to be an improvement on existing masks?	6

Comments (improvements, suggestions, opinions): **Collection of useful comments** “Protection is good but would not be helpful in protecting eyes from turf beads that get kicked up” “Most of our game is spent looking down so being able to clearly see the ground without barriers is very important” “The straps could be elastic instead [of polyester] creating a tighter seal to the face” “The simple style is smart and implements more visibility than most masks but the weight of the mask would create movement when running”	Overall Score: 7