Design of a Load Absorption Device for Ice Hockey Shoulder Pads

A Major Qualifying Project Report submitted to the faculty of Worcester Polytechnic Institute in partial fulfillment of the requirements for the degree of Bachelor of Science

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Abstract

In contact sports, especially hockey, players experience upper extremity injuries from collisions during play. The loads associated with these collisions can tear the ligaments that stabilize the acromioclavicular (AC) joint, causing shoulder separation. Current technology uses a combination of foams and plastics as a barrier between the load and the AC joint. Using axiomatic design, the team designed a device integrated into a shoulder pad to dissipate injurious loads to areas around the AC joint. Although the team observed the effectiveness of the device through validation testing, additional testing to understand how the loads are dissipated throughout the device and around the shoulder is recommended.

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1. Introduction

All over the globe, sports are enjoyed by participants and fans, as they represent not only a form of exercise, but also an outlet for people to enjoy taking part in something that brings individuals together and allows them to escape some of the stresses of their daily lives. In the United States, roughly 19% of the population exercises every day or participates in contact sports, such as football, hockey, lacrosse, and rugby, to name a few (Woods, 2017). With the risk of injuries, such as ACL tears and concussions, being a major concern for athletes of all ages, engineers, physicians, and manufacturers are combining efforts to decrease the potential for injury through better equipment, proper technique, and effective strength and conditioning training. On average, the cost per child to play a sport is approximately $400, which is a sum of participation fees and equipment costs. Contact sports such as ice hockey, football, and men's lacrosse average $572.67 for equipment, such as helmets and pads (Ohio University, n.d.).

Between the years of 2010 and 2015, in the NCAA alone, there was an estimated 1,053,370 injuries that occurred (Kerr et al., 2015). A separate study of 573 collegiate athletes participating in 16 NCAA Division I institutional sports revealed that 70.7% of injuries were the result of high speed and full-body contact sports, while only 29.3% occurred due to overuse (Yang et al., 2015). In ice hockey alone, it was found in a particular study of 760 upper extremity injuries experienced by athletes, 233 of these injuries occurred at the shoulder and 170 were the result of contact with the boards or other players on the ice (Mölsä et al., 2003). The increasing number of injuries in college athletes, specifically, raises concerns about the effectiveness of equipment and calls for improvements to be made to ensure athletes are as safe as possible when taking part in these contact sports. Although bulkier and more restrictive equipment may help in increasing the probability of avoiding injuries, players typically prefer lightweight equipment that does not hinder their range of motion. Therefore, it is critical that engineers remember this when designing new equipment and make sure that it keep athletes safe without hindering their performance. Current devices on the market merely provide a layer of material between the shoulder and injurious surface, reducing a portion of the overall force, but still forcing the shoulder to accommodate a large portion of the injurious load. Although there is no gold standard currently on the market for shoulder pads, current shoulder pads primarily differ in areas such as thickness of padding, the surface area the pad covers on the shoulder, the weight of the pad, and the material used to fabricate the pad. From sport to sport, some regulations may differ for the size and shape of the pads that are required for each sport, but the pads themselves bare significant similarities and primarily act as layer of material that interferes with the direct contact of the shoulder with the contact surface. More recently, athletes and manufacturing companies are buying and selling equipment that is lighter and minimizes interference with their range of motion in order to increase their level of play. However, this increases their risk of injury in the process (Shinzawa, 2012). Besides altering the size and shape of the shoulder pad, there is a gap in manufactured athletic equipment, as there is a need for a shoulder pad that does not influence play, but specifically functions to reduce the load on the shoulder to the point where serious injury is avoided.

Our team was tasked with developing an improved shoulder pad mechanism for athletes to reduce the risk of shoulder separation injuries. The overall goal of developing this mechanism is to attenuate the load on the shoulder to a point below the injury threshold. Shoulder separation injuries due to contact typically result from a compressive force tearing the acromioclavicular and calcaneocuboid ligaments that hold the collarbone and shoulder blade together (Cook et al., 2019). The figure below shows the region where shoulder separation occurs.

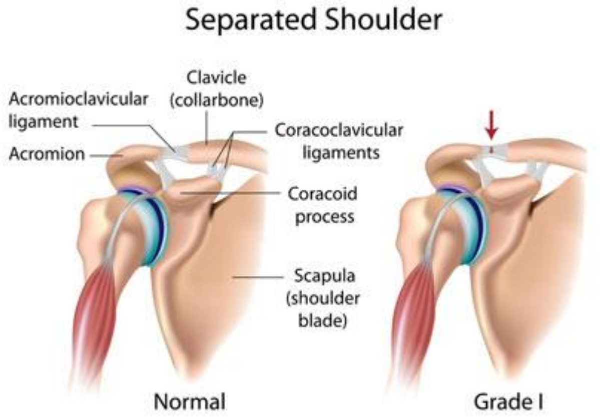


Figure 1. Shows region where shoulder separation occurs (Cook et al., 2019)

Our team is attempting to reduce the load on this area of the shoulder by altering a traditional shoulder cap. The device should increase the distance and time over which injurious forces act, while also dispersing the forces over a larger surface area to keep the magnitude of forces below injury-provoking levels.

In order to test the functionality of our design, we will subject our device to a series of relevant testing of validation protocols to examine compressive strength, motion kinematics, and range of motion. Before testing our device, a traditional shoulder pad on the market will be analyzed and subjected to the same set of tests to develop a baseline. These tests include an Instron test to analyze compressive strength and tensile strength of the materials and an impact drop test to further analyze fracture strength and compressive strength of the materials.

The following sections will provide insight into the methods used to develop and test our device, as well as provide background for the need of such a device and how it could impact the health and well-being of athletes. The following literature review will cover topics such as mechanism of injuries, risk factors relating to shoulder separation injuries, the anatomy of the shoulder, regulations and NCAA rules pertaining to shoulder equipment, the prevalence of shoulder separation injuries, and the current devices on the market that our team found were important to investigate, in order to better understand the injury and how to prevent it with our device. In addition to the literature review, the project strategy section will outline the needs of our client, as well as the objectives and constraints that influenced how we will be approaching the project over the four terms. Following our strategy outline, the specifications and functionalities for our design, the standards our team followed, and the design concepts our team developed while analyzing the parameters that will influence the success of our device will be presented. The modeling and testing performed to validate the effectiveness of our design will be presented next, along with the results and our team's decisions based on the conclusions that were drawn from the testing. To conclude, our team will present concepts for future work that could be done on similar designs and a brief summary of the project, as a whole.

1.1. Objective

The goal of this project is to design an improved shoulder pad or a mechanism on existing shoulder pads to reduce shoulder separations by minimizing loads on the shoulder.

1.2. Rationale

Shoulder injuries are the third most common type of injury that occurs for NCAA hockey players, the fifth most common type of injury in NCAA lacrosse players, and the sixth most common type of injury in NCAA football players. (Flik et al., 2005; Dragoo et al., 2012). Over half of these injuries (51.4%) were caused by collisions with either the boards or opposing players (Dragoo et al, 2012). Players must wear protective shoulder pads, however these collisions are still causing injuries. Therefore, the team found it important to identify a proper protective mechanism to help mitigate these injuries. This protective mechanism must abide by the rules and regulations of each sport, while also being fully functional for the athlete. The main objective of this project is to improve upon an existing shoulder pad with a protective mechanism that does not hinder the movements of the athlete.

When designing a shoulder pad that is beneficial for the athlete, there are constraints and customer needs that are important to the overall design. Shoulder pads that are available today are typically made from a foam-like material that is used to absorb forces when an athlete is hit during a play. This mechanism does not offer the proper protection needed against the various types of contact the athlete endures with other players, sports equipment, and the playing surface. There is a current gap with shoulder pads on the market today that can offer the necessary protection against shoulder injuries and that are also not too restrictive, high weight, or uncomfortable. Our team is tasked with developing and implementing a design for a protective mechanism against shoulder injuries that still allows the athlete complete mobility of the shoulder complex.

1.2.1. Initial Client Statement

There is currently a wide range of shoulder pads available for athletes of all different sports. These shoulder pads must protect the athlete from injury, while also not hindering the athlete's ability to play, such as limiting range of motion or slowing them down. The NCAA designates rules and regulations to protect athletes, some of which apply to the equipment that must be worn while playing and limitations on equipment that may be harmful to other players. Our team was tasked with protecting the health of these athlete's, while also allowing them to play to their maximum capacities. Our team was tasked with the following client statement:

Design an improved shoulder pad that will protect athletes from shoulder separation injuries, while also providing them with adequate range of motion and stability, so that the shoulder pads do not influence their level of play.

1.3. State of the Art

1.3.1. Mechanism of Injury

As stated in the rationale section, shoulder separations (sprain to the AC joint area) are most common in contact sports like football and hockey. Lynch et al. performed an epidemiological study in 2013 and found that the incidence rate of shoulder injuries in the NFL over a twelve season span was 8.2%. Of these shoulder injuries, 29.2% were AC joint related (Lynch et al., 2013). Tummala et al. performed a similar epidemiological study of NCAA football from 2004 to 2014, focusing on injuries to the quarterback position. They found an injury rate of one shoulder injury per 1,221 athlete exposures (defined as one practice or game session). They found that 45.1% of these injuries were AC joint related (Tummala et al., 2015). Furthermore, Melvin et al. performed an epidemiological study of upper extremity injury in NCAA men's and women's ice hockey from 2004 to 2014 and found that injuries to the AC joint were the most common (29.1% for men and 13.8% for women) and resulted in the most player time lost (Melvin et al., 2018). The president of the Boston Bruins, of the National Hockey League, said back in 2012, "I don't know why it's that difficult to look at the equipment and say, 'We really need to do something with the shoulder pads and elbow pads," highlighting the importance of improved protection (Shinzawa, 2012). This quote and statistics tell us that injuries to the AC joint are a common injury in high level contact sports and exposes a need for shoulder pads that can better protect athletes from the forces responsible for these injuries.

Understanding the mechanism of injury in these sports is crucial in determining the gaps in current shoulder protection strategies and effective ways to fill these gaps. A shoulder separation injury is defined as a tear in the ligaments that are attached to the underside of the clavicle. These ligaments are used to surround and stabilize the acromioclavicular joint (AC joint). When these ligaments are torn, a separation between the collarbone and the shoulder blade occurs resulting in a shift downward of the shoulder blade and a bump that can be seen on top of the shoulder (Cunha and Balentine, n.d.). Athletes are exposed to many types of impacts during contact sports including impacts with the playing surface, other players, and the boards in the case of ice hockey, which cause AC joint injury. Direct loads at the point of the shoulder drive the acromion and clavicle downwards. Since the clavicle bone is fixed to the sternum, it cannot move down with the induced force. This causes a shear force over the AC joint and the adjacent coracoclavicular ligaments. With a strong enough force, injury to the joint and ligaments will occur. The degree of injury is dependent on the magnitude of the force placed on the shoulder complex (Usman et al., 2015). The figure below shows the direction of injurious loads on the AC joint.

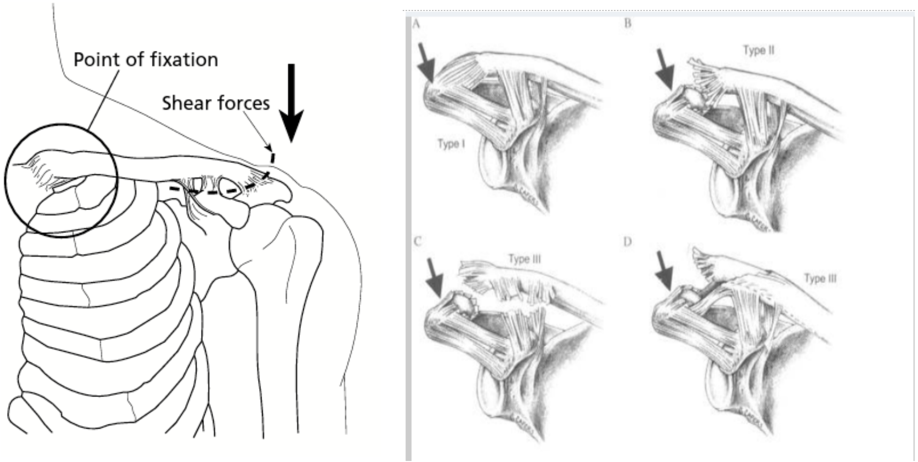


Figure 2. Force diagrams on AC Joint (Beim, 2000)

1.3.2. Current Technology

The most common form of athletic shoulder protection in contact sports is shoulder pads. Pad design among the different contact sports are mostly similar. The general structure of football pads are shown in the figure below.

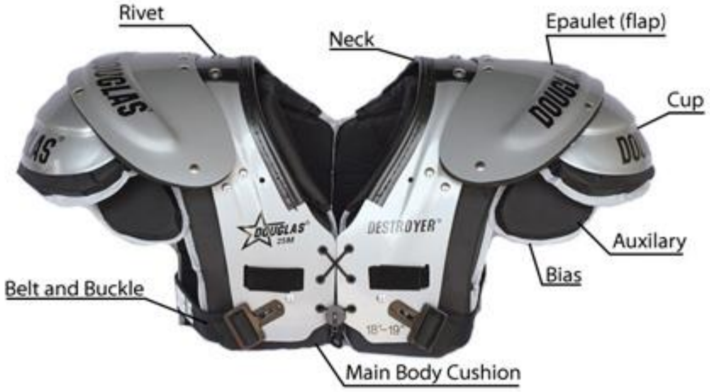


Figure 3. Common shoulder pad parts. This project mainly focuses on the Neck, Epaulet, Cup, Bias, and Auxiliary (Sports Unlimited, 2015)

Patents filed by Riddell Inc., a major football protective equipment manufacturer, highlight the protection strategies of shoulder pad design. In terms of AC joint protection, Riddell uses “cantilever straps,” which lie on top of a base layer of open-cell foam. The goal of these pads is to disperse the energy of loads on the shoulder using foams varying in density and increased space between the epaulets and the AC region. The epaulets and shoulder cups are made of plastic that is strong and rigid enough to withstand forces normally encountered in football. “Athletic shock absorbing pad,” a patent filed by Riddell in 1988, includes cantilever straps that are thicker (up to four inches) and are positioned above the base layer of padding, leaving a space. The inventors state that this maximizes the distance a force can act before affecting the shoulder itself, while the pad attenuates the load. This configuration is shown in the figure below. The diagram is a side view of the shoulder portion and the cantilever straps and base layer of padding are labeled 100 and 88, respectively (Wingo, 1989).

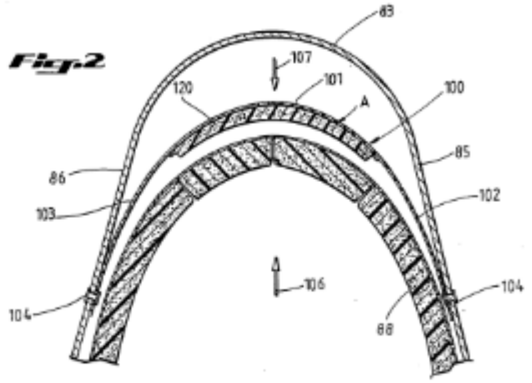


Figure 4. Diagram of Cantilever Strap Design in Football pads (Wingo, 1989)

Bauer Hockey LLC. owns a patent for ice hockey shoulder pads filed in 2012 called protective athletic garment. The patent is an example of the current design of hockey shoulder pads, comprising of a protective polycarbonate shell that sits on the AC region of the shoulder. The shell is stitched to an underlying foam liner and offers a bicep portion that straps to the player’s bicep for added protection. The protection strategy is similar to the football pads, in that its goal is to maximize the space between padding and the shoulder using plastics and foam to absorb impacts. The difference is that hockey shoulder pads are designed for mobility, therefore lighter materials and designs promoting free range of motion are selected (Contant & Leblanc, n.d.). Another difference is the fact that the flexibility of the foam liner material allows for a sort of spring back motion of the cap back towards the player’s neck as shown by the arrow in the diagram below. A diagram of Bauer’s shoulder pad shoulder region is shown below.

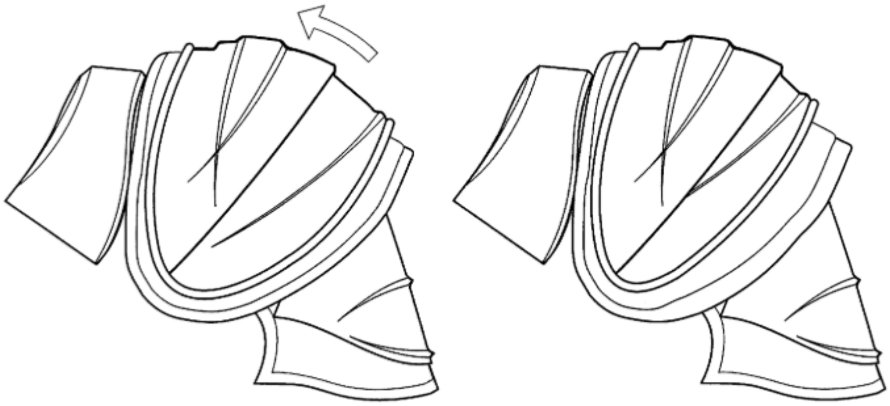


Figure 5. Shoulder region of Bauer shoulder pads (Contant & Leblanc, n.d.)

An emerging technology from G-Form LLC. is material used in padding that is soft when impacts are not occurring but hardens upon a large magnitude force. They are designed to be lightweight and conforming to the body, but still hard enough upon impact to protect from injurious loads (Wyner et al., 2018). XRD Foam, an open cell polyurethane foam material, is a similar type of foam being used in protective athletic equipment. X-Tech is a company creating football shoulder pads incorporating XRD foam and a cantilever and yoke system to more effectively absorb and transmit injurious loads. The yoke works to transfer loads on the “epaulets” of the shoulder pads to the rest of padding (Monica, 2013).

1.3.3. Impact Absorption Mechanisms

Besides existing shoulder pads, there are other mechanisms that could be useful for the design of protective shoulder pad equipment. Other mechanisms to consider when designing the equipment include car bumpers, air bags, and helmets. These all have properties that help to absorb forces to lessen injuries to people. Each mechanism absorbs forces from an impact in different ways that can be helpful when designing equipment for high impact collisions.

Car bumpers are the first form of defense against collisions and other car accidents. This is similar to a shoulder pad where the pad itself is the first form of defense for the athlete. The three main parts of a car bumper are the fascia, the energy absorber, and the bumper beam. The fascia is used to reduce aerodynamic drag forces, the energy absorber is used to dissipate some of the kinetic energy that comes with a collision, and the bumper beam is used to absorb the lower impact energy as well as the higher impact kinetic energy. Similar to changing rules and regulations of sports, car bumpers are constantly being redesigned based on government safety regulations and new styles of cars (Davoodi, 2012). There is increased use of plastics for car parts because it reduces the total weight of the vehicle by replacing the less load-bearing parts with a lighter material. Plastics are also being used to create shapes of more complicated parts by plastic injection. High Impact Polypropylene (HIPP) is commonly used in car bumpers (Kozderka, 2017). Other companies use composites of multiple materials and fibers in different directions to modify the strength of the materials. The main objective of car bumpers is to keep the car intact during high impact collisions while dampening the kinetic energy that comes with that. A shoulder pad used in sports follows similar guidelines. The protection of the shoulder from a shoulder pad can be compared to protecting the vehicle and passengers from a car bumper.

The design and functionality of a football helmet is very important to protect against head collisions such as concussions. A general football helmet uses multiple components to fully protect the head from high-impact. The foam utilized in the helmet can be a PVC nitrile foam or polyurethane foam that has a compression deflection of at least 25% per 8 psi. Another football helmet was recently designed with varying shock absorbance. The helmet contains two sets of shock absorbers that each have a different pressure threshold (McGurkin, 2015). When the player is hit, the first set of shock absorbers reach a certain pressure threshold, and a valve containing air pockets in the helmet is relieved, releasing the pressure. This mechanism holds true for the second set of shock absorbers except the pressure is released at a different pressure threshold. There is a low friction shell on the external layers in order to deflect the forces away from it being a direct hit. Another form of impact absorption for football helmets is the use of polygonal apertures that are adjacent to the energy absorbing layer made from expanded polypropylene (Simpson, 2017). This energy absorbing layer in the helmet has a higher compressive strength that the outer liner of the helmet. The figure below shows this helmet and its layers.

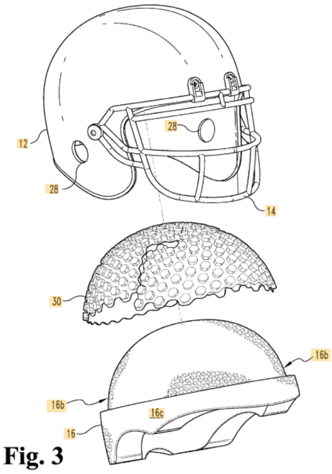


Fig. 3

Figure 6. Diagram of helmet showing the polygonal absorbing layer (Simpson, 2017)

Air bags are a safety mechanism that are commonly put in cars to keep passengers safe during a collision. They are made of nylon and act as a pillow when a collision occurs by filling with nitrogen gas. Airbags are meant to help prevent injury to people by distributing the load from the crash to lessen the force of impact on the passenger. The sensing and diagnostic module (SDM) of a car senses when a collision might occur through door sensors and accelerometers. If the collision is forceful enough, then the airbags deploy. Deployment of airbags after an impact is detected happens within 8-40 milliseconds, and an airbag that is roughly 2.5 cubic feet can inflate in about 20-30 milliseconds. Similar to airbags, shoulder pads are meant to prevent injury to players by distributing the load from a hit (Huffman, 2015). However, the quick inflation of a load lessening mechanism could potentially be harmful to an opponent if it inflates too forcefully. There is also no quick return of airbags to their original position, which would not be good during a fast-paced game. While the concept of an airbag would be good for a shoulder protecting mechanism, there would need to be some modifications to the idea if it were to be used in shoulder pads.

Outside the realm of devices, the team also investigated biological specimens that utilize some form of protective mechanism to shield themselves from the environment or from predators. The Golden Shell Snail, or C. squamiferum, has a tri-layer shell consisting of a rigid outer layer for energy dissipation, a rubber-like middle layer for supporting the rigid outer shell, and a rigid inner layer for stability and structural support of the whole shell (Yao et al., 2010).

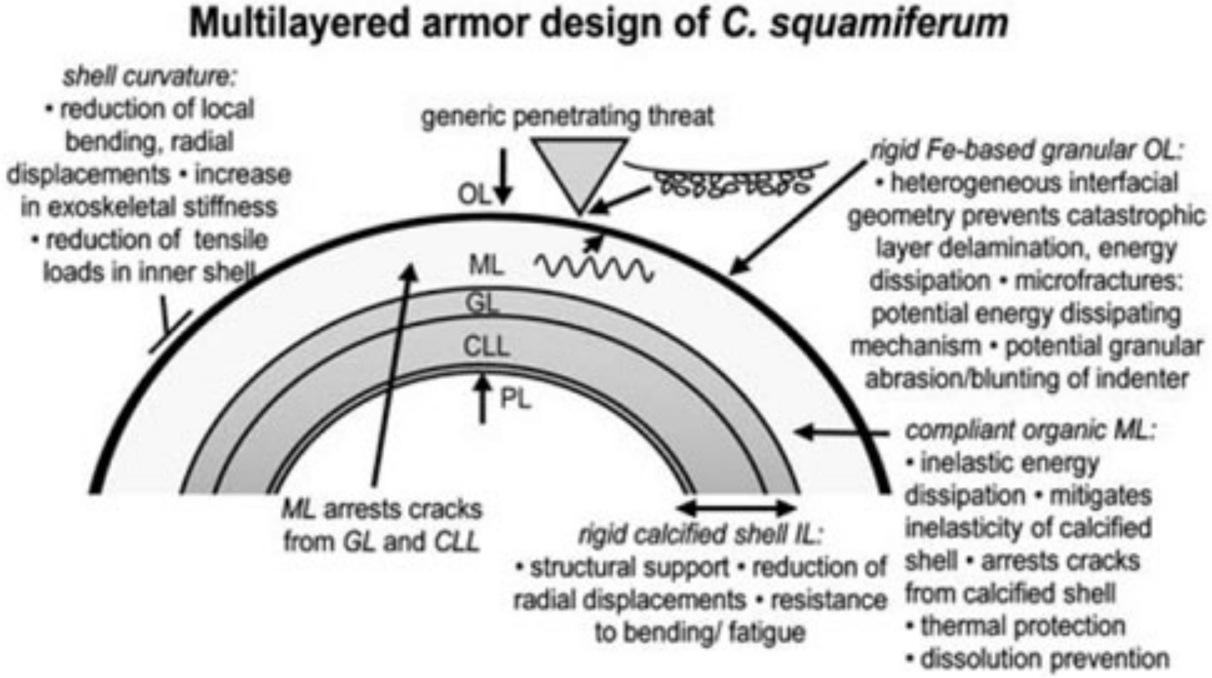


Figure 7. Breakdown of the shell of the Golden Shell Snail (Yao et al., 2018)

The innermost layer was the hardest material (5.4 GPa), but also had the greatest elastic modulus (98.9 GPa), as it acted as the last line of defense from an injurious force. The team researched further biological models to see the advantageous features that could be implemented into shoulder cap design, such as segmenting the cap, similar to a lobster's shell, or providing multiple cap layers, similar to the Golden Shell Snail (Yao et al., 2010).

1.4. Approach

Shoulder pads on the market today are similar in that they rely on foams and hard plastics to absorb and dissipate loads applied at the shoulder. Current designs consist of hard plastic caps either resting directly on or suspended on top of a liner made of foam, based on the idea that the key to attenuating forces on the AC area is to maximize the space or distance the force travels through with absorbing materials or actual distance. This design has been successful in terms of its longevity, because this type of pad structure has not changed drastically since the late 1980s, only slightly improved upon with better foams and plastics. Shoulder pad designers and manufacturers today also are designing with the goal of maximizing range of motion and minimizing weight, which, if done incorrectly, can result in further injury. Equipment manufacturers Reebok and CCM designed hockey shoulder pads in 2012 that were 750 grams versus the average set of pads that weigh 1000-1500 grams (Shinzawa, 2012). Our approach involves improving the protection of shoulder pads while also maximizing range of motion. Similar to shoulder pad design today, we will try to maximize the distance or space the force travels through, while still working to maximize the time over which the force acts, something that shoulder pads today aren't as concerned with.

Impact attenuation relies on two physics principles or equations:
(1) $v^2 = 2as$
(2) $F\Delta t = m\Delta v$

These equations express two means of minimizing the magnitude of impacts. The first is space, given by equation one. If v^2represents the velocity component of the energy an impact contains, the force of the impact can be reduced by increasing s, the distance over which the force acts. This is what shoulder pads today attempt to do with foams and suspended liners. Our approach involved maximizing Δt, from equation two (Impulse-momentum). In theory, if the time over which a force acts is increased, the force of the impulse will decrease, which in turn decreases the effects felt by the surface or body being impacted. Our team will attempt to maximize the time over which injurious loads on the AC region can act, using controlled movement of the shoulder caps to disperse the loads over a larger area.

The team designed such a mechanism using axiomatic design. It is based on the application of two axioms to the design process: maintain independence of the functional elements and minimize information content, or maximize success by reducing the amount of instruction needed to fulfill functional requirements (FRs) (Brown, 2006). The FRs and design parameters (DPs) were decomposed and will be discussed in section 2.

1.4.1. Revised Client Statement

Based on the constraints, objectives, functions, and design parameters identified by our team, we have revised our client statement. The revised client statement incorporates the functional aspects of our design, with the desired and expected outcomes our team plans on completing.

The objective of this project is to develop a device or mechanism capable of reducing athletes' risk of shoulder separation injuries in contact sports, while avoiding any influences on the athlete's range of motion. The device will provide a compressible barrier from direct forces on the shoulder, as well as the ability to move the shoulder cap to increase the distance and time over which the force acts.

1.4.2. Project Strategy

Once the project objective and background research were completed, a timeline and list of goals were created to outline the needs and requirements of the project throughout the year. The team started with a basic outline of what needed to be accomplished. The main points of this outline included research of products, axiomatic design decomposition of designs, prototype iterations, and development of a final product that meets the needs of the client. This can be accomplished by assigning goals to be met by each term and utilizing a Gantt chart that outlines each task and appropriate time of completion.

1.4.2.1. Technical Approach

The objective and client statement of the project are used to ensure the approach of the project is addressed completely. The goals to be accomplished each term can be seen in the table.

A Term 2018	
Soft Goals	Reach Goals:
- Define Objectives and Constraints - Complete relevant background research - Identify target audience for client statement - Decomposition of axiomatic design - Section 1-3: Introduction, Background, and Approach	- Complete axiomatic design - SolidWorks of designs

B Term 2018	
Soft Goals:	Reach Goals:
- Research of materials - Complete Axiomatic Design - Preliminary design evaluation - Paper outline/ organization	- Begin prototyping - Manufacturing/ machining of prototype

C Term 2019	
Soft Goals:	Reach Goals:
- Materials Testing - Prototyping of Design - Machining of Design	- Interface with equipment - Complete Design Verifications - Final Tests of Prototype

D Term 2019	
Soft Goals:	Reach Goals:
- Complete Design Verifications & Testing - Interface with Equipment - Completed Final Report - Patent Filing	- Manufacturability

The goals of A-term focused on the beginning steps of the MQP project. The team conducted background research in order to understand the needs of the client and what could be improved in designs on the market today. This background research was used to write the introduction and the literature review sections in the proposal. The team decided on goals that would be accomplished throughout the term and the direction of the project. A major component of this project is using axiomatic design to develop functional requirements of improved shoulder pads. These functional requirements allowed the team to produce a variation of design parameters, customer needs, and constraints. The team created decompositions of axiomatic designs and revised them multiple times.

The goals for B term focused on bringing axiomatic design closer to completion as well as coming up with preliminary designs for the shoulder cap mechanism. The team came up with different iterations throughout the term of what the mechanism may look like based on the axiomatic design and ultimately came up with a final design from those drawings. Testing methods and materials were also researched during this term. The team came up with a list of materials that would be good to use for the mechanism and came up with testing methods to use to analyze the mechanism. Adjustments were made to the paper to help with the organization and flow of the information provided.

The focus of C term was to gain a better idea of how the prototype would come together and be created. The team ordered different materials and tried them out to see which ones would work best for the device. Ideas of how the prototype would be machined and put together were also brainstormed until the team reached a consensus on what they wanted it to look like. From here, the team began creating different parts of the device and prototyping the entire thing. Moving into D term, the team wanted to make sure they had everything in a good place. They made sure the paper was as up-to-date as it could be and had all parts of the device ready for final prototyping.

D term marked the term of finalizing everything for this project. The team focused first on finalizing the prototype by completing design verifications and testing of the device. Once this part was complete, the team began interfacing the device with the shoulder pads they had previously purchased. After interfacing, the prototype was finally complete. The team then focused on filing for a provisional patent and completing the report.

1.4.2.2. Financial Approach

A budget of $250 per person was assigned to complete the project through the Mechanical Engineering and Biomedical Engineering Departments. This allowed for a total budget of $1,000 for the year. The budget will be allocated based on what goals need to be accomplished throughout the term. The team will have a working prototype by the end of the year. A large portion of the budget will be spent on materials to prototype the mechanism and make the final design, and some of the budget may also be used to buy materials needed to test the design.

1.4.2.3. Management Approach

The team created Gantt charts to visualize the project approach. There was a separate Gantt chart created for each term that includes the sections for the proposal, axiomatic design, prototyping, and other tasks. The complete Gantt chart is available in Appendix A.

2. Design Methods

2.1. Axiomatic Design

The team used axiomatic design to begin developing shoulder pad designs. Axiomatic design is a design methodology developed by Nam Suh while he was a professor at MIT in the 1970s. Our use of axiomatic design was mainly based on the writing by Professor Chris Brown in 2006, his PowerPoint slides, and in-person conversations the team has had with him. It is based on two axioms, from which the decomposition of a particular design follows.

2.1.1. Axiom One: maintain the independence of functional elements

The first axiom in axiomatic design says that a design should maximize the independence of functional elements. Following this design minimizes the number of prototype iterations and steps to a final product because if each function is independent of the others, design elements fulfilling that particular function can be manipulated without affecting multiple aspects of the design. Functional requirements logically flow from this axiom.

2.1.2. Axiom Two: minimize information content of the design

The second axiom of axiomatic design states that designers should minimize the information content of a product or device. Information content refers to the amount of instruction needed for the product or device to be manufactured or for a user to use the device. Minimizing the information content increases the product's probability of success. If multiple designs satisfy axiom one, axiom two is used to determine which will have the highest probability of success.

2.1.3. Functional Matrix: Decomposition and Constraints

The axioms influence the design through a structure of domains and hierarchies. An axiomatic design decomposition results in a structure of horizontal categories and vertical detail. Defining Customer Needs (CNs) is the first step of the design process and involves defining the needs of the potential users of the product or device. They are often broad requirements and lack specifics or technical language. From CNs, Functional Requirements (FRs) are defined, which are functions of the design. Design Parameters (DPs),are the next domain and are the physical solutions to satisfy FRs. Process Variables (PVs) have to do with the process of satisfying DPs. Our team moved through the horizontal categories of the design elements, and added vertical detail in the functional requirements and design parameters.

The team first defined CNs for the design: protect the shoulder from injurious loads and compliment the shoulder anatomy. The next important consideration was constraints for the design. They were defined from NCAA regulations and other factors based on potential users and are listed below:

- Pads should protect from normal play loads and injurious loads, which from literature, can range from 1650 N for normal play and above 3340 N for injury (Usman, McIntosh, & Fréchède, 2011).
- Pads should be comfortable, lightweight, and allow full range of motion. They should weigh less than or equal to hockey pads currently on the market.
- Mechanism in the shoulder pads should be applicable to pads in various sports.
- The only regulation on shoulder cap height is for the goalies. Goalies cannot have anything exceeding 1” of thickness under their shoulder caps (USA Hockey: Section 3 - Equipment, 2019)
- Pads and mechanism should not pose greater risk of injuries to other players.

With constraints defined, the customer needs were adjusted into more detailed and technical FRs. Each FR gets a corresponding DP to physically satisfy the requirement. Broad FRs and DPs were defined, then vertically decomposed to make a more detailed and robust design. It is often useful to use a theme when decomposing a design, so the team used the impact energy and impulse principles described in Section 1.4. It was also crucial to continually check that the FRs were collectively exhaustive and mutually exclusive, to ensure all ideas and aspects were being considered. Selection criteria and optimization criteria were defined used during the decomposition process to decide on different possibilities for design parameters or aspects of a design parameter.

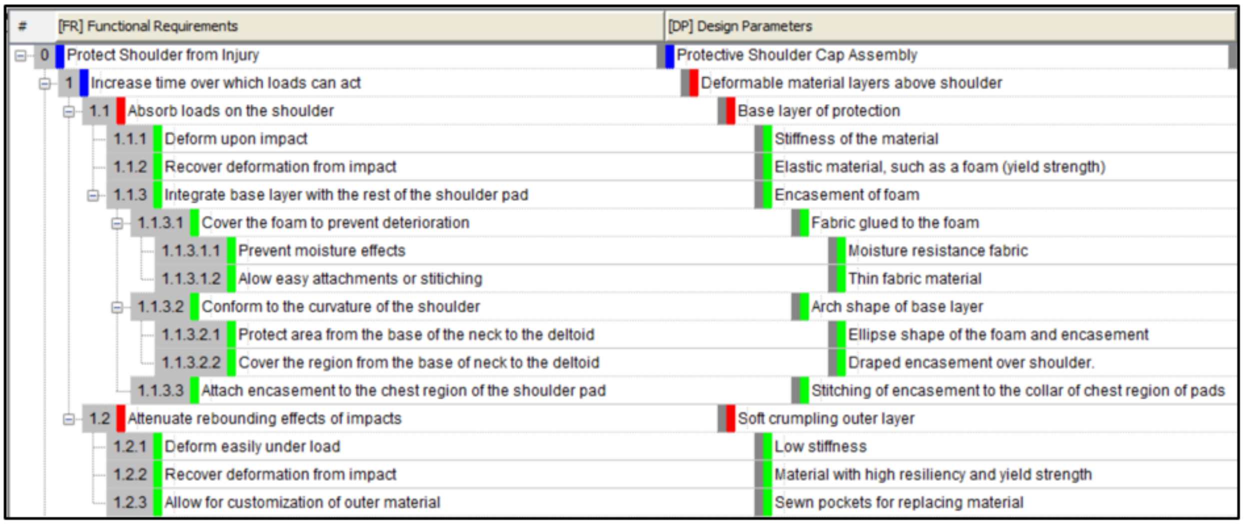
With these guiding principles in mind, the team used Acclaro, an axiomatic design software, to decompose a shoulder cap assembly to satisfy the consumer need of protecting athletes' shoulders from shoulder separation. The team iterated through the decomposition process many times before finalizing a decomposition. One of the benefits of using axiomatic design for this project was that the decomposition process resulted in alternative DPs to satisfy FRs. Some of the alternative design decompositions can be found in Appendix B, and alternative designs are discussed in Section 3.1. The rest of this section details the decomposition process and resulting design solution. The functional matrix the team moved forward with is described below.

FR0: Protect shoulder from Injury

FR0 is the highest level FR from which the detail of the decomposition follows. It represents the overall goal of the design and is the most closely related to our customer need of protecting the athlete's shoulder. All of the following FRs and DPs will try to satisfy this objective.

DP0: Protective shoulder cap assembly

DP0 is the highest level DP to satisfy FR0. The team tried to describe the overall design solution in a broad way as to not limit the opportunities for subsequent DPs. We chose the word, "assembly" so that the detailed DP components resulted in a full protective device. The shoulder cap refers to the hard plastic material used in shoulder pads to cover the shoulder joint, and we set to improve this region with a protective assembly.



#	[FR] Functional Requirements	[DP] Design Parameters
0	Protect Shoulder from Injury	Protective Shoulder Cap Assembly
1	Increase time over which loads can act	Deformable material layers above shoulder
1.1	Absorb loads on the shoulder	Base layer of protection
1.1.1	Deform upon impact	Stiffness of the material
1.1.2	Recover deformation from impact	Elastic material, such as a foam (yield strength)
1.1.3	Integrate base layer with the rest of the shoulder pad	Encasement of foam
1.1.3.1	Cover the foam to prevent deterioration	Fabric glued to the foam
1.1.3.1.1	Prevent moisture effects	Moisture resistance fabric
1.1.3.1.2	Alow easy attachments or stitching	Thin fabric material
1.1.3.2	Conform to the curvature of the shoulder	Arch shape of base layer
1.1.3.2.1	Protect area from the base of the neck to the deltoid	Ellipse shape of the foam and encasement
1.1.3.2.2	Cover the region from the base of neck to the deltoid	Draped encasement over shoulder.
1.1.3.3	Attach encasement to the chest region of the shoulder pad	Stitching of encasement to the collar of chest region of pads
1.2	Attenuate rebounding effects of impacts	Soft crumpling outer layer
1.2.1	Deform easily under load	Low stiffness
1.2.2	Recover deformation from impact	Material with high resiliency and yield strength
1.2.3	Allow for customization of outer material	Sewn pockets for replacing material

Figure 8. FR0 and FR1 of Functional Decomposition

FR1: Increase time over which loads can act

The team followed the theme of decreasing the impulse and energy that the shoulder absorbs during the decomposition. FR1 and FR2 were based on the goal of increasing the time and distance over which injurious loads on the shoulder can act, therefore FR1 was to increase time over which loads can act.

DP1: Deformable material layers above the shoulder

One method of increasing the time over which loads can act is the addition of materials that can deform and absorb as much energy as possible before it reaches the anatomy of the shoulder. The wording and idea of this DP was to leave it as broad as possible to provide opportunities for different materials, number, and type of layers to be used to protect the shoulder.

FR1.1: Absorb loads directly above shoulder

The layers were thought of from the shoulder up, and providing protection directly on the shoulder was important to provide a last line of defense as well as comfort for the user.

DP1.1: Base layer of protection

The team defined a base layer of protection as the design parameter to absorb loads directly above the shoulder.

FR1.1.1: Deform upon impact

DP1 defined deformable materials to satisfy FR1 of increasing time over which loads can act. Therefore, the material placed directly on the shoulder should deform under loads to absorb some of the impact energy.

DP1.1.1: Stiffness of the material

Stiffness was an important consideration, and the characteristic helps determine how much deformation the material can withstand as well as the comfort for the user.

FR1.1.2: Recover deformation from impact

The material chosen to protect the shoulder directly must be able to recover deformation so it can be effective against many impacts.

DP1.1.2: Elasticity (Yield Strength) of material

A material with a high yield strength was defined as the design parameter so that the deformation would be elastic and not plastic during impacts.

FR1.1.3: Integrate the base layer with the rest of the shoulder pad

The base layer of the cap assembly needed to be incorporated with the rest of a shoulder pad, specifically the chest protection region, so it could be worn by the user. This FR has three more children or sub-FRs that can be seen in the decomposition in Figure 6.

DP1.1.3: Encasement of base layer material

The base layer material needed to be encased in order to protect the material from degradation, as well as to provide means for the base layer material to be stitched or attached to other components.

FR1.2: Attenuate rebounding effects of impacts

The idea behind this FR is to mitigate the effects of a stray stick or impact rebounding, decreasing the time required for another impact to affect the shoulder. The device should cause the player to “stick” during the impact. However, these preferences change from user to user, so other FRs were defined to allow for customization.

DP1.2: Soft crumpling outer layer

A soft material with a high coefficient of friction would allow for a sticking mechanism during impacts. This layer also serves to lessen the impact of the shoulder pad on the opponent during body checks.

FR1.2.1: Deform easily under load

The soft layer of material had to be soft in order to allow for easy deformation.

DP1.2.1: Low stiffness of material

The material was selected using stiffness as the material characteristic and DP. The material had to be soft enough to compress and stay compressed during impacts, reducing the velocity by which the object would deflect off of the foam surface.

FR1.2.2: Recover deformation from impact

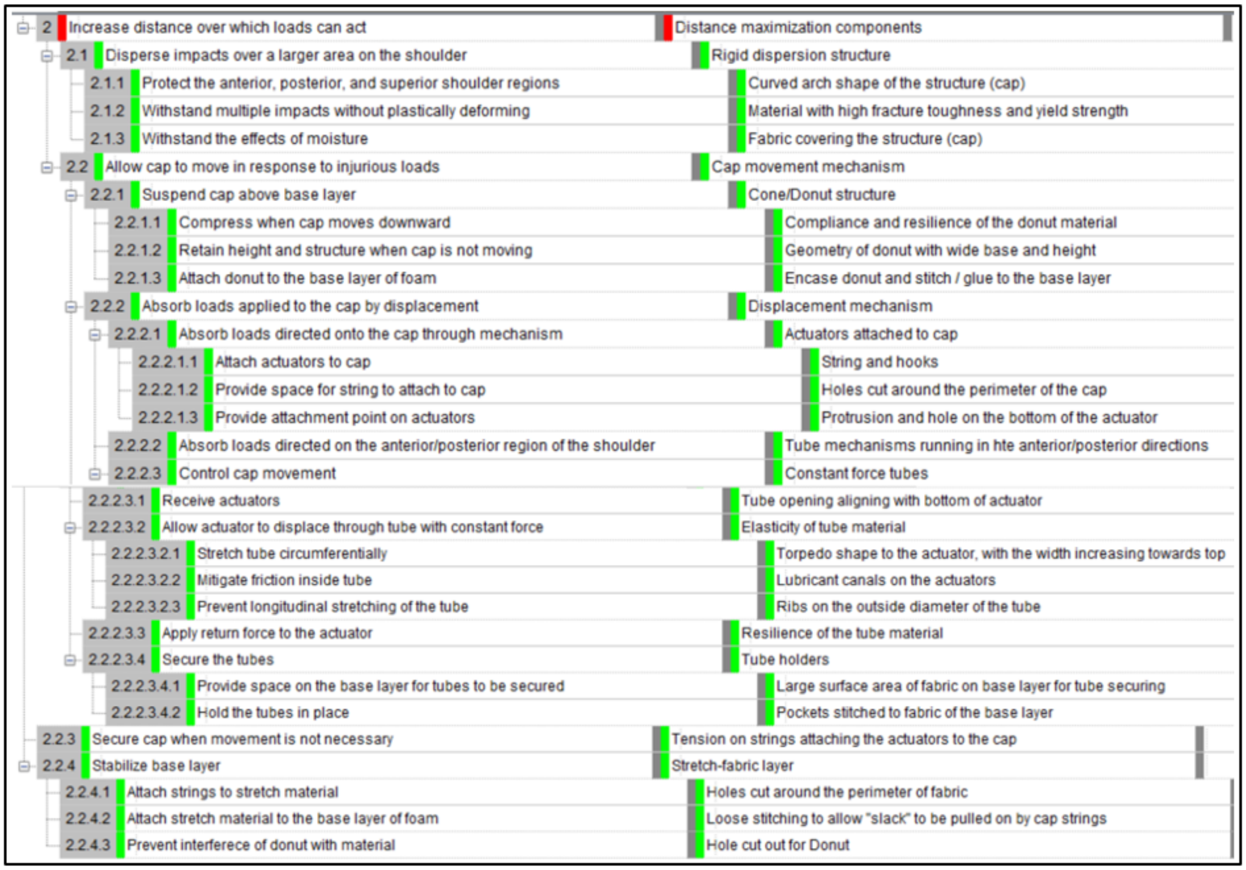
Similar to FR1.1.2, the material needed to withstand multiple impacts and not plastically deform, so a material with high yield strength and high fatigue strength was needed.

FR1.2.3: Allow for customization of outer material

One goal of the design was for the pads to be customizable depending on the user’s position or comfort. In some cases, it would be advantageous for other players to “stick” to the pads during impacts, and in other cases it would be advantageous for players to slide off easily. This FR accounts for this customization of the outer material.

DP1.2.3: Sewn pockets for replacing material

Sewn pockets that maintain pressure on the material allowed for switching of the material in an out of the cap assembly.



2	Increase distance over which loads can act	Distance maximization components
2.1	Disperse impacts over a larger area on the shoulder	Rigid dispersion structure
2.1.1	Protect the anterior, posterior, and superior shoulder regions	Curved arch shape of the structure (cap)
2.1.2	Withstand multiple impacts without plastically deforming	Material with high fracture toughness and yield strength
2.1.3	Withstand the effects of moisture	Fabric covering the structure (cap)
2.2	Allow cap to move in response to injurious loads	Cap movement mechanism
2.2.1	Suspend cap above base layer	Cone/Donut structure
2.2.1.1	Compress when cap moves downward	Compliance and resilience of the donut material
2.2.1.2	Retain height and structure when cap is not moving	Geometry of donut with wide base and height
2.2.1.3	Attach donut to the base layer of foam	Encase donut and stitch / glue to the base layer
2.2.2	Absorb loads applied to the cap by displacement	Displacement mechanism
2.2.2.1	Absorb loads directed onto the cap through mechanism	Actuators attached to cap
2.2.2.1.1	Attach actuators to cap	String and hooks
2.2.2.1.2	Provide space for string to attach to cap	Holes cut around the perimeter of the cap
2.2.2.1.3	Provide attachment point on actuators	Protrusion and hole on the bottom of the actuator
2.2.2.2	Absorb loads directed on the anterior/posterior region of the shoulder	Tube mechanisms running in hte anterior/posterior directions
2.2.2.3	Control cap movement	Constant force tubes
2.2.2.3.1	Receive actuators	Tube opening aligning with bottom of actuator
2.2.2.3.2	Allow actuator to displace through tube with constant force	Elasticity of tube material
2.2.2.3.2.1	Stretch tube circumferentially	Torpedo shape to the actuator, with the width increasing towards top
2.2.2.3.2.2	Mitigate friction inside tube	Lubricant canals on the actuators
2.2.2.3.2.3	Prevent longitudinal stretching of the tube	Ribs on the outside diameter of the tube
2.2.2.3.3	Apply return force to the actuator	Resilience of the tube material
2.2.2.3.4	Secure the tubes	Tube holders
2.2.2.3.4.1	Provide space on the base layer for tubes to be secured	Large surface area of fabric on base layer for tube securing
2.2.2.3.4.2	Hold the tubes in place	Pockets stitched to fabric of the base layer
2.2.3	Secure cap when movement is not necessary	Tension on strings attaching the actuators to the cap
2.2.4	Stabilize base layer	Stretch-fabric layer
2.2.4.1	Attach strings to stretch material	Holes cut around the perimeter of fabric
2.2.4.2	Attach stretch material to the base layer of foam	Loose stitching to allow "slack" to be pulled on by cap strings
2.2.4.3	Prevent interference of donut with material	Hole cut out for Donut

Figure 9. FR2 of Functional Decomposition

FR2: Increase distance over which loads can act

The second major FR of the device is to increase the distance over which loads can act thereby reducing the energy of impacts felt by the shoulder. From this parent FR stemmed lower level FRs and DPs that defined a movement mechanism for the shoulder pad to dissipate forces.

DP2: Distance maximization components

The DP to satisfy FR2 was distance maximization components, to allow for multiple solutions to be considered. The result of leaving the DP broad was other options for distance maximizations, which are highlighted in the Section 3.1 and Appendix B.

FR2.1: Disperse impacts over a larger surface area on the shoulder

Part of increasing distance over which loads can act on the shoulder was dispersing the load over a larger surface area. This is so that stress and energy are not focused on one area because this would increase risk of injury.

DP2.1: Rigid dispersion structure

With inspiration from pads currently on the market, the team defined a rigid structure to disperse loads over the shoulder as the DP to satisfy FR2.1.

FR2.1.1: Protect the anterior, posterior, and superior shoulder regions

The device should protect all regions of the shoulder anatomy, therefore this needed to be an FR for the dispersion structure.

DP2.1.1: Curved arch shape of the structure (cap)

The team defined a curved structure, called a cap, as the dispersion structure. The cap would have a rigidity allowing it to withstand multiple impacts and a curvature to promote force dispersion over and around the shoulder.

FR2.1.2: Withstand multiple impacts without plastically deforming

It was crucial for the cap to withstand multiple impacts without damage that would put the player at risk.

DP2.1.2: Material with high fracture toughness and yield strength

The material chosen to make up the cap needed to have a high fracture toughness and yield strength to avoid brittle fractures and plastic deformation.

FR2.1.3: Withstand the effects of moisture

The cap will be in an environment with the athlete’s sweat as well as water from ice melting during the course of a hockey game. The cap should be able to withstand this moisture.

DP2.1.3: Fabric covering the cap

A moisture resistant fabric covering the cap would help mitigate the effects of moisture and provide a means for more tightly securing outer layer of soft foams to the cap.

FR2.2: Allow cap to move in response to injurious loads

The team defined this FR as a means to increase the distance over which forces can act on the shoulder. The children FRs of this FR define a mechanism for movement of the cap.

DP2.2: Cap movement mechanism

A mechanism is defined to move the cap in response to injurious forces.

FR2.2.1: Suspend cap above base layer

The goal for the cap movement is that the cap can move in all direction and downwards in compression. In order for the cap to move in these directions, it was important that the cap was suspended to offer more space for it to move.

DP2.2.1: Cone/Donut structure

The cone/donut structure was modeled after the donut found in ankle and knee braces, which are elevated on top of the joint. This structure would offer stability and height to suspend the cap on. The donut also needed to be soft enough to compress.

FR2.2.2: Absorb loads applied to the cap by displacement

This is the overall FR for the mechanism of the cap movement. The overall goal of the mechanism is to displace so that forces can be more effectively absorbed.

DP2.2.2: Displacement mechanism

The displacement mechanism will act as a system that can allow the cap to "give" under loads. The sub-structure in the axiomatic design describing this mechanism can be seen in the full decomposition (Figure 7). The mechanism will be described in detail in Section 4.

FR2.2.3: Secure cap when movement is not necessary

Movement of the cap when loads are not applied to it would pose a risk to the athlete because the cap would not be in its correct position. This FR serves to define a means to secure it.

DP2.2.3: Tension on strings attaching the actuators to the cap

Tension on the strings of the mechanism also satisfied the function of securing the cap when movement wasn't necessary. However, this results in a coupled design because the strings satisfy FR2.2.2.1.1 as well. Future iterations should aim to decouple this aspect of the design.

FR2.2.4: Stabilize base layer

This FR describes the function required to keep the base layer stationary during cap movement.

DP2.2.4: Stretch-fabric layer

The stretch-fabric layer stabilizes the base layer by creating a separate layer of fabric that the strings and mechanism apply force to during movement.

2.2. Prototyping/ Proof of Concept

Before moving forward with fabricating the components for our final design, the team chose to prototype different models of the actuator and tube, so that they could be tested against one another to examine which model displayed the desired properties. The team also used polyplastic to form a mold of the intended cap shape, based on the dimensions of a shoulder cap that is already on the market.

3. Iteration

3.1. Alternative Designs

Throughout the course of the design process, our team researched and performed several iterations of the shoulder cap, implementing different force-attenuation mechanisms into our design. Each iteration contained its own assortment of design parameters (DPs) to match with the functional requirements (FRs) outlined in our axiomatic design. As more FRs were added, our team was responsible for researching and including their respective DPs, leading the team to our current axiomatic design outline and the final design for the cap.

3.1.1. Foam Tunnel

Before researching and fabricating the tube and actuator for our force-attenuation mechanism, the team debated using a 3D-printed tunnel with XRD adhered to the inside of it, with a prism shaped actuator as the primary mechanism underneath the cap. The CAD models are shown in Figures 8 and 9 below.

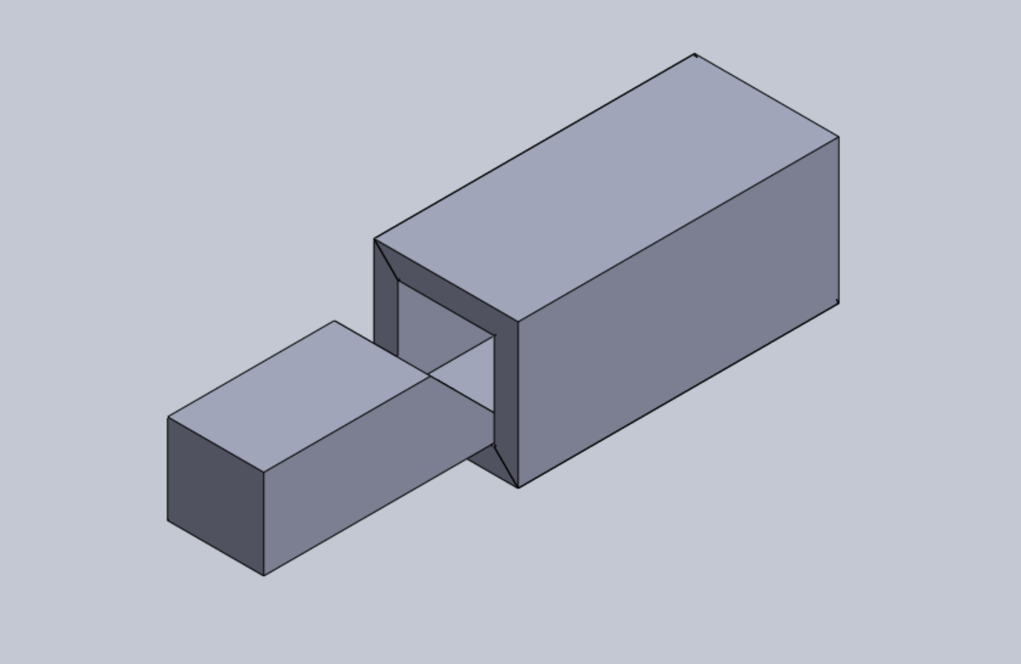


Figure 10. Isometric View of the Foam Tunnel and Actuator

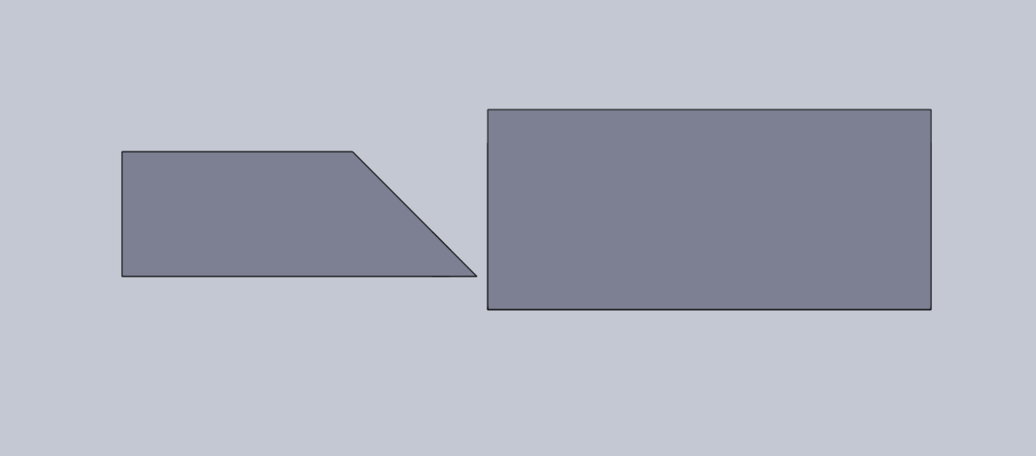


Figure 11. Right Side view of the Foam Tunnel and Actuator

Similar to the tube and actuator, the interaction between the actuator and the foam within the tunnel would produce a similar constant force attenuation as the cap was compressed downward due to a load. The benefits of this design included the ease of production, as the tunnel and actuators could be 3D-printed and the XRD could be commercially bought and adhered using specialized foam-to-plastic glue. This design could, theoretically, fulfill the functional requirement of providing controlled force absorption, in comparison to the linear spring force attenuation model. The reasoning behind the team moving away from this mechanism was that the team felt that the tube and actuator presented a more promising option, due to the variability of actuator and tube designs, as well as decreased risk of interference between the mechanism and the shoulder as the cap is compressed. Due to the size, shape, and material selection options for the tunnels, there was the potential for the tunnels to contact the players shoulder and either cause injury or fail.

3.1.2. Joystick

The team began to investigate mechanisms to improve upon the integrity and strength of the shoulder cap, without the traditional polyethylene cap with foam layers underneath. The team considered the potential of having the cap move, in order to increase the time and distance over which the force acts and therefore decrease its magnitude below the injury threshold. Due to the shape of the cap, the relative anatomical dimensions that needed to be protected, and the forces that could be applied to the shoulder from a variety of directions, the team began researching devices that would allow the cap to move in a controlled manner, in all directions. Research into a design similar to a joystick began, meaning that the cap would be suspended in the middle by a support that was rounded at its base, so that it could rock back and forth in all directions. The benefits of this design was that the cap could respond to forces from all directions, the movement of the cap would, in theory, absorb more of the impact from collisions, and with the addition of springs, the cap could return to its original position allowing for a controlled collision between the center support and the edge of the base layer. The cons related to this design were that if the cap moved out of position and a second force was applied, the shoulder would be left unprotected. Also, the movement of the cap, especially as it contacted the springs, possessed a threat to the opposing player, and due to the relative geometries required for the movement of the cap to be possible, the cap may have been suspended too far off of the shoulder.

3.1.3. Gate

Pertaining to the joystick mechanism idea the team had decomposed in a prior version of the axiomatic design, we began researching the functional benefits of including small barriers, in addition to the joystick, to control its motion over a range of forces. The joystick/cap mechanism would only be able to move within a confined area on the base layer, as the barriers would keep it within a set region. If the forces were over a particular magnitude, the barriers would open, similar to how two gates would swing up in the same direction, which would allow for the cap to move over a greater distance, therefore reducing the load experienced by the shoulder. A series of these barriers would be included in a circular fashion around the suspension support, with a total of 2 complete circles being formed before the cap could be allowed to reach its maximum distance of motion. The benefits of this design were that the team could now control the motion of the cap and prevent excessive motion of the cap during normal play. In addition, by tuning the barriers to only open in response to a certain magnitude of force, the team could perform calculations on when to allow the shoulder cap to move farther, such that the force would not cause any injuries, under those conditions. The team did not pursue this mechanism further, due to potential difficulties with tuning the gates, the lack of return mechanism present within the design, and the fact that the design would not possess a responsive mechanism to a compressive mechanism, besides the cap material and foam.

3.1.4. Sandbags

An alternative idea to foams utilized in the cap design was implementing a layer of encapsulated sand, capable of providing an initial, compressible layer to lower magnitude forces, but also able to become more rigid as a high impact force was applied. Sand would be relatively cheap to manufacture with, and there were relatively no risks of material failure in this design, besides the encapsulating material. The team quickly moved away from this idea, due to the design missing a more constant force attenuation component, the potential for the component to be heavy, and the potential for rupture.

3.1.5. Airbag

As a form of compression, the team proposed and researched inserting a reverse airbag system underneath the shoulder cap, that would be able to deflate and control the force absorption as a load was applied. Custom slit valves along the edges of airbag would allow the airbag to stay inflated during normal play, and in response a compressive force, the airbag would deflate at a controlled rate and re-inflate with air from the play environment once the load was removed. The team moved away from the design parameter due to difficulties with controlling the airflow to produce the similar, constant force attenuation and concerns with the airbag's dimensions, as they may resist range of motion and be against hockey regulations.

3.1.6. Hydraulics/ Pneumatics

An alternative design parameter for absorbing force in a constant force manner that was discussed was either hydraulic or pneumatic systems. These systems would have worked by actuation of a piston in response to a load applied to the cap. Specific fluids or air pressures would have been tested to attain the constant force behavior objective. The benefits of hydraulics/pneumatics for force absorption are the constant force attenuation and the ability to adjust the fluids or air pressures, and the stiffness of the hydraulic (Fluid Power Journal, 2018). Some of the reasons the team did not pursue this design option for this project was because the testing and fabrication of a pneumatic or hydraulic system would have been too complex for the scope of this project, and integration would have increased the weight of the pads and thus affected the range of motion for the athlete.

4. Final Design Selection

4.1. Decision Matrix Criteria

The decision matrix below was created based on team opinions and assumptions. On the top row is our design ideas, and on the left column is features that we felt were important in the design. We ranked each design based on how well it fits each feature. Our rankings range from 1-5 with 1 being the worst (design does not fit that feature well) and 5 being the best (design fits the feature well).

Table 1. Decision Matrix

	Tubes and actuators	Foam Tunnel	Joystick	Gate	Sandbag	Airbag	Hydraulics/ Pneumatics
Lightweight	4	3	4	3	1	5	2
Controlled	3	4	3	3	3	2	4
Force Attenuation	4	3	3	4	4	4	4
Ease of Manufacturing	3	3	3	2	4	2	2
Return Mechanism	4	2	4	2	2	1	3
TOTAL	18	15	17	14	14	14	15

4.2. Results from Decision Matrices

As seen with the matrix above, the tube and actuator mechanism has the highest overall score based on being lightweight, controllable, attenuating forces, being easy to manufacture, and having a good return mechanism. The team decided to go ahead with the tube and actuator design for the shoulder cap device and began coming up with ways to manufacture it.

4.3. Materials and Costs

Below is a table of all the materials that were purchased for our prototype. Prices of all materials are given, as well as a price per unit, which is highlighted in blue.

Table 2. Materials used in our prototype and their costs

Carbon Fiber Fabric-3k 2x2 Twill Weave. 0.012” thick, 50 inches wide	$35.99 per yard One Unit: $4.50
Epoxy resin	$54.95 for a quart of epoxy $24.95 for half pint of epoxy cure One unit: $19.98
1/4” Extra Soft Polyurethane Foam	$12.35 for 12”x12” One Unit: $10.80
2mm thickness XRD Foam	Around $13.45 for 12”x12” (ours was donated for testing) One Unit: $11.77
8 Tubes	$0.80 per tube One Unit: $6.40
8 Actuators	$0.30 per tube One Unit: $2.40
Sunline Siglon PEx8 Dark Green	$14.39 for 165 yards

Braid 165 Yards Braided Fishing Line	One Unit: $0.35
Eagle Claw Barrel Swivel with Interlock Snap clips for actuators	$1.49 for 10 One Unit: $1.19
Orange Micro Mesh Knit Fabric	$4.65 per yard One Unit: $0.29
Black 2 Way Stretch Upholstery Faux Leather Vinyl Fabric	$14 per yard One Unit: $10.50
TOTAL for One Unit	Using polyurethane foam: $56.41 Using XRD foam: $57.38

*the costs per unit were based on estimates of how much of each material the team actually used

Based on the following costs above, the price to make one prototype of our device would be around $56-$57. The cost difference between the two units is based on the interchangeable foams that we picked.

4.4. CAD Models

The following images are screenshots of the actuator and tube designs the team chose to use in their final design. The pictures are labeled with the respective functional requirements from the axiomatic design that use design parameters within these components to accomplish them.

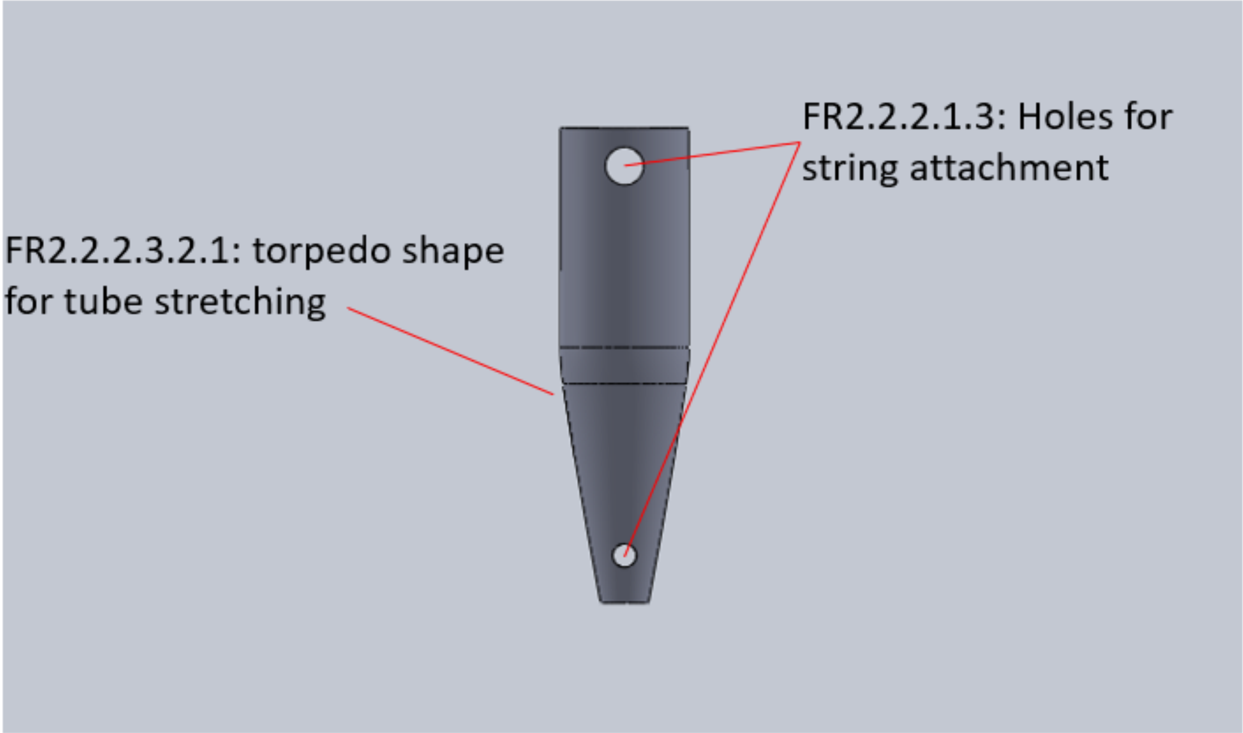


Figure 12. Solidworks Model of Torpedo Design Used in Final Design

Within the actuator design, there were two main functional requirements that team satisfied. FR2.2.2.3.2.1 corresponds to allow the tube to stretch circumferentially by including a dome shape at the end of the actuator, leading to a cylindrical base. FR2.2.2.1.3 corresponds to the attachment points on the actuator for the strings, which are holes at the top and bottom of the actuator, so that it can attach to the cap and to mesh layer.

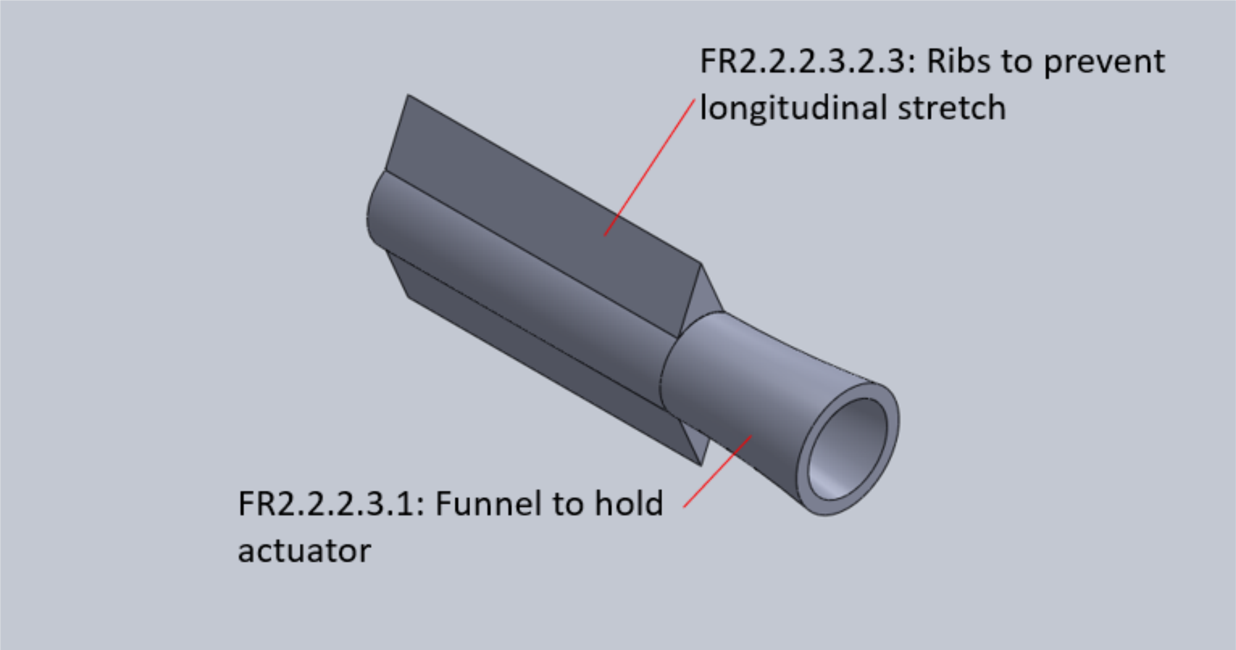


Figure 13. Solidworks Model of Tube Design Used in Final Design

Within the tube design, there were two main functional requirements that team satisfied. FR2.2.2.3.1 corresponds to the tube receiving the actuator and the design parameter used was a funnel shaped entrance that would complement the shape of the actuator and guide it into the tube when a force was applied. FR2.2.2.3.2.3 corresponds to the prevention of longitudinal stretch of the tube, which called for the ribs on the outside of the tube on two opposite sides, stretching from one end of the tube to the other.

4.5. Manufacturing Process

The team assigned roles to create the shoulder pad mechanism. Two students focused on the cap and two focused on the mechanism. Once both were complete the team came together to assemble the device.

Cap formation began with finding best fit materials for the cap itself. After doing research and axiomatic design, it was decided that carbon fiber would work best as the cap material due to its strong but lightweight properties. Carbon fiber fabric and epoxy were ordered to make the cap. The carbon fiber was molded over a pre-existing Bauer hockey cap to mimic the shape of the original cap that we also did testing on for comparison. To correctly form the cap, we started by cutting out smaller pieces of carbon fiber from our yard roll that would better fit the cap. Then, we created the epoxy resin by combining system 2000A epoxy with a 2020A epoxy cure at a four to one ratio. This resin created the glue-like substance, which was used to combine all layers together and allow them to harden as one. Once the hard part of the cap was formed, it was time to figure out how to attach a protective foam layer on top and enclose the entire thing in fabric. We decided that the foam should be interchangeable, in order to allow players to choose which one would be best based on their role. As mentioned in one article that talked about ice hockey equipment, forwards tend to look for lighter pads that allow them to move quicker while defensive players tend to look for pads that are larger and allow for more protection from flying pucks (Parks and Recreation: The City of Cleveland Heights, 2017). Based on this, it is likely that forwards would want a harder foam that could allow them to slip by other players, and defensive players would want a softer foam to absorb the force of a flying puck. We bought two-way stretch fabric and sewed three layers together to create an encasement for the cap and foam. The cap sits in between the bottom and middle layer fabrics, and the foam sits in between the middle and top layer. One side of the fabric was left open to allow for the easy changing of foams. By providing a way to change the foam for each player, our device becomes more universal.

Underneath the cap is the protective donut piece and the mechanism. The donut piece is made of XRD foam and surrounds the AC joint to provide more protection to the joint as well as to balance the cap. Surrounding the donut is the mechanism, which consists of series of tubes with actuators. The tubes and actuators were 3D printed with TPU and SLA FormLabs "Tough" material, respectively. It took a few iterations of the tubes and actuators to figure out the best materials to make them function the way we wanted them to. In terms of how the mechanism functions, the actuators are attached with string, on one end to the fabric surrounding the carbon fiber cap and the other end on a layer of mesh that lays over the donut piece. When a force hits the cap, the actuators are pulled through the tubes with the string and tighten on both ends. The fabric we used allows for a little bit of stretch to allow the actuators to pull to max distance. In addition, the tubes were made to expand circumferentially and not longitudinally in order to slow down the force and eventually allow the actuators to return to their normal position. This mechanism was strategically placed around the shoulder so that the cap can move and lessen all forces that hit it no matter what direction the force comes from.

After the mechanism and cap were formed, the device was assembled as one onto the existing shoulder pad. To begin, the XRD foam that was acting as our base layer was sewed into the existing shoulder pads. From there, a mesh layer was sewed over the donut piece, and the entire thing was then sewed onto a layer of fabric. This fabric was used to cover the base layer and therefore was sewed over the base foam and into the existing shoulder pads as well. Once the base layering was figured out, it was time to integrate the tubes and actuators. The tubes were placed around the donut into slits that were cut into the base fabric, and they were sewed in place for reinforcement. The actuators had string attached on both ends of it. One end had the string attached to the mesh with clips, and the other end had the string attached to the fabric that was encasing the cap Finally, the cap encasement, which included the cap and XRD foam that was covered in the two-way stretch fabric, was suspended with the tubes and actuators over the shoulder. The assembly of the mechanism with base layer components are shown in Figure 12 below. The components with are labeled with the FRs they satisfy.

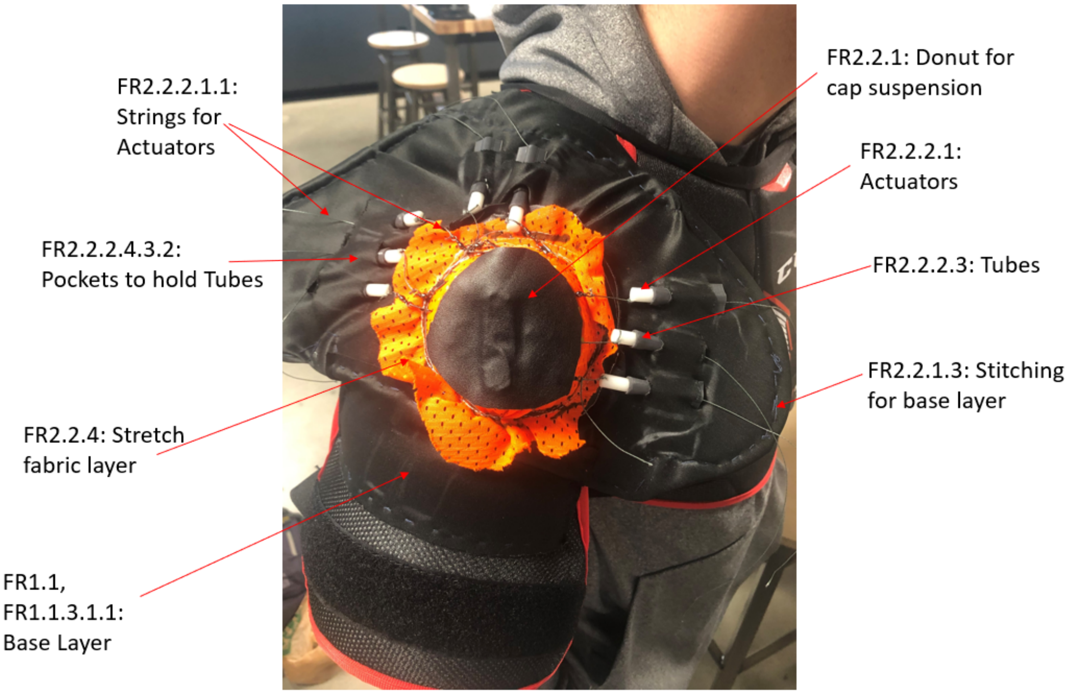


Figure 14. Assembly of the mechanisms under the cap

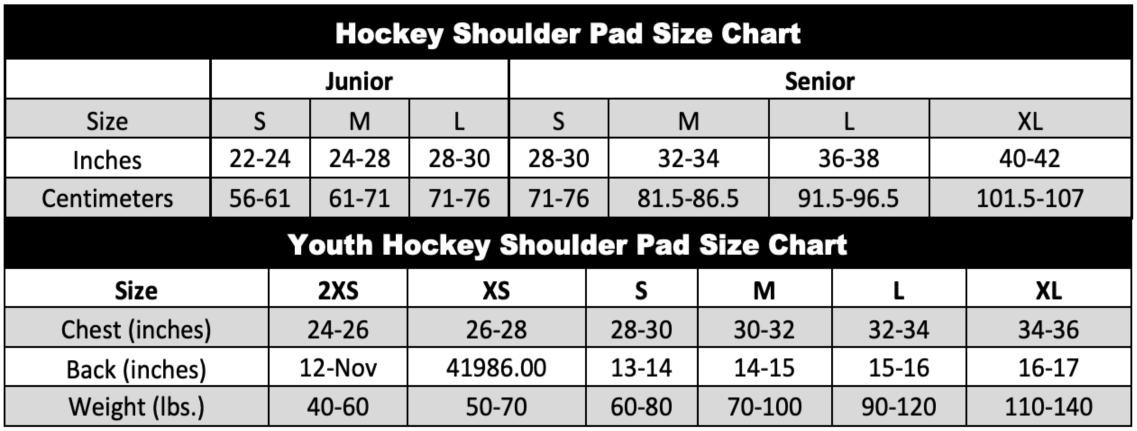
4.6. User Safety

Our device reduces injurious loads that are put on the shoulder during play without hindering the player’s performance. The mechanism that is incorporated into our device will work to protect the shoulder without causing harm to the player wearing it or any other player.

This device is also universal and is meant to be easily added to and removed from all shoulder pads found on the market today. Easy addition of the device to all shoulder pads makes it user friendly while easy removal makes it simple to clean and simple to change any necessary components, such as foam, if and when they start to wear down.

Since our device can be added to any shoulder pads, it is also important to make sure the player is wearing shoulder pads that properly fit. Properly fitting shoulder pads will provide the best base for protection, while our device will give added protection. In order to get shoulder pads that fit, it is best to measure your chest right under the armpits with a tape measure (Parks and Recreation: The City of Cleveland Heights, 2017). The chart below shows a general guide to what size pads you should get based on the size of your chest.

Table 3. General Hockey Pad Sizing



Hockey Shoulder Pad Size Chart

	Junior			Senior			
Size	S	M	L	S	M	L	XL
Inches	22-24	24-28	28-30	28-30	32-34	36-38	40-42
Centimeters	56-61	61-71	71-76	71-76	81.5-86.5	91.5-96.5	101.5-107

Youth Hockey Shoulder Pad Size Chart

Size	2XS	XS	S	M	L	XL
Chest (inches)	24-26	26-28	28-30	30-32	32-34	34-36
Back (inches)	12-Nov	41986.00	13-14	14-15	15-16	16-17
Weight (lbs.)	40-60	50-70	60-80	70-100	90-120	110-140

4.7. Standards and Regulations

Shoulder pads are necessary and required for all levels of hockey. They are important because they protect the shoulders, chest, back, upper chest, upper arms, and collarbone. As mentioned above in the manufacturing process section, forwards tend to look for lighter pads that allow them to move more freely while defensive players want larger pads with more protection against getting hit by pucks (Parks and Recreation: The City of Cleveland Heights, 2017). The device we created is both lightweight and provides protection against forces, such as a flying puck, making it a good option for all players.

The only regulation for most hockey players, both offensive and defensive, is that they wear shoulder pads. Other than that there are no rules out there. Since our device is aimed towards these players, we were free to design our device how we wanted.

5. Testing Methods

5.1. Force Plate Testing and Rationale

The team chose to perform a force plate drop test to examine the forces that would be applied to the shoulder, while the shoulder cap was acting as protection. We compared the polyethylene cap on the on-the-market pair of CCM shoulder pads to our carbon fiber cap to see how well they upheld under various forces. The team hypothesized that that the carbon fiber would perform better, due to its mechanical properties, in terms of reducing the amount of force experienced by the shoulder. Originally, we performed theoretical calculations to get a baseline for the magnitude of force the caps might endure when different weights were dropped from different heights.

To calculate the force that the shoulder cap device absorbs during each of the drop tests, we first used the work energy principle to determine the expected force that the cap with experience under set conditions. The net work during an impact can be defined as the average force of the impact multiplied by the distance from the initial drop. Because this is a drop test, we are assuming that the initial velocity with be zero.

$$W_{net} = 1/2mV_f^2 - 1/2mV_i^2$$
$$W_{net} = 1/2mV_f^2$$

With the initial velocity at zero, we can use a kinematic equation to calculate the final velocity experienced when the weight dropped is at impact with the cap.

$$V = \sqrt{2gh}$$

From this, we can calculate the average impact force that is experienced using the net work equation and the distance of the compressed cap and foam base. In the equation below, the net work is in the numerator and the compressed distance is the denominator.

$$F = \frac{W_{net}}{d}$$

To get a variety of forces that the cap may experience, we altered the weight dropped to get different forces. In this testing method we dropped from 0.915m (3 feet) and dropped weights including 10lbs and 25lbs.

At 3 feet and a 10lbs weight:

$$V = \sqrt{2 * 9.81m/s * 0.915m} = 4.24m/s$$
$$W_{net} = 1/2 * 4.54kg * (4.24m/s)^2 40.81J$$
$$F = 40.81J\ /\ 0.025m = 1632.37N$$

At 3 feet and a 25lbs weight:

$$V = \sqrt{2 * 9.81m/s * 0.915m} = 4.24m/s$$
$$W_{net} = 1/2 * 11.34kg * (4.24m/s)^2 = 101.93J$$
$$F = 101.93J\ /\ 0.025m = 4080.9N$$

Table 4. Drop Test Theoretical Calculations

Weight	**Height**	**Work**	**Force**
4.54kg	0.915m	40.80J	1632.37N
11.34kg	0.915m	101.93J	4077.31N

For testing, a force plate was used to monitor the amount of force being put on the cap during drop testing, and AMTI-NetForce software was used to collect the data. We connected the force plate to the computer and set the software to collect 60 data sets per second for a duration of 30 seconds. The caps were placed separately onto a foam base on top of the force plate and then subjected to different loads. The loads we put on the cap were 10 lbs and 25 lbs of force from a height of three feet. Each material was given three trials of experiencing forces from both the 10 lbs and 25 lbs weights being dropped from three feet, in order for the team to perform a statistical analysis on the data. After setting up the equipment and making the necessary inputs into the software, we began the drops and collected all necessary data. The complete testing protocol can be found in Appendix C. Below is a picture of what the drop test looked like.

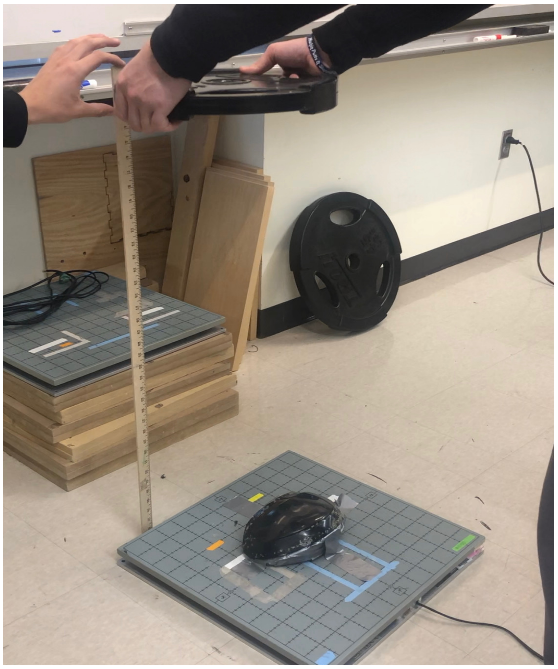


Figure 15. Picture of drop test setup for testing

5.2. Instron Testing and Rationale

In order to examine the constant force properties of the tube and actuator mechanism, the team performed a custom tensile test, capable of simulating the movement of the cap into the tube. By simulating this motion, the team could gather data related to the relative forces the tube mechanism was capable of withstanding, while still capable of returning the actuator to its original position, outside of the tube. The team performed this form of testing with four potential tube models and gathered data for three trials. The parameters for the testing are included in the full testing protocol, available in Appendix C. The team used an Instron 5544 to perform the tensile test, and used the set-up, pictured below, to stabilize the tube and rig the actuator to move upward, in response to the top gauge of the Instron being directed in that direction by the software.

Figure 16. Picture of Instron setup for testing

The team realized that there were limitations to this testing method, such as the team's 3D-printed actuator lacked an attachment component that would allow for the string to pull it up through the tube, completely straight, and, due to the flexible and elastic materials used to fabricate the tubes, they were more inclined to bend as the actuator moved through them at an angle. The team attempted to mitigate these by further stabilizing the tube, using a chemistry test-tube stand clamp to surround the tube at a central location, to minimize how much the tube could bend, while still allowing the actuator to enter. Other trials called for an individual of the team to ensure the tube did not get pushed out of the clamp by stabilizing the position and shape of the tube by hand. These attempted solutions could have influenced our data, in the sense of interfering with the natural properties of the tube, as well as the overall forces the tube should have been experiencing on its own. Further recommendations for this form of testing in the future are mentioned in Section 10.1, but are typically based around increasing the number of trials to allow for additional statistical analysis and developing a fixture to stabilize the tube, so that user interference isn't required and the actuator can enter at its intended angle (90 degrees). The complete testing protocol can be found in Appendix C.

6. Results

6.1. Force Plate Testing Results

After completing the trials for each of the cap materials, the team began to evaluate the data within each of the text files for each trial (18 trials in total). The team analyzed the data in MATLAB to determine the greatest value in the z-value column, which would correspond to the maximum force experienced on the force plate during testing. However, the team was also responsible for checking this value within the text file because during some trials, the plate used to impact the cap contacted the force plate a second time, while falling off, which could produce a force greater than the force experienced when the load was on the cap.

Once these values were isolated, the team organized each trial by the weight used during the testing, which would correspond to the load experienced on the cap, as well as by the material the testing was conducted on. This resulted in six sub-groups of three trials each. These values were then compared side-by-side to examine which material was capable of reducing the load more effectively. The results are displayed in the bar graph below:

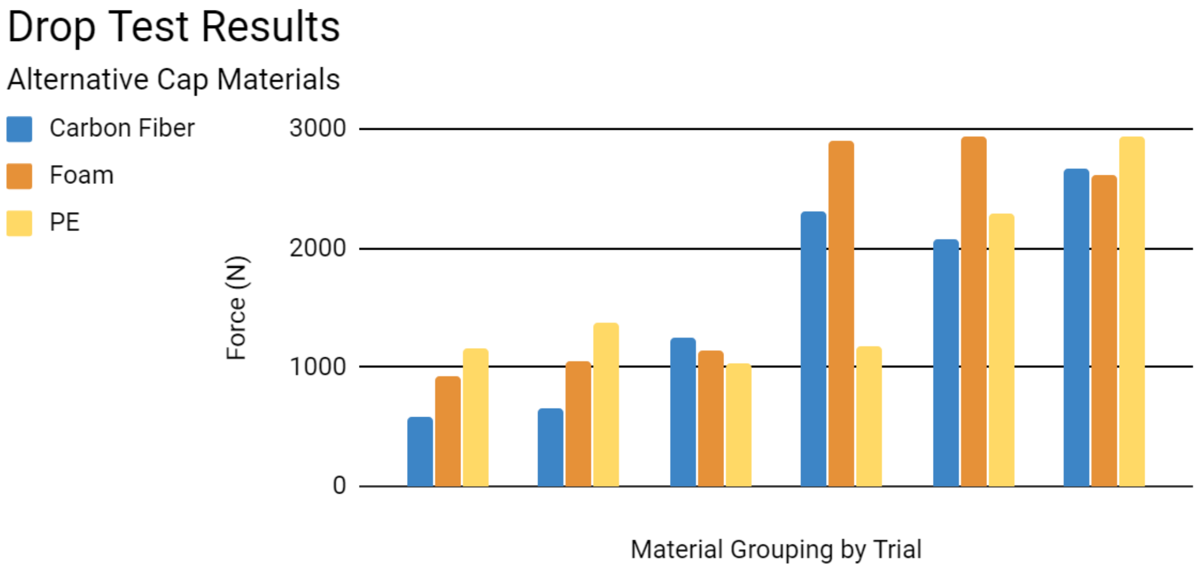
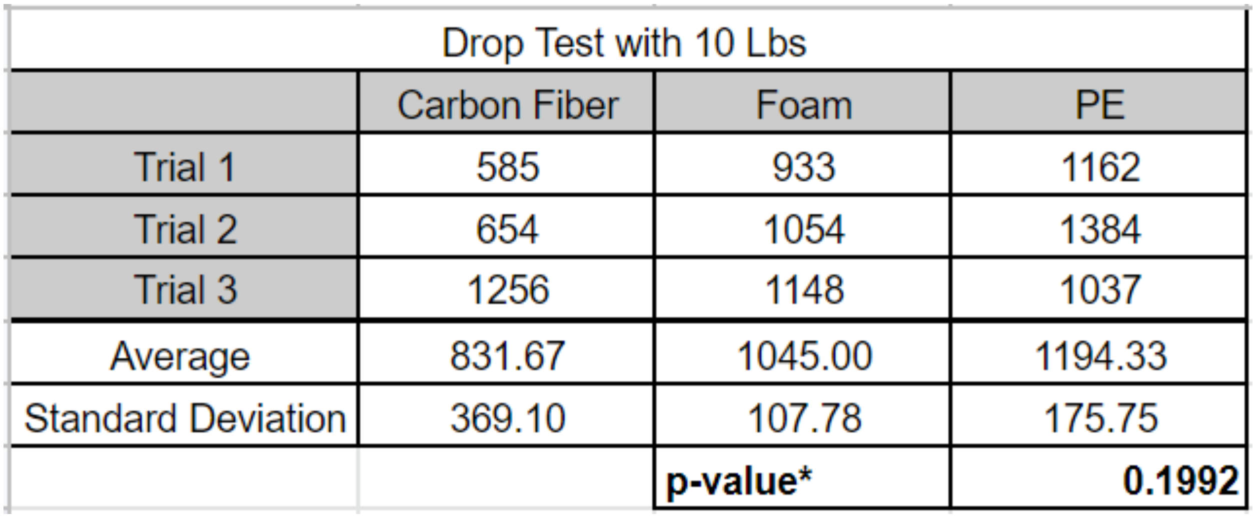


Figure 17. Bar graph of force attenuation based on cap material

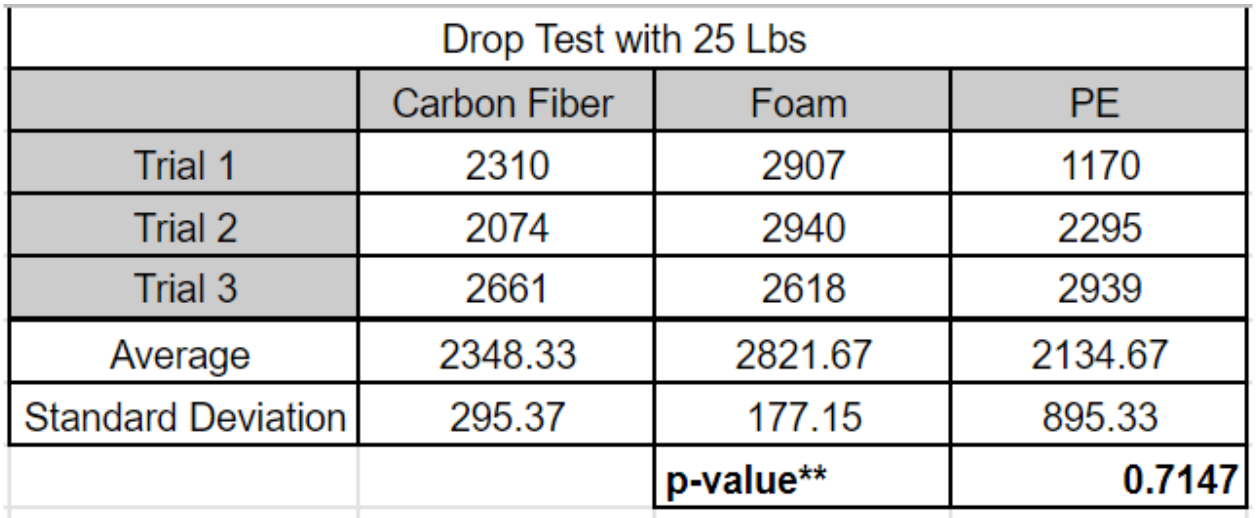
The team divided each set up data by the trial number, as well, to mitigate the influence of how exposure to multiple loads may have impacted the integrity of each cap material. This was not entirely effective, due to the fact that for some trials the force plate did not hit the cap in the intended location leading to an inaccurate force plate reading with skewed data. In this case, the team chose to perform the trial again to collect more accurate data, however, we acknowledged that these additional trials could have skewed our data in the sense of altering the strength of each cap material without consistency between types of materials. In order to examine the statistical significance and identify any outliers in the data, the team performed a Grubb's Outlier Test and a two way unpaired t-test between the average forces experienced of the polyethylene and carbon fiber caps. The results of these tests are included in Tables 2 and 3 below:

Table 5. Drop Test Data with 10 lbs weight



Drop Test with 10 Lbs			
	Carbon Fiber	Foam	PE
Trial 1	585	933	1162
Trial 2	654	1054	1384
Trial 3	1256	1148	1037
Average	831.67	1045.00	1194.33
Standard Deviation	369.10	107.78	175.75
		p-value*	**0.1992**

Table 6. Drop Test Data with 25 lbs weight



Drop Test with 25 Lbs			
	Carbon Fiber	Foam	PE
Trial 1	2310	2907	1170
Trial 2	2074	2940	2295
Trial 3	2661	2618	2939
Average	2348.33	2821.67	2134.67
Standard Deviation	295.37	177.15	895.33
		p-value**	**0.7147**

The p-values for both t-tests performed between the means of forces experienced for the polyethylene and carbon fiber caps were greater than .05, meaning that the differences between the means for both 10 lbs and 25 lbs tests were not statistically significant, meaning we cannot say that the carbon fiber is more effective at absorbing forces.

6.2. Instron Testing Results

Once the data from the Instron testing was obtained, the data was exported and analyzed using a MATLAB code that used a plotting function to achieve a graphical representation of the data. The Instron test was completed with four different types of tubing: a straight TPU tube, a TPU tube with a funnel, an SLA Formlabs “Flexible” material tube, and an SLA Formlabs “Flexible” material tube with a funnel. These four types were tested in the Instron to obtain data that aimed to show a graph similar to that of a constant force spring as shown in figure X. The Instron testing was performed three times for each type of tube which resulted in 12 tests in total. The graph shown below has all four types of tubes and three trials for each tube.

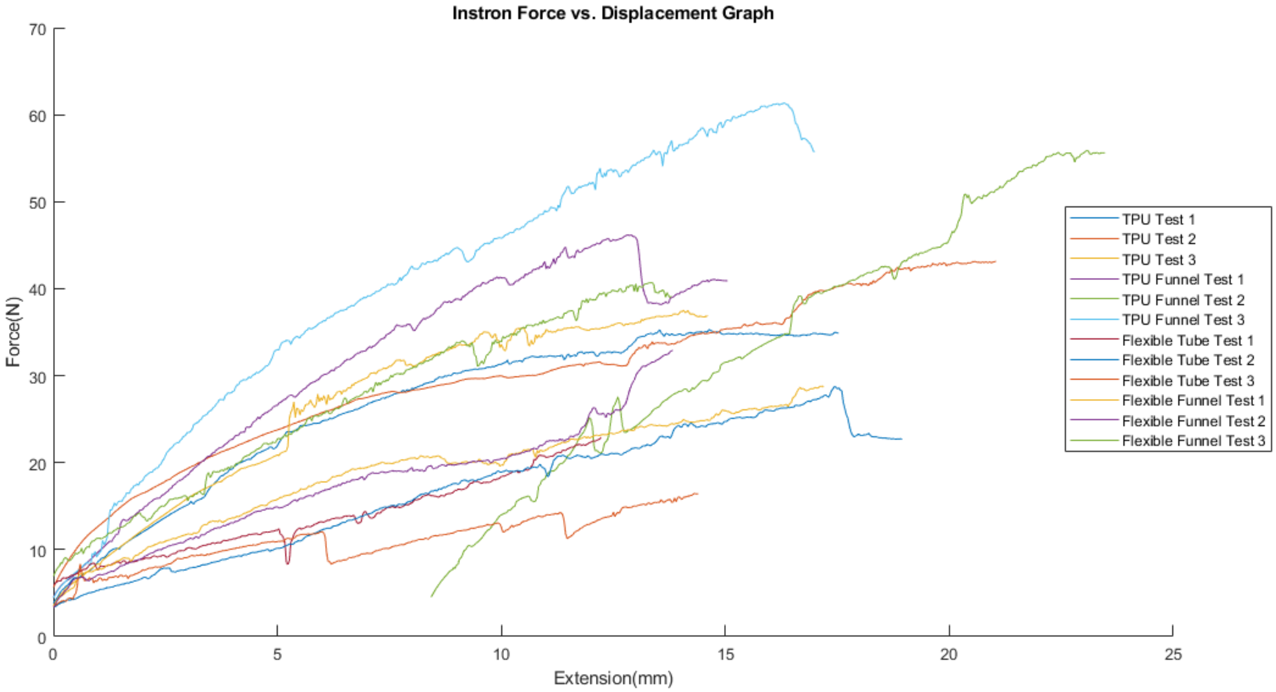


Figure 18. Line graph showing the force vs. displacement of all tube types

This graph gives the extension in mm on the x-axis and the Force in Newtons on the y-axis. Each color line corresponds to a different type of tubing on a different trial. After reviewing this data all on one graph, the team indicated the outliers but wanted to break down each type of tubing into its own graph.

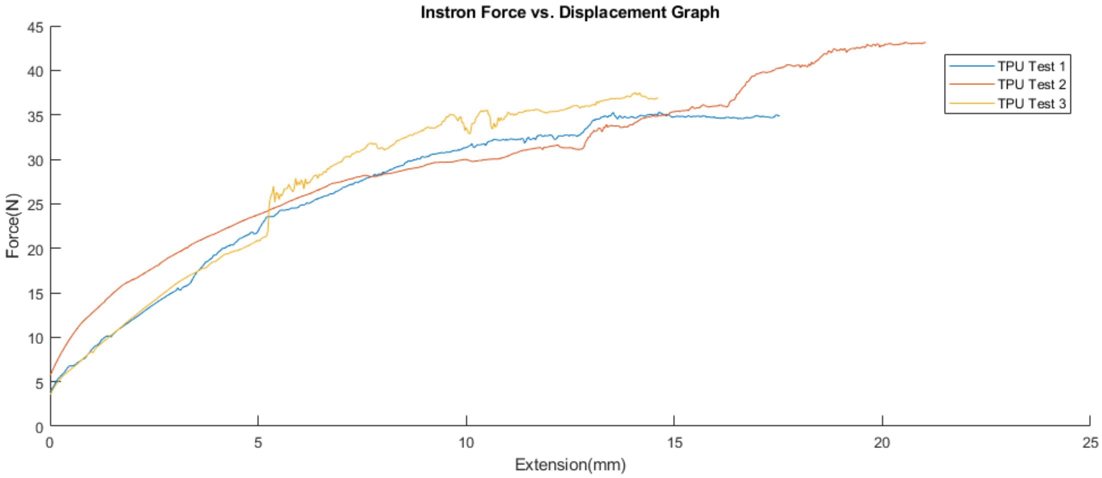


Figure 19. Line graph showing the force vs. displacement of the TPU tube

The graph above shows the results for the tubes that were made out of TPU that had no funnel. Each color indicates a different trial as shown on the right. Although test 2 showed the largest amount of force absorbed, test 1 follows the graph of the constant force spring the most accurately because it is able to slightly level off as it reaches an extension of 10mm.

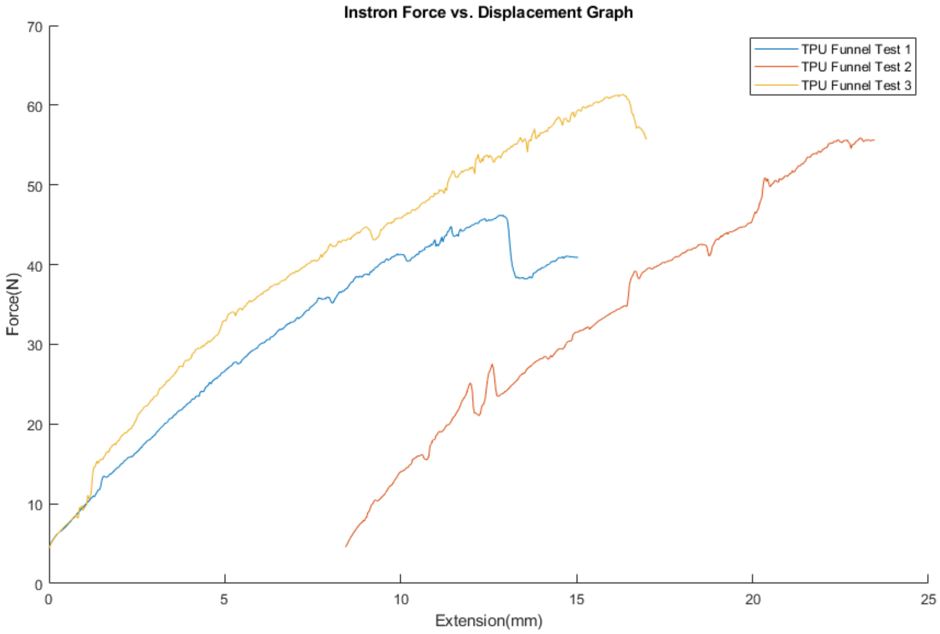


Figure 20. Line graph showing the force vs. displacement of the TPU Funnel tube

The next type of tubing that was tested and shown in the graph above is the TPU material with a funnel. The funnel was added to guide the actuator into place. Although this concept expected promising results, the data showed no clear indication of the lines on the graph leveling off as seen by a constant force spring.

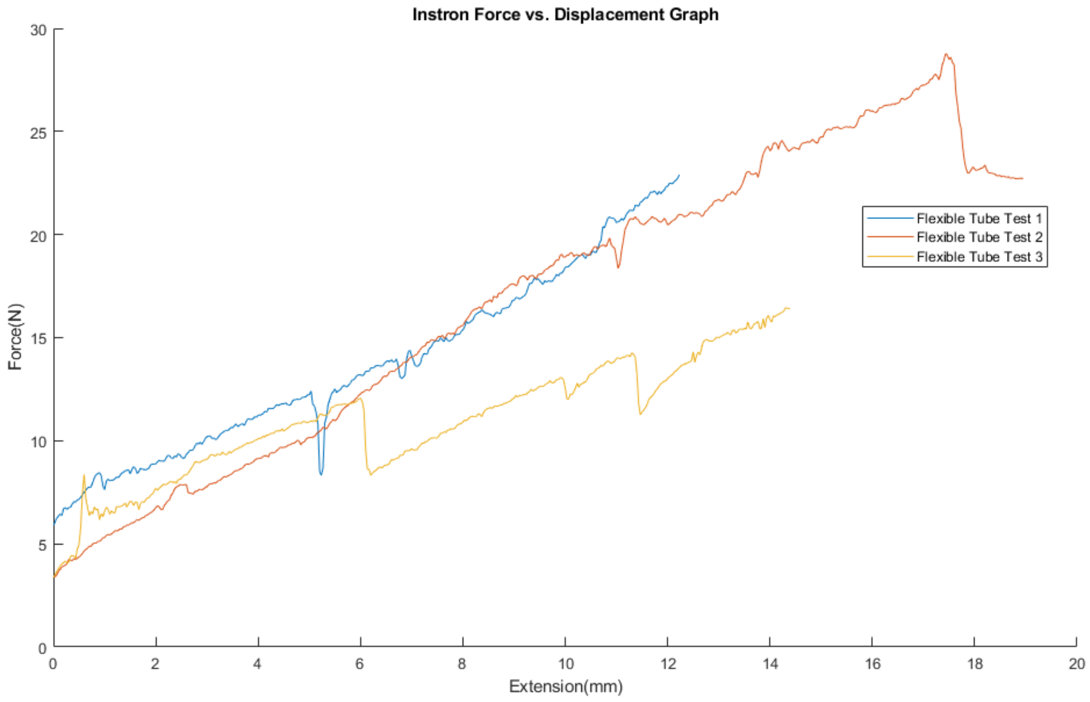


Figure 21. Line graph showing the force vs. displacement of the "Flexible" tube

The "Flexible" tubing material from Formlabs without a funnel was then tested under the same conditions as the TPU tubes. The lines on this graph are much noisier when compared to the TPU tubes but this could be due to human error with the procedure. None of these "Flexible" tubes indicate any leveling off in the lines.

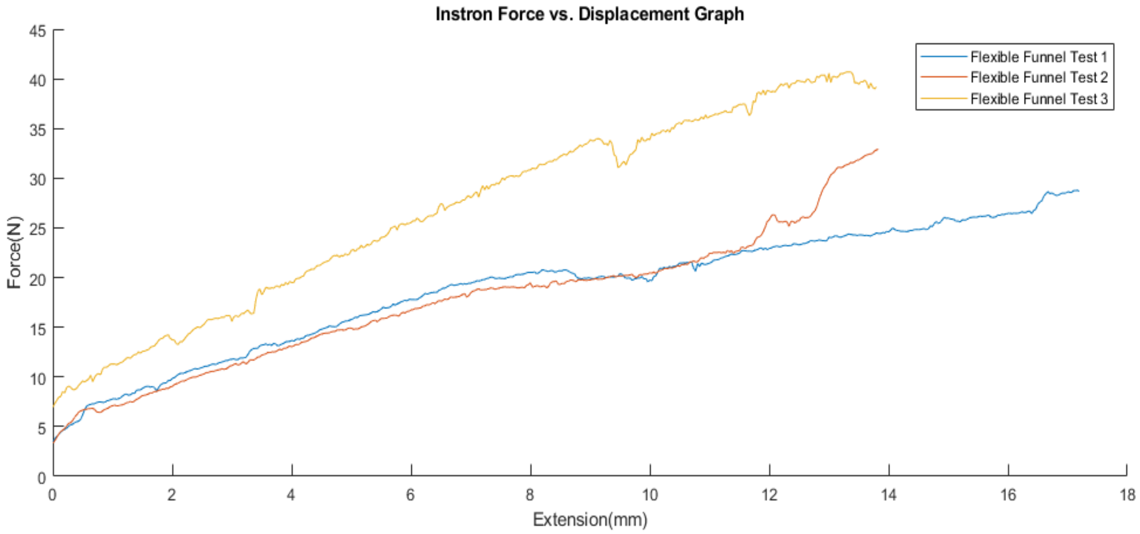
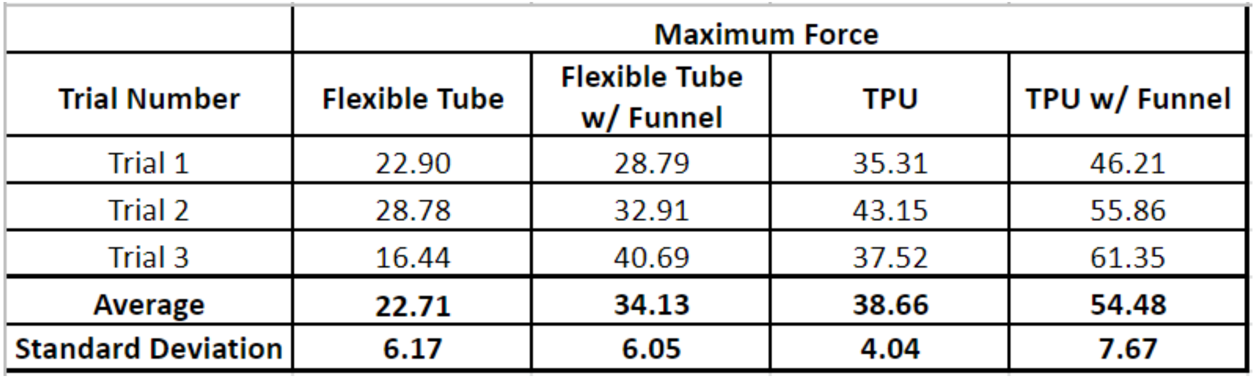


Figure 22. Line graph showing the force vs. displacement of the "Flexible" Funnel tube

The tubes chosen in the final design can be seen in the graph above. This test was performed using the Formlabs "Flexible" material with a funnel. Test 1, which can be seen as the blue line on the graph, shows clear indication of where the line begins to level off around 8mm. The other two trials also show some indication of the line trying level off and not increase linearly. The team decided on this material for the tubes because of its similar properties to a constant force spring and having the funnel allows guidance for the actuator.

Table 7, shown below, highlights the maximum forces the tubes experienced during each trial along with the average force and standard deviation.

Table 7. Maximum force absorbed by tubes during Instron Testing



	Maximum Force			
Trial Number	**Flexible Tube**	**Flexible Tube w/ Funnel**	**TPU**	**TPU w/ Funnel**
Trial 1	22.90	28.79	35.31	46.21
Trial 2	28.78	32.91	43.15	55.86
Trial 3	16.44	40.69	37.52	61.35
Average	**22.71**	**34.13**	**38.66**	**54.48**
Standard Deviation	**6.17**	**6.05**	**4.04**	**7.67**

7. Conclusions

7.1. Force Plate Testing Conclusions

Before testing, our team hypothesized that the carbon fiber cap would absorb more of the force from the 10lbs and 25lbs plates that were dropped, when compared to the polyethylene cap that is currently used for the shoulder cap. Based on the results our testing, the team concluded that, although in some trials the carbon fiber showed a lesser force reading when compared to the polyethylene, there was no clear indication that the carbon fiber could absorb more force from the load that was dropped when compared to the polyethylene cap. These conclusions are based on the fact that the data shows no decrease in absorbed force by the carbon fiber, which would show that the carbon fiber cap works better with the mechanism for energy absorption.

7.2. Instron Testing Conclusions

Before testing, our team hypothesized that the Formlabs “Flexible” tubing material, with a funnel on one end for actuator alignment, would perform best to reflect a constant force spring graph. Based on the results our testing, the team concluded that, although the “Flexible” material by Formlabs offered promising results that can be seen by the leveling of the Force vs. Extension line, the tube does not completely follow the constant force graph the team was trying to achieve. The TPU material also showed some results that followed a constant force graph, which can be seen in the data for the TPU tubes without the funnel. These conclusions are based on the fact that, although we wanted a graph that showed a large area under the curve, the tubes tested showed some of the results we were looking for, but not quite the curve of a constant force spring.

8. Discussion

8.1. Design Review

The goal of our project was to create a shoulder cap device that would absorb the loads produced during collisions between hockey athletes and the boards around the rink. By researching the loads attained during play, the team was able to use axiomatic design to create a device that satisfied the needs of hockey athletes. Our final design consisted of a carbon fiber cap that provided the support for the constant force mechanism. This device was integrated into a hockey shoulder pads as one piece and took the place of the on the market shoulder cap with foam used for protection.

Through multiple iterations of axiomatic design, the team manufactured the device and started testing on the carbon fiber cap and mechanism. A drop test on the shoulder cap and an Instron test for the actuators were performed to gather data to make improvements on the device. Further testing that more accurately models hockey game time play will be needed to further the overall design review.

8.2. Overall impact

8.2.1. Economics

Protective sports equipment is continuing to increase in demand, due to the wide range of injuries attained by athletes of all levels. When purchasing hockey equipment, the main pieces of equipment being purchased are skates, sticks, and protective gear, with protective gear being the highest purchased item, with sales totaling 105.3 million USD in 2017. This number has increased over the past ten years, which can be seen with an almost 25 million dollar increase since 2007 (SFIA, 2018). When manufacturing our device, the team would aim to enter into this market of protective equipment for ice hockey players.

8.2.2. Environmental Impact

The production and disposal of sports equipment plays a key role in environmental impact. The materials used to create our device specifically posed risks to the environment. The epoxy resin mixture that was used to create the hard carbon fiber cap is not environmentally friendly and can pose a risk when released into the environment and may harm aquatic life. This would be a concern when manufacturing on a larger scale because the epoxy and resin can have serious health effects on humans, including respiratory problems, skin irritation, and, when inhaled or absorbed through the skin, dizziness and nausea. The EPA labeled Epichlorohydrin, mainly used in epoxy resins, in Group B2, a probable human carcinogen (U.S. Environmental Protection Agency, 2016).

Carbon fiber manufacturing often has excess waste for landfill because of its manufacturing process, where sheets are laid out and cut by hand. The trimmed pieces often lose most of their original size and the excess material is moved into landfills. Carbon fiber gets its strength from the long, aligned fibers that can be seen woven through the fabric. The material, once cured, cannot be melted down and reformed like aluminum (Harris, 2017). Research is being done to recycle carbon fiber to be used again by placing the fibers in liquid and realigning them with another curing process. Other recycling processes are also available at a larger cost and will continue to be developed for future needs.

8.2.3. Societal Influence

Ice Hockey is a common sport in the US and is played currently by 562,145 registered athletes and many other recreational people. The sports industry, especially for younger athletes, revolves around protective gear and making sure kids are safe during play. In 2011, two out of every 100 kids playing hockey attained an injury that required a trip to the ER (Nettleman, 2013). For this reason, parents are hesitant to enroll their children in such an injury prone sport without the necessary equipment that our device can help offer.

8.2.4. Ethical Concerns

With further testing that is required to determine the amount of force the shoulder cap device can absorb, one test might involve human subjects wearing the device during normal play. This can lead to some concern for the safety of test subjects. When further testing is pursued, we will have to take into account the overall safety of the subjects when modeling tests after hockey game play. It would be best to test on volunteers that currently play hockey or have played hockey in the past, so they understand what types of forces to expect. They would also be more comfortable wearing the equipment so that more accurate data can be obtained.

8.2.5. Health and Safety Issues

The players that will be using our product are already at risk of health concerns, primarily relating to upper extremity injuries. The goal of our design was to reduce the likelihood of these injuries. However, there are still aspects of the design that could pose a threat to the health and well-being of both the player using the device and opposing players. A function of the constant force mechanism underneath the cap was to control the movement of the cap, as it was compressed and returns back to its original position. But there is the potential for the cap's movement, specifically in the returning phase, to strike another player who could be in the vicinity of the shoulder cap during this time. Additionally, if the shoulder mechanism cannot withstand the high impact forces during the play, the mechanism could be pressed into the shoulder region, along with the load, causing injury to the player that may be more extensive than the shoulder separation injury, but injury to the clavicle region, as well. The failure of the device puts the shoulder at increased risk, but the movement of the cap can also cause harm, if the mechanism were to fail and the cap was capable of moving and striking the player in the neck, causing additional injuries.

8.2.6. Manufacturability

This final design was manufactured by the team, but another system should be put in place to manufacture the device to be sold on the market. Because our device only replaces the main shoulder cap piece, we would have to work with another company that manufactures entire hockey shoulder pads and integrate our device into the manufacturing process. This device was also aimed at having the opportunity to be integrated into shoulder pads of other sports, such as football and lacrosse. The constant force spring mechanism can be useful on other playing environments and for a wide variety of players at different ages.

The cost of manufacturing will rely on the final types of materials used and the company that we will be working with to integrate the device. To incorporate the interchangeability of the foams depending on the needs of the athlete, we will need to manufacture the different types of foam with Velcro strapping, so that the player is able to use various options.

8.2.7. Sustainability

This project focused on using axiomatic design to generate a final product that included the carbon fiber cap and underlying mechanism. We did not focus on the sustainability of the products being used or how they were manufactured but focused more on creating a product that lasted longer than shoulder pads currently being used. Current shoulder pads on the market are not recyclable and are often thrown away after the material begins to fail or the pads absorb too much sweat. In these cases, it would be beneficial if the material could be taken off the main parts of the pads to be washed or if certain parts of the pads could be replaceable when they fail or begin degrading. With our device, we have interchangeable foams that can be washed with the outer fabric, so that the carbon fiber cap can be used for many years.

8.2.8. Political Issues

With the market constantly fluctuating, based on supply and demand of the customers, there could be a decrease in future athletes that require high contact protective equipment. This decrease would eliminate the need for our product.

9. Recommendations/ Future Work

During initial brainstorming, the team came up with a few different design ideas and used axiomatic design to figure out the functions that the device should have. Due to time constraints, we hit a point in which we had to move forward with a design and being fabrication and experimentation, meaning we could not break down all ideas fully. Future work for this device could include more testing to see how well the device absorbs forces, looking at the materials selected and other design parameters, and focusing on user experience with this device.

9.1. Testing

Further testing of the shoulder device should be done to better determine how well each layer is absorbing forces. The carbon fiber cap, mechanism, and base layer of the pads are all responsible for helping to absorb loads being put on the shoulder. Although the device does absorb force throughout the three layers, it is hard to tell exactly how much each layer is absorbing and how efficient each layer is when independent of each other. More testing would help determine how each layer performs under certain forces and help determine what could be changed in each layer to make the device better.

A form of fatigue testing would also be beneficial, in order to observe the lifetime of different aspects of the cap as they experience the loads. Using the Instron, the mechanism could be subjected to repeated tensile forces that would simulate the actuator entering the tube in response to a force, until the point of failure. As for the cap, the cap could be subjected to a variation of a 3-point bend test that would produce repeated loads onto the cap for different magnitudes of stress, to provide data on the strength of the cap over time. These tests would provide additional evidence that our device is not only capable of attenuating the injurious loads, but the device can also avoid failure over time. It will also allow the team to provide the consumer with information regarding the conditions at which they may expect the product to fail.

In addition to the testing of each layer separately, the entire device should be tested during mimicked play. Figuring out a test system that could apply various forces of various magnitudes on different areas of the device could provide crucial information of how efficiently the device would function during actual play. This would, again, help to see what could be changed in the device to make it better.

9.2. Material Selection/Design Parameters

When first decomposing the axiomatic design, a range of design parameters were proposed for different functional requirements. These design ideas included devices made up of different materials, as well as different compressive and impact absorption mechanisms. While the team chose the design we felt would best meet the functional requirements we created, it would be beneficial to review the axiomatic design again. There may be some initial designs that would need to be researched and tested more to see about their potential and see if they could fit our functional requirements more effectively.

If our design best fits the functional requirements, the materials we selected should be looked at again. We chose carbon fiber as the cap material for its strong and lightweight properties, we chose TPU as the tube material, and we chose SLA FormLabs “Tough” material as the actuator material. While the materials we chose provide protection to the shoulder and allow the device to function properly, there may still be better materials out there. Whether they be cheaper materials, materials that will last longer, or materials that provide better force absorption, different ones should be researched and considered more for a final design.

9.3. User Experience

User experience is one of the most important features when it comes to designing the protective shoulder pad device. More user feedback should be collected to see how well the device is liked by players who would be wearing it for practical uses. We want to make sure that this device would be competitive in the market, and if players do not like it, it will not do well on the market. To get some user feedback, we would want to have players put on the shoulder pads, with our device integrated, and receive feedback on their experiences. We want to make sure the device is comfortable and does not inhibit their playing ability. We would have the players skate around a little bit to see how sturdy the device is and to make sure it only moves in response to contact and not during regular play. Finally, we would want to see the fatigue or wear time of the device. It would take a few years of a player using our device to gather all necessary info, but ultimately, we want to make sure our device has an adequate lifetime, without breaking or wearing down too much.

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Contant, Mathieu, and Alexandre Leblanc. Protective Athletic Garment. LLC Bauer Hockey, assignee. Patent US8869315B2Dec 11, 2018

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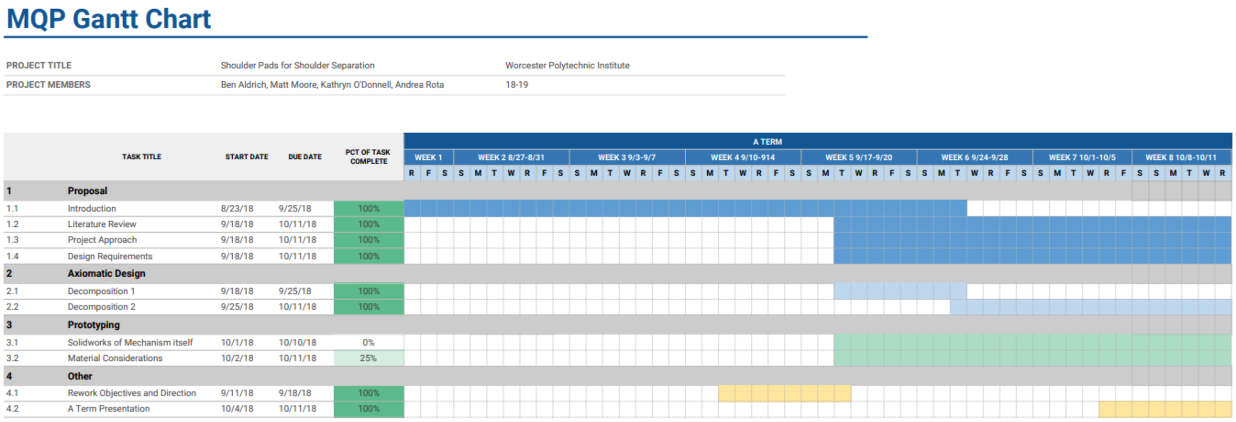
Appendices

A. Gantt Chart

A Term

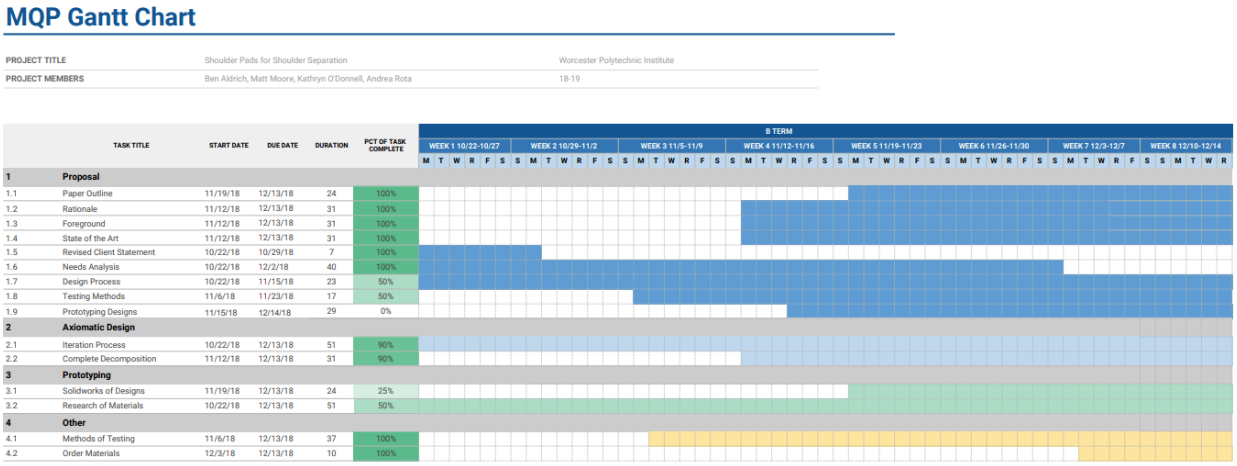


MQP Gantt Chart

PROJECT TITLE	Shoulder Pads for Shoulder Separation	Worcester Polytechnic Institute
PROJECT MEMBERS	Ben Aldrich, Matt Moore, Kathryn O'Donnell, Andrea Rota	18-19

	TASK TITLE	START DATE	DUE DATE	PCT OF TASK COMPLETE
1	**Proposal**			
1.1	Introduction	8/23/18	9/25/18	100%
1.2	Literature Review	9/18/18	10/11/18	100%
1.3	Project Approach	9/18/18	10/11/18	100%
1.4	Design Requirements	9/18/18	10/11/18	100%
2	**Axiomatic Design**			
2.1	Decomposition 1	9/18/18	9/25/18	100%
2.2	Decomposition 2	9/25/18	10/11/18	100%
3	**Prototyping**			
3.1	Solidworks of Mechanism itself	10/1/18	10/10/18	0%
3.2	Material Considerations	10/2/18	10/11/18	25%
4	**Other**			
4.1	Rework Objectives and Direction	9/11/18	9/18/18	100%
4.2	A Term Presentation	10/4/18	10/11/18	100%

B Term

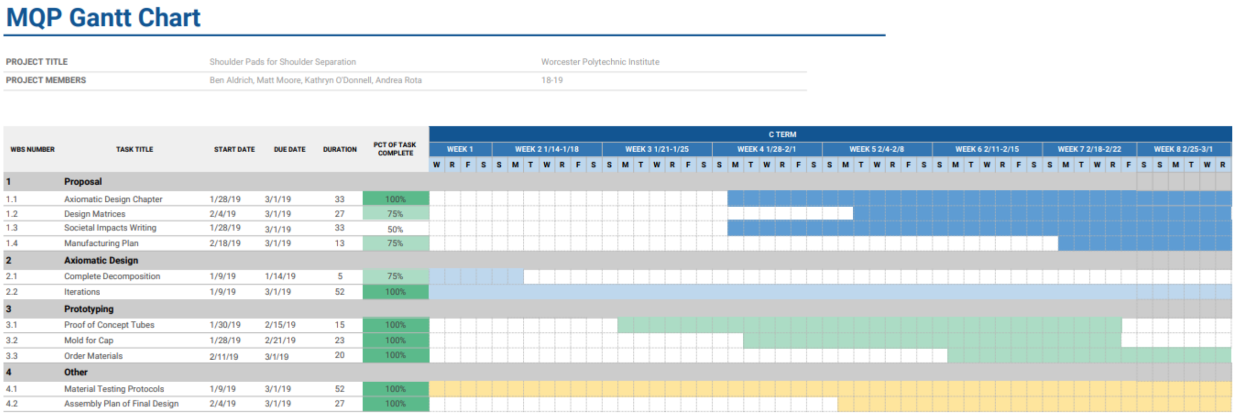


MQP Gantt Chart

PROJECT TITLE	Shoulder Pads for Shoulder Separation	Worcester Polytechnic Institute
PROJECT MEMBERS	Ben Aldrich, Matt Moore, Kathryn O'Donnell, Andrea Rota	18-19

	TASK TITLE	START DATE	DUE DATE	DURATION	PCT OF TASK COMPLETE
1	**Proposal**				
1.1	Paper Outline	11/19/18	12/13/18	24	100%
1.2	Rationale	11/12/18	12/13/18	31	100%
1.3	Foreground	11/12/18	12/13/18	31	100%
1.4	State of the Art	11/12/18	12/13/18	31	100%
1.5	Revised Client Statement	10/22/18	10/29/18	7	100%
1.6	Needs Analysis	10/22/18	12/2/18	40	100%
1.7	Design Process	10/22/18	11/15/18	23	50%
1.8	Testing Methods	11/6/18	11/23/18	17	50%
1.9	Prototyping Designs	11/15/18	12/14/18	29	0%
2	**Axiomatic Design**				
2.1	Iteration Process	10/22/18	12/13/18	51	90%
2.2	Complete Decomposition	11/12/18	12/13/18	31	90%
3	**Prototyping**				
3.1	Solidworks of Designs	11/19/18	12/13/18	24	25%
3.2	Research of Materials	10/22/18	12/13/18	51	50%
4	**Other**				
4.1	Methods of Testing	11/6/18	12/13/18	37	100%
4.2	Order Materials	12/3/18	12/13/18	10	100%

C Term

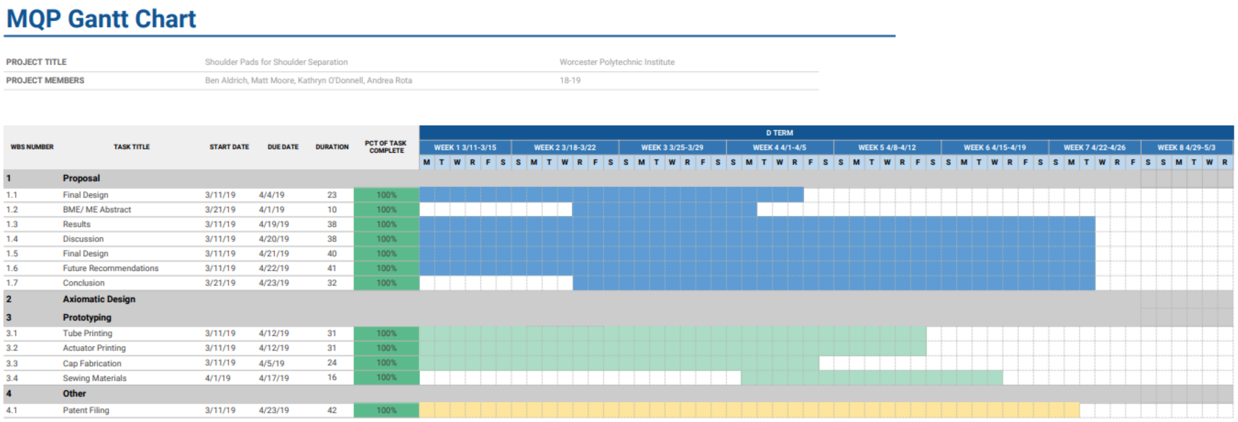


MQP Gantt Chart

PROJECT TITLE	Shoulder Pads for Shoulder Separation	Worcester Polytechnic Institute
PROJECT MEMBERS	Ben Aldrich, Matt Moore, Kathryn O'Donnell, Andrea Rota	18-19

WBS NUMBER	TASK TITLE	START DATE	DUE DATE	DURATION	PCT OF TASK COMPLETE
1	**Proposal**				
1.1	Axiomatic Design Chapter	1/28/19	3/1/19	33	100%
1.2	Design Matrices	2/4/19	3/1/19	27	75%
1.3	Societal Impacts Writing	1/28/19	3/1/19	33	50%
1.4	Manufacturing Plan	2/18/19	3/1/19	13	75%
2	**Axiomatic Design**				
2.1	Complete Decomposition	1/9/19	1/14/19	5	75%
2.2	Iterations	1/9/19	3/1/19	52	100%
3	**Prototyping**				
3.1	Proof of Concept Tubes	1/30/19	2/15/19	15	100%
3.2	Mold for Cap	1/28/19	2/21/19	23	100%
3.3	Order Materials	2/11/19	3/1/19	20	100%
4	**Other**				
4.1	Material Testing Protocols	1/9/19	3/1/19	52	100%
4.2	Assembly Plan of Final Design	2/4/19	3/1/19	27	100%

D Term



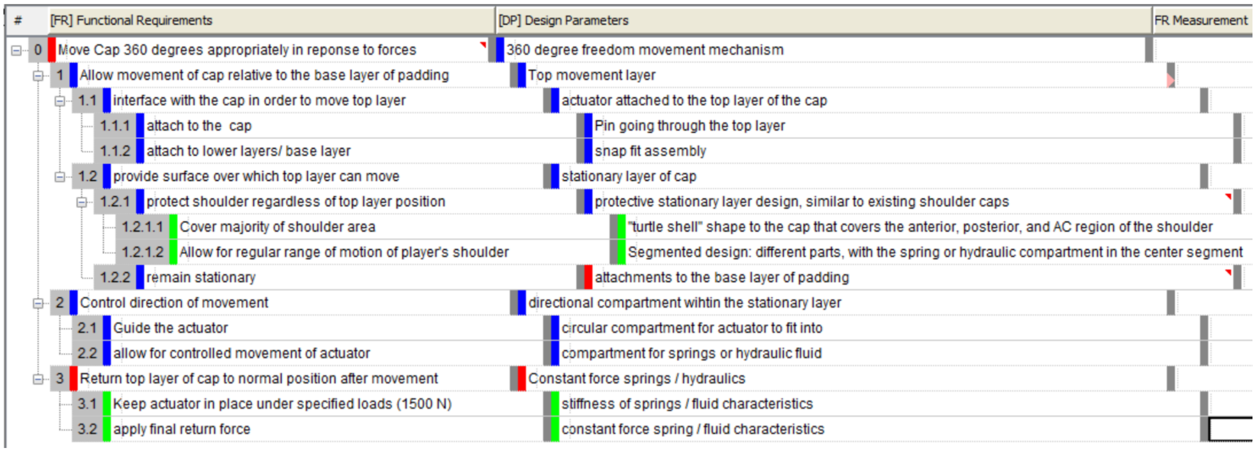
MQP Gantt Chart

PROJECT TITLE	Shoulder Pads for Shoulder Separation	Worcester Polytechnic Institute
PROJECT MEMBERS	Ben Aldrich, Matt Moore, Kathryn O'Donnell, Andrea Rota	18-19

WBS NUMBER	TASK TITLE	START DATE	DUE DATE	DURATION	PCT OF TASK COMPLETE
1	**Proposal**				
1.1	Final Design	3/11/19	4/4/19	23	100%
1.2	BME/ ME Abstract	3/21/19	4/1/19	10	100%
1.3	Results	3/11/19	4/19/19	38	100%
1.4	Discussion	3/11/19	4/20/19	38	100%
1.5	Final Design	3/11/19	4/21/19	40	100%
1.6	Future Recommendations	3/11/19	4/22/19	41	100%
1.7	Conclusion	3/21/19	4/23/19	32	100%
2	**Axiomatic Design**				
3	**Prototyping**				
3.1	Tube Printing	3/11/19	4/12/19	31	100%
3.2	Actuator Printing	3/11/19	4/12/19	31	100%
3.3	Cap Fabrication	3/11/19	4/5/19	24	100%
3.4	Sewing Materials	4/1/19	4/17/19	16	100%
4	**Other**				
4.1	Patent Filing	3/11/19	4/23/19	42	100%

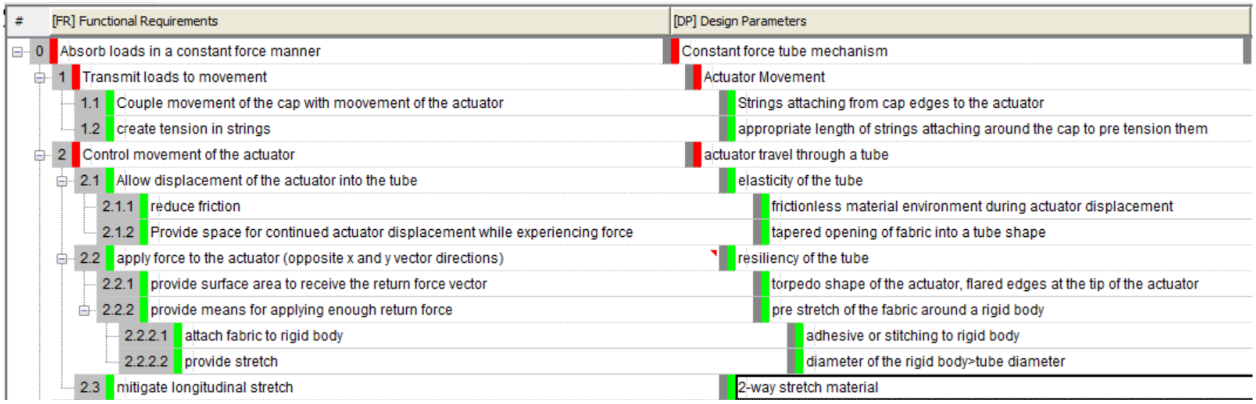
B. Axiomatic Design Iterations

360 Degree Movement Mechanism



#	[FR] Functional Requirements	[DP] Design Parameters	FR Measurement
0	Move Cap 360 degrees appropriately in reponse to forces	360 degree freedom movement mechanism	
1	Allow movement of cap relative to the base layer of padding	Top movement layer	
1.1	interface with the cap in order to move top layer	actuator attached to the top layer of the cap	
1.1.1	attach to the cap	Pin going through the top layer	
1.1.2	attach to lower layers/ base layer	snap fit assembly	
1.2	provide surface over which top layer can move	stationary layer of cap	
1.2.1	protect shoulder regardless of top layer position	protective stationary layer design, similar to existing shoulder caps	
1.2.1.1	Cover majority of shoulder area	"turtle shell" shape to the cap that covers the anterior, posterior, and AC region of the shoulder	
1.2.1.2	Allow for regular range of motion of player's shoulder	Segmented design: different parts, with the spring or hydraulic compartment in the center segment	
1.2.2	remain stationary	attachments to the base layer of padding	
2	Control direction of movement	directional compartment wihtin the stationary layer	
2.1	Guide the actuator	circular compartment for actuator to fit into	
2.2	allow for controlled movement of actuator	compartment for springs or hydraulic fluid	
3	Return top layer of cap to normal position after movement	Constant force springs / hydraulics	
3.1	Keep actuator in place under specified loads (1500 N)	stiffness of springs / fluid characteristics	
3.2	apply final return force	constant force spring / fluid characteristics	

Initial Tube Iteration

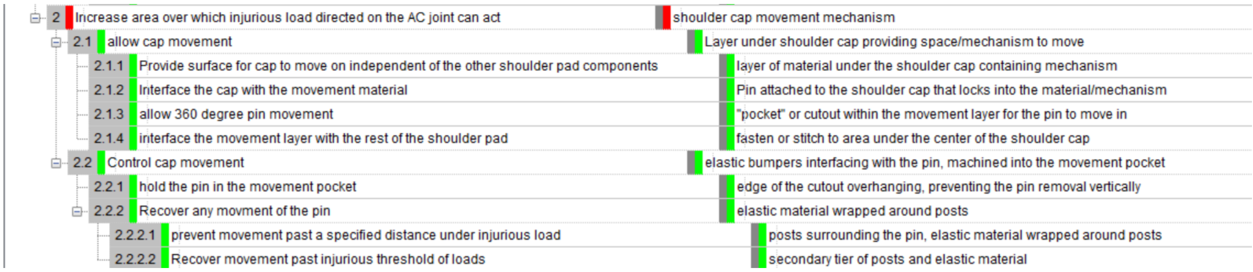


#	[FR] Functional Requirements	[DP] Design Parameters
0	Absorb loads in a constant force manner	Constant force tube mechanism
1	Transmit loads to movement	Actuator Movement
1.1	Couple movement of the cap with moovement of the actuator	Strings attaching from cap edges to the actuator
1.2	create tension in strings	appropriate length of strings attaching around the cap to pre tension them
2	Control movement of the actuator	actuator travel through a tube
2.1	Allow displacement of the actuator into the tube	elasticity of the tube
2.1.1	reduce friction	frictionless material environment during actuator displacement
2.1.2	Provide space for continued actuator displacement while experiencing force	tapered opening of fabric into a tube shape
2.2	apply force to the actuator (opposite x and y vector directions)	resiliency of the tube
2.2.1	provide surface area to receive the return force vector	torpedo shape of the actuator, flared edges at the tip of the actuator
2.2.2	provide means for applying enough return force	pre stretch of the fabric around a rigid body
2.2.2.1	attach fabric to rigid body	adhesive or stitching to rigid body
2.2.2.2	provide stretch	diameter of the rigid body>tube diameter
2.3	mitigate longitudinal stretch	2-way stretch material

Second Tube Mechanism Iteration

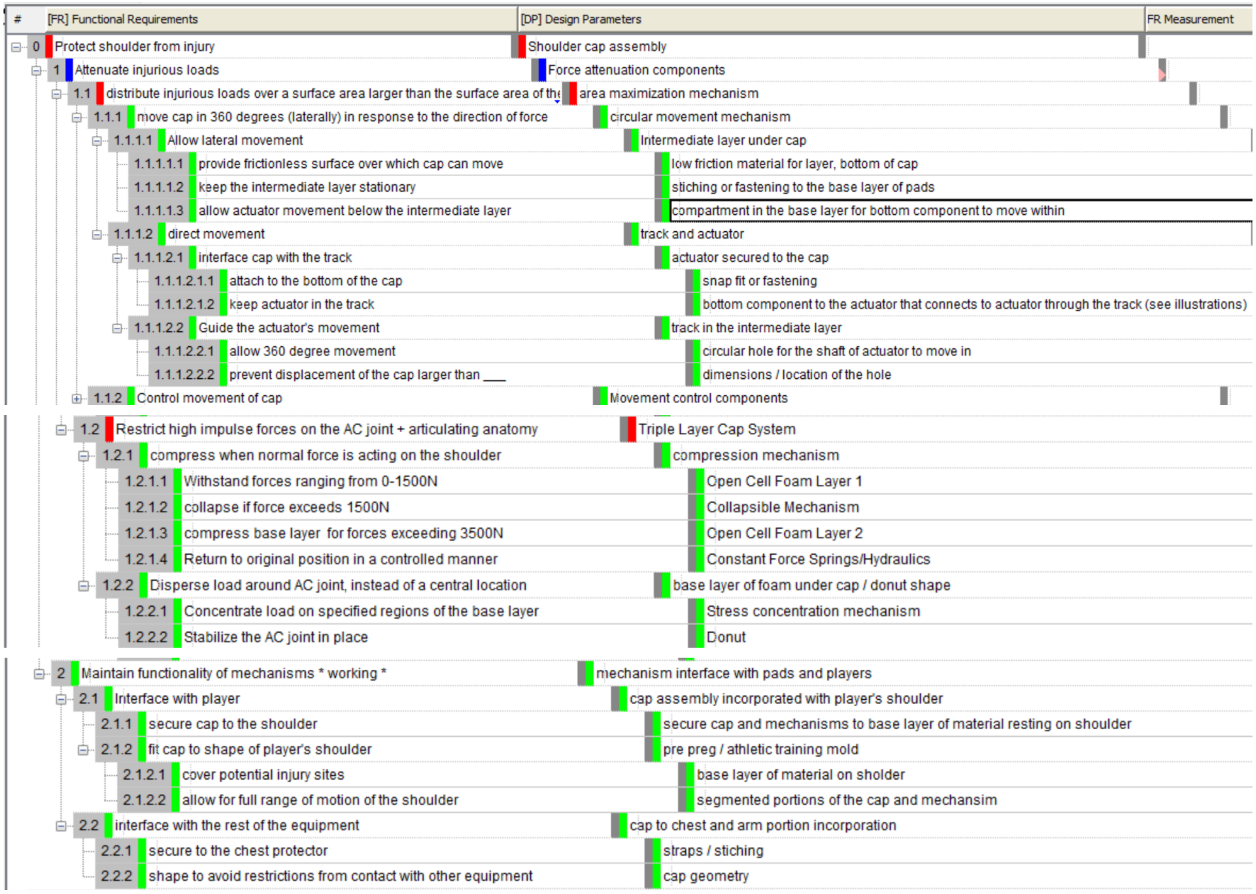
#	[FR] Functional Requirements	[DP] Design Parameters
0	Protect Shoulder from Injury	Protective shoulder cap assembly
1	attenuate injurious loads	load attenuation components
1.1	increase distance over which loads act	constant force tubes
1.1.1	enable cap movement under specific conditions	Partial independence of the cap from a base layer
1.1.1.1	allow movement of the cap over the base layer	stationary base layer underneath the cap
1.1.1.2	suspend the cap over the mesh and base layer	hinge components / curvature of the cap
1.1.1.3	control the direction of cap movement	strategic placement of tube mechanisms
1.1.1.4	provide low friction for movement	teflon layer between the cap and base layer
1.1.2	Control cap movement with constant force	Displacement of actuators through tubes
1.1.2.1	Interface cap with actuators	string or cable attachments to the exterior of cap to hole in the actuator
1.1.2.2	Allow actuator displacement	compliance of tube material and lubricant on inside of tube
1.1.2.3	control actuator displacement	characteristics of the tube and actuator
1.1.2.3.1	apply restorative force to the actuator	stiffness / yield strength of the tube material
1.1.2.3.2	ensure force is effectivly applied to the actuator	curved end of the actuator (torpedo shape)
1.1.2.4	pre-load the actuator	embed the actuator in the track in starting position
1.1.2.5	prevent significant actuator displacement below force threshold	"slack" in the string or cable connecting the actuator to cap
1.2	increase time over which loads act	tri-layer cap assembly
1.2.1	withstand initial loads / soften impacts	soft open cell foam layer / adjustable cellulose and air compartment
1.2.1.1	provide first layer of load absorption	outermost layer
1.2.1.2	separate from first layer	separate enclosure and stitching (would allow for adjustability of air components)
1.2.2	Withstand greater loads than the first layer can handle	harder plastic material (cap)
1.2.2.1	distribute loads over the shoulder	curvature of the cap
1.2.2.2	provide rigid protection	material selection and material reinforcements
1.2.2.3	enclose the cap material	cloth material stitched to the cap
2	Complement the anatomy of the shoulder	Base layer interface
2.1	conform to the shape of the shoulder	flexible foam
2.2	act as last line of defense to high loads	material capable of some force absorption
2.3	stabilize the shoulder joint	compression aspects of the base layer
2.4	cover the important anatomical structures of the shoulder up to the	larger surface area of the base layer than the above cap /segmented regions of base material
3	integrate into rest of shoulder pad design	interfacing components
3.1	interface with the player	cap to shoulder interface components
3.1.1	accomodate the AC joint under the cap	"donut" structure in the base layer of foam
3.1.2	shape the base layer of foam to the shoulder	attach the base layer to portions of the chest padding
3.2	Protect anatomical structures near the AC Joint	Different segments of padding and attachments
3.2.1	protect anatomy closer to the neck (clavice, trap)	similar tri-layer design, like cap construction
3.2.1.1	attach to the main chest portion	strap through a loop stitched / velcro
3.2.1.2	cover area effectively	curved shape over the trap and clavicle
3.2.2	protect upper portion of the arm	upper arm and bicep padding (similar tri-layer)
3.2.2.1	attach to the cap	strap or buckle system without interference of mechanisms
3.2.2.2	attach to players arm	velcro strap around pad

Alternative movement decomposition



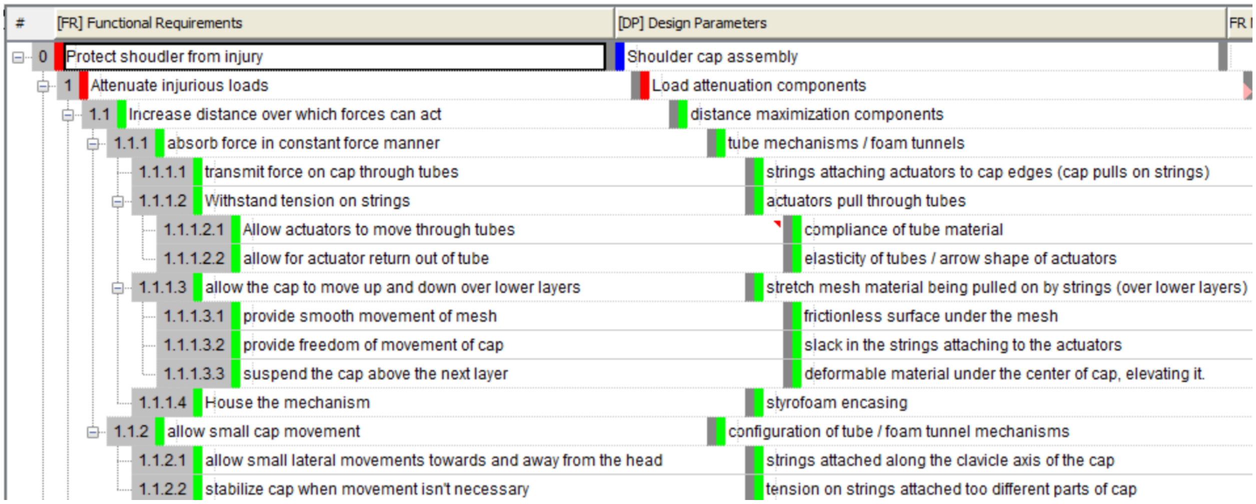
#	[FR] Functional Requirements	[DP] Design Parameters
2	Increase area over which injurious load directed on the AC joint can act	shoulder cap movement mechanism
2.1	allow cap movement	Layer under shoulder cap providing space/mechanism to move
2.1.1	Provide surface for cap to move on independent of the other shoulder pad components	layer of material under the shoulder cap containing mechanism
2.1.2	Interface the cap with the movement material	Pin attached to the shoulder cap that locks into the material/mechanism
2.1.3	allow 360 degree pin movement	"pocket" or cutout within the movement layer for the pin to move in
2.1.4	interface the movement layer with the rest of the shoulder pad	fasten or stitch to area under the center of the shoulder cap
2.2	Control cap movement	elastic bumpers interfacing with the pin, machined into the movement pocket
2.2.1	hold the pin in the movement pocket	edge of the cutout overhanging, preventing the pin removal vertically
2.2.2	Recover any movment of the pin	elastic material wrapped around posts
2.2.2.1	prevent movement past a specified distance under injurious load	posts surrounding the pin, elastic material wrapped around posts
2.2.2.2	Recover movement past injurious threshold of loads	secondary tier of posts and elastic material

Alternative movement mechanism decomposition



#	[FR] Functional Requirements	[DP] Design Parameters	FR Measurement
0	Protect shoulder from injury	Shoulder cap assembly	
1	Attenuate injurious loads	Force attenuation components	
1.1	distribute injurious loads over a surface area larger than the surface area of th	area maximization mechanism	
1.1.1	move cap in 360 degrees (laterally) in response to the direction of force	circular movement mechanism	
1.1.1.1	Allow lateral movement	Intermediate layer under cap	
1.1.1.1.1	provide frictionless surface over which cap can move	low friction material for layer, bottom of cap	
1.1.1.1.2	keep the intermediate layer stationary	stiching or fastening to the base layer of pads	
1.1.1.1.3	allow actuator movement below the intermediate layer	compartment in the base layer for bottom component to move within	
1.1.1.2	direct movement	track and actuator	
1.1.1.2.1	interface cap with the track	actuator secured to the cap	
1.1.1.2.1.1	attach to the bottom of the cap	snap fit or fastening	
1.1.1.2.1.2	keep actuator in the track	bottom component to the actuator that connects to actuator through the track (see illustrations)	
1.1.1.2.2	Guide the actuator's movement	track in the intermediate layer	
1.1.1.2.2.1	allow 360 degree movement	circular hole for the shaft of actuator to move in	
1.1.1.2.2.2	prevent displacement of the cap larger than ___	dimensions / location of the hole	
1.1.2	Control movement of cap	Movement control components	
1.2	Restrict high impulse forces on the AC joint + articulating anatomy	Triple Layer Cap System	
1.2.1	compress when normal force is acting on the shoulder	compression mechanism	
1.2.1.1	Withstand forces ranging from 0-1500N	Open Cell Foam Layer 1	
1.2.1.2	collapse if force exceeds 1500N	Collapsible Mechanism	
1.2.1.3	compress base layer for forces exceeding 3500N	Open Cell Foam Layer 2	
1.2.1.4	Return to original position in a controlled manner	Constant Force Springs/Hydraulics	
1.2.2	Disperse load around AC joint, instead of a central location	base layer of foam under cap / donut shape	
1.2.2.1	Concentrate load on specified regions of the base layer	Stress concentration mechanism	
1.2.2.2	Stabilize the AC joint in place	Donut	
2	Maintain functionality of mechanisms * working *	mechanism interface with pads and players	
2.1	Interface with player	cap assembly incorporated with player's shoulder	
2.1.1	secure cap to the shoulder	secure cap and mechanisms to base layer of material resting on shoulder	
2.1.2	fit cap to shape of player's shoulder	pre preg / athletic training mold	
2.1.2.1	cover potential injury sites	base layer of material on sholder	
2.1.2.2	allow for full range of motion of the shoulder	segmented portions of the cap and mechansim	
2.2	interface with the rest of the equipment	cap to chest and arm portion incorporation	
2.2.1	secure to the chest protector	straps / stiching	
2.2.2	shape to avoid restrictions from contact with other equipment	cap geometry	

Iteration with Tubes before Final Iteration



#	[FR] Functional Requirements	[DP] Design Parameters	FR
0	Protect shoudler from injury	Shoulder cap assembly	
1	Attenuate injurious loads	Load attenuation components	
1.1	Increase distance over which forces can act	distance maximization components	
1.1.1	absorb force in constant force manner	tube mechanisms / foam tunnels	
1.1.1.1	transmit force on cap through tubes	strings attaching actuators to cap edges (cap pulls on strings)	
1.1.1.2	Withstand tension on strings	actuators pull through tubes	
1.1.1.2.1	Allow actuators to move through tubes	compliance of tube material	
1.1.1.2.2	allow for actuator return out of tube	elasticity of tubes / arrow shape of actuators	
1.1.1.3	allow the cap to move up and down over lower layers	stretch mesh material being pulled on by strings (over lower layers)	
1.1.1.3.1	provide smooth movement of mesh	frictionless surface under the mesh	
1.1.1.3.2	provide freedom of movement of cap	slack in the strings attaching to the actuators	
1.1.1.3.3	suspend the cap above the next layer	deformable material under the center of cap, elevating it.	
1.1.1.4	House the mechanism	styrofoam encasing	
1.1.2	allow small cap movement	configuration of tube / foam tunnel mechanisms	
1.1.2.1	allow small lateral movements towards and away from the head	strings attached along the clavicle axis of the cap	
1.1.2.2	stabilize cap when movement isn't necessary	tension on strings attached too different parts of cap	

	Function	Means
1.2	🟩 Increase time over which forces can act	🟩 layers of force absorption
1.2.1	🟩 absorb energy of load on cap	🟩 deformable layers between point of impact and shoulder
1.2.1.1	🟩 soften initial impact	🟩 soft layer on top of cap
1.2.1.1.1	🟩 mitigate foam deterioration	🟩 fabric enclosure for cap and soft foam
1.2.1.1.2	🟩 recover shape after impact	🟩 material selection: foam with high resilience and yield strength
1.2.1.2	🟩 disperse load	🟩 harder cap material and arch geometry
1.2.1.3	🟩 soften the movement of the cap on the shoulder	🟩 closed cell foam directly under the cap
1.2.1.4	🟩 stabilize the athlete's shoulder	🟩 donut and base layer foam
1.2.2	🟩 configure mechanisms to effectively maximize time	🟩 layout of layers
1.2.2.1	🟩 order layers	🟩 soft, hard,closed cell, base layer
1.2.2.2	🟩 attach layers where necessary	🟩 stitching or adhesives
2	🟥 Integrate with rest of shoulder pad	🟥 pad interface components
2.1	🟩 attach base layer to chest region of pads	🟩 stitch a compression sleeve containing base layer
2.2	🟩 attach bicep protection to compression sleeve	🟩 stitching

C. Test Protocols

Drop Test on Shoulder Cap Device

Purpose

The purpose of this test is to determine how much of a load the shoulder cap with integrated mechanism can absorb under various weight drop tests. The shoulder cap device will be tested under various conditions as a testing method for the final design.

Set Up

Using a force plate at the base of the set-up, different weights will be dropped from a height of 12 inches (0.305 m) above the plate to obtain a force reading. With nothing on the force plate, a five pound weight and a ten pound weight will be dropped each three times to get three different readings at each weight. Once the initial readings are recorded, the shoulder cap device will be placed on the force plate and stabilized with a foam mold that holds it in place. The force plate will be zeroed out so that any force recorded by the plate will be the result of the dropped weight. The weight will also be dropped on the cap three times to get an average reading.

- Height of weights: 36 inches (0.915 m)
- Weight 2: 10 pounds (4.536 kg)
- Weight 3: 25 lbs (11.34 kg)

Calculations

To calculate the force that the shoulder cap device absorbs during each of the drop tests, we first used the work energy principle to estimate the expected force that the cap with experience under set conditions. The net work during an impact can be defined as the average force of the impact multiplied by the distance from the initial drop. Because this is a drop test, we are assuming that the initial velocity with be zero.

$$W_{net} = 1/2mV_f^2 - 1/2mV_i^2$$
$$W_{net} = 1/2mV_f^2$$

With the initial velocity at zero, we can use a kinematic equation to calculate the final velocity experienced when the weight dropped is at impact with the cap.

$$V = \sqrt{2gh}$$

From this, we can calculate the average impact force that is experienced using the net work equation and the distance that the foam and cap compress. In the equation below, the net work is in the numerator and the distance traveled in the denominator.

$$F = \frac{W_{net}}{d}$$

To get a variety of forces that the cap may experience, we altered the weight dropped to get different forces. In this testing method we dropped from 0.915m (3 feet) and dropped weights including 10lbs and 25lbs

At 3 feet and a 10lbs weight:

$$V = \sqrt{2 * 9.81m/s * 0.915m} = 4.24m/s$$
$$W_{net} = 1/2 * 4.54kg * (4.24m/s)^2 = 40.81J$$
$$F = 40.81J\ /\ 0.025m = 1632.37N$$

At 3 feet and a 25lbs weight:

$$V = \sqrt{2 * 9.81m/s * 0.915m} = 4.24m/s$$
$$W_{net} = 1/2 * 11.34kg * (4.24m/s)^2 = 101.93J$$
$$F = 101.93J\ /\ 0.025m = 4080.9N$$

Weight	**Height**	**Work**	**Force**
4.54kg	0.915m	40.80J	1632.37N

11.34kg	0.915m	101.93J	4077.31N

These calculated results can be compared to the test that is completed with the foam base on the force plate and then when the cap is placed on the force plate. By calculating the differences between the tests with nothing on the plate and the tests run with the cap to absorb the load, we can calculate how much of the dropped load is dissipated by the shoulder cap device.

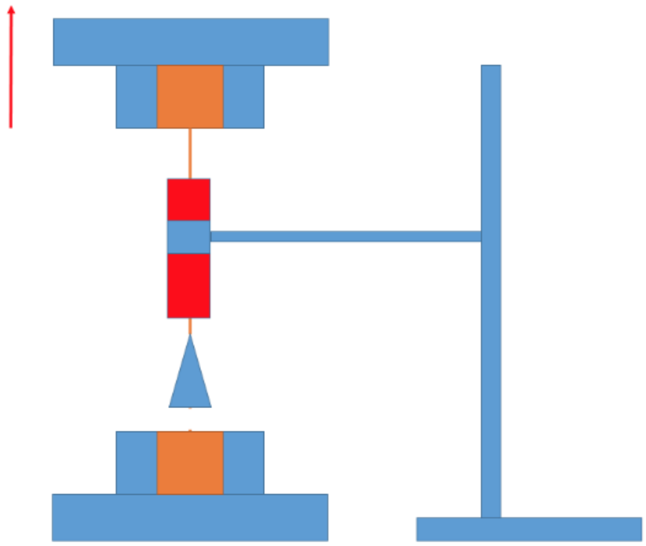
Instron Tensile Testing of Tubes and Torpedo Mechanism

Purpose

The purpose of this test is to determine the force displacement curve for the travel of the torpedo through tubes, the loads the tubes experience, and whether they are behaving in a constant force manner.

Set Up

Two 2” x 2” x 2” cubes of wood with screw in hooks will be clamped into the jaws of the Instron. The strings will be tied to the hooks. The string of the top cube will attach to the hole at the bottom of torpedo (the nose end that travels through the tube). The string of the bottom tube will be attached to the top of the torpedo with enough slack for it to not interfere with torpedo travel. Fishing line (30lbs test, high impact) will be used.



In terms of securing the tube, it needs to be held stationary. A stand and clamp, like the ones used in chemistry labs could be used.

Test Method

- Strain rate: 20 mm/min
- Preload: 5 N (don't want it to constantly be moving, this will be below the threshold for the tunnels)
- Precycling: N/A
- Recording frequency: 10Hz
- Steps:
  a. Use separate test tube holder to suspend the tunnel in place near the instron
  b. Attach strings to blocks of wood
  c. Calibrate load cell
  d. Balance with grips in place
  e. Apply preload
  f. Jog the top load cell up until the torpedo is in contact with the bottom of the tube
  g. Zero the displacement
  h. Use caliper to measure the length of the string attached to the actuator and the grip
  i. Mark the location where the grip started and monitor for how high it moves up to determine how far into the tunnel the actuator moved