Developing a Modernized Ballistic Vest

A Major Qualifying Project Report

Submitted to the Faculty
of the Mechanical Engineering Department

WORCESTER POLYTECHNIC INSTITUTE

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Abstract

Contrary to popular belief, current ballistic vests are only bullet resistant and leave officers vulnerable to high caliber ammunition. These vests are preventative in nature and provide minimal additional protection once punctured. This project aimed to combat this shortcoming by implementing a hemostatic gel component to quickly clot bleeding following a gunshot wound. In addition, we developed a wire-grid bullet detection system equipped with a GPS locator intended to notify emergency services immediately after an officer's vest is penetrated. The work of this project is vital to provide officers with additional protective measures which help to reduce the issues found in modern technology.

1.0 Introduction

In the middle of a crowded square in Chicago, 1897, an inventor stood directly in front of the barrel of his assistant's revolver. Moments later, a shot was fired. The inventor keels over upon impact, but moments later stands up unscathed. He was wearing an invention of his own creation, the first practical ballistic vest, one centimeter thick, composed of many layers of silk (Oleksiak, 2017).

Modern ballistic vests have been worn by officers since the 1970s, and since then the use of ballistic vests has continued to increase (Greene, 2018). Officers have reaped the benefit of the added protection with over 3100 officer's lives saved since 1987. However, these modern devices made mostly from kevlar and steel are only bullet resistant and still leave officers vulnerable in unprotected areas against high caliber ammunition. In the last decade alone, 334 officers have been feloniously shot with firearms while wearing ballistic vests and succumbed to their wounds (FBI).

Ballistic vests are preventative. Although offering an additional layer of protection, once penetrated, the vest offers no additional support. At this point, wounded officers do not receive medical assistance right away as it takes time for emergency personnel to arrive at the scene. Every second counts in the event of a gunshot wound to the torso where hemorrhage could occur. Our team will investigate adding the following features to complement ballistic vests:

- Hemostatic gel pouches to stop bleeding quickly,
- A bullet detection system with a GPS beacon to identify when and where an officer is wounded and transmit the location of the officer to dispatched first responders, and
- A mobile app to collect sensor data and transmit it to incoming paramedics.

These features will work in conjunction to greatly improve an officer's chance of survival in the event of a potentially otherwise fatal wound.

2.0 Background

With many technologies and iterations of ballistics vests currently available, our team plans to further protective technologies through critical assessment, redesigns, and testing a modified police vest. The end goal is to increase injured officers' survival rates by activating blood-clotting gels and sending data to paramedics indicating critically harmed regions of the officer when shot. This chapter will focus on the current technologies available, statistics about officers feloniously killed, hemostatic gel, gel casing materials, previous projects, and ballistic vests.

2.1 Current Technology

Body armor is a preventative method that allows for ballistic vests to come in two different forms. They can either be hard body armor or soft body armor. Soft armor vests are typically made of flexible high strength materials such as kevlar, while hard body armor uses sturdy plates that are inserted into pockets within the vest

Currently, ballistic armor is designed and manufactured to different standards depending on the type of vest. In our project, we will be working on a vest daily worn by officers that is flexible and uses kevlar as the primary ballistic material.

Table 2-1: Different Bullet Dimensions and Statistics

Vest Type	Bullet Class	Caliper	Bullet Mass	Bullet Speed	Energy
Type IIA	Handgun	9 mm .40 S&W	8.0 g 11.7 g	373m/s 352m/s	556 J 724 J
Type II	Handgun	9 mm .357 Magnum	8.0 g 10.2 g	398 m/s 436 m/s	633 J 969 J
Type IIIA	Handgun	.357 SIG .44 Magnum	8.1 g 15.6 g	448 m/s 436 m/s	813 J 1483 J
Type III	Rifles	7.62 mm	9.6 g	847 m/s	3443 J
Type IV	Armor Piercing Rifle	.30 AP	10.8 g	878 m/s	4163 J

Most officers wear Type II ballistic vests on a daily basis (Kaiser). As shown in Table 2-1, these vests are rated to stop up to 9 mm round and a .357 magnum round. Therefore, in situations where perpetrators have high caliber handgun rounds of rifles, officers are left vulnerable to injury.

2.1.1 Our Team’s Ballistic Vest

Our team was able to meet with Deputy Stephen Marsh of the WPI Police who showed us what a typical IIA ballistic vest looks like. This vest is typically worn under the uniform with a t-shirt underneath. It weighs approximately 4 pounds and has velcro adjustments on the shoulders and waist to customize the fit. The kevlar-woven material takes up the size of the entire vest, and the vest also has additional pockets on the front and back for an additional plate if desired. The inside of the vest is made of a thin mesh sport fabric, while the exterior is a thick and stiffer fabric. Figure 8 depicts the vest described above.

Figure 2-1: WPI Police Type IIA Ballistic Vest

2.2 Statistics

The Federal Bureau of Investigation (FBI) compiles information about officers feloniously and accidentally killed every year. From the years 2010-2019 a total of 510 officers have been feloniously killed (FBI, 2019). Figure 2-2 shows a breakdown of the situation where officers are killed each year.

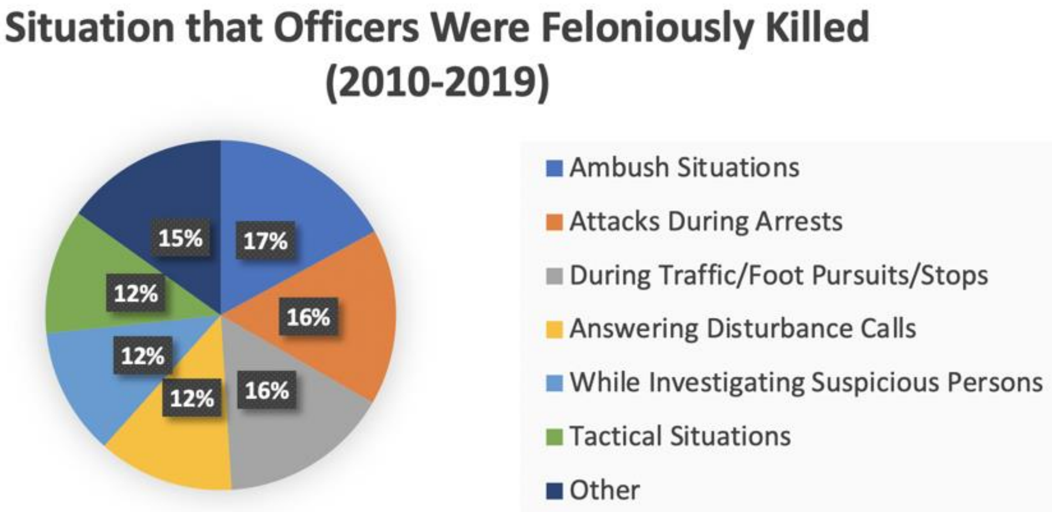


Figure 2-2: Situations of Officers Feloniously Killed (2010-2019)

The most likely situation that an officer will be feloniously killed on the job is when they are ambushed. In these situations, it is highly likely that the officer is not prepared and not able to defend themself. In the event an officer is incapacitated during an ambush and unable to radio for backup, the details and location are difficult to locate without the assistance of an eyewitness reporting the incident.

Of the 510 officers who were feloniously killed between the years 2010 and 2019, 334 were shot and killed while wearing body armor, an average of 33 each year. The FBI database also divides up the location of the fatal wound which is shown in Figure 2-3 (FBI, 2019).

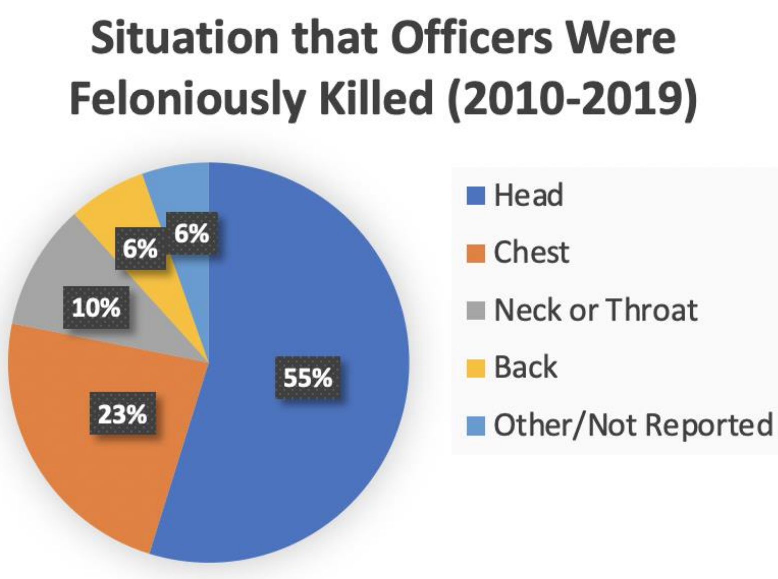


Figure 2-3: Location of Fatal Wounds for Officers Killed Wearing Body Armor (2010-2019)

The majority of officers who were feloniously killed were shot in the head (55%) followed by the chest (23%). This means that 23% of officers died from wounds to the chest while wearing body armor and therefore body armor is not completely effective at protecting officers in its current state (FBI, 2019). More data can be found in **Appendix A: FBI Data for Officers Feloniously Killed.**

2.3 Hemostatic Gel

A primary component of our vest design is the implementation of a hemostatic gel agent. The most effective hemostatic agent in the industry is produced by the startup company Cresilon, founded by Joe Landolina. Their main advertisement and our source of research is their success with Vetigel, a plant-based polymer that can be used to seal virtually any type of wound in just 15 to 20 seconds (Landolina, 2014). It is currently being used for animal wounds and in practice with veterinarians. While Vetigel is only approved for veterinary use, Cresilon is also the manufacturer for Traumagel which has the intended applications for military combat use and civilian emergency medical services use. It should be noted that Traumagel is still not FDA approved.

This product is made of plant derived polymers through extraction of cell wall pieces from algae. They reassemble into the pattern of what it is applied to, including skin and organs. It has a high clot strength and claims to be able to clot a gunshot wound to the renal artery within 15 seconds and keep the wound from bleeding (Landolina, 2014). The gel is provided in a 5mL syringe and applied directly to the wound, almost immediately reacting with tissue and increasing coagulation. The polymers themselves change their properties which morph into the skin cells when applied to a wound, forming a fibrin patch over it (Landolina, 2014). More details of the chemical structure of Vetigel can be found in **Appendix B: Vetigel Chemical Structure.**

Currently, in order to stop blood flow from a wound, constant pressure must be applied. An advantage to Vetigel is that it does not require constant applied pressure. This is important for police officers who are shot when they are alone, or not in a situation where they can receive constant medical attention. In addition, Vetigel is the fastest-acting agent on the market, clotting the wound in under 20 seconds as opposed to 4-5 minutes for other blood-controlling products. Figure 2-4 shows how fast Vetigel can reach hemostasis with a much higher clotting strength than its competitors.

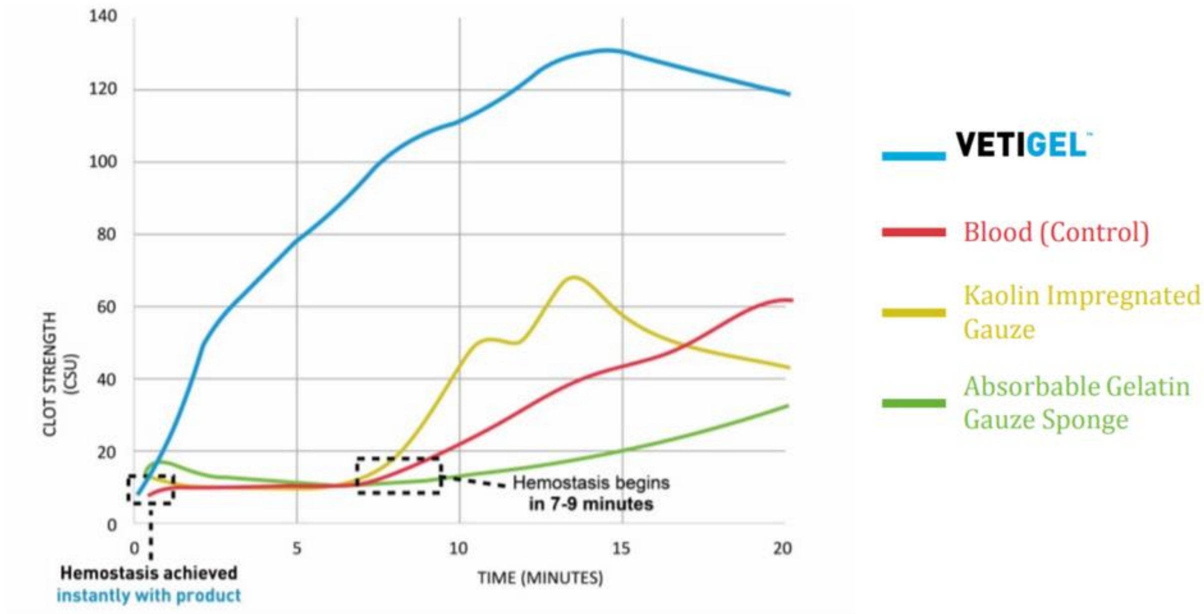


Figure 2-4: Comparison of Vetigel's Rapid Clotting Ability to Competitors (Landolina, 2014)

2.4 Gel Casing

Following a similar approach to the previous team's models, our team worked to create a housing for the hemostatic gel. The two materials that were chosen were PLA (a common material used in additive manufacturing) and engineered "flexible" resin, which is a type of rubber material used in the rapid prototyping process (**Appendix C: Manufacturing Processes**). The reasons we chose these two materials over others were cost and availability. We had sufficient funds to use both materials for all of our design iterations and both the PLA and resin were readily available on campus. The PLA was quite rigid and held its shape well. In contrast, the resin was chosen as a more comfortable option for the user in materials readily available to our group for manufacturing. The pouch coverings differed between latex and polyethylene, both of which are stretchable materials. Again, both were easily accessible through internet purchases. Each had varying thicknesses and elasticities which would help us determine what properties a final product should have to be highly effective. Property comparisons for each material can be found in **Appendix D: Previous MQP Gel Casings**.

2.5 Previous Projects

Within the last ten years there have been a variety of project teams that have looked into how modern technologies can improve the design and safety of ballistic vests. Although none of these projects have focused on a system to slow bleeding and give paramedics more time to arrive on scene, many projects have focused on a system that detects impacts and immediately alerts EMS, to allow wounded officers to receive proper medical treatment faster. Two projects in particular will be further discussed in this section.

2.5.1 WPI MQP: Body Armor Impact Map System (2016)

One project from a previous MQP team titled “Body Armor Impact Map System” was developed in 2016. This team planned to implement biotelemetric sensors that could detect heart rate, heart rhythm, and oxygen saturation However, they determined to keep the scope of the project narrow and focus solely on an impact map system and an app that would receive the information from the impact sensors.

In order to detect a bullet strike to the vest, the team designed their own impact sensors out of multiple layers of a piezoelectric material, a material property which allows us to convert mechanical stress to an electric charge, surrounded by a layer of conductive fabric as shown in Figure 2-5.

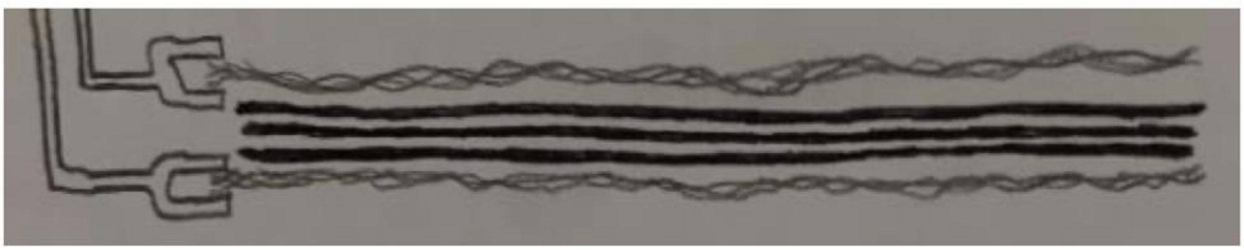


Figure 2-5: Model of Single Conductive Strip

To implement these sensors into the vest, the team decided to overlap horizontal and vertical strips which can be seen in Figure 2-6. The system had a set resistance based on the thickness of the piezoelectric material and when a mechanical stress was introduced (i.e. a gunshot) the piezoelectric layer would compress causing the resistance of the circuit to change. Since the sensors were overlapped, the resistance would change on two strips, one vertical and one horizontal, so the team was able to use a DAQ Board to determine which sensors had the change in resistance and the general region of where the bullet made contact with the vest. The impact information and GPS location of the officer’s phone was then sent to emergency responders to help improve response times.

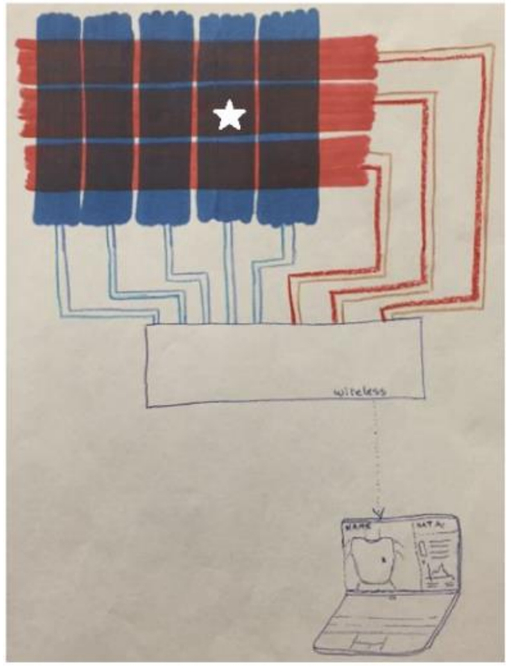


Figure 2-6: Representation of Sensor Grid to DAQ

2.5.2 Patented Impact Sensing of a Ballistic Vest (2016)

Another project titled "Impact Sensing Ballistic Vest and Method for Communicating Data There Of" was conducted by Joseph Maybank and William Broman. They filed for a patent in April 2015, however, abandoned it in February of 2018 (Broman & Maybank, 2016). These inventors also focused solely on a system to detect the impact of a bullet and send a distress signal to a mobile device.

Instead of force sensors, this vest makes use of wires laid both horizontally and vertically across the vest (shown in Figure 2-7). The wires were connected to a processor and charged with an electric current. When the vest was shot, the bullet would break a wire and the current through that wire and into the processor would stop. The system identified the loss of current as a breakage in the wire and based on which vertical and horizontal wires were broken, the system could identify the precise location on the vest in which the officer was shot. Based on a general layout of the organs, the processor would determine the affected organs and send a distress signal to a mobile device.

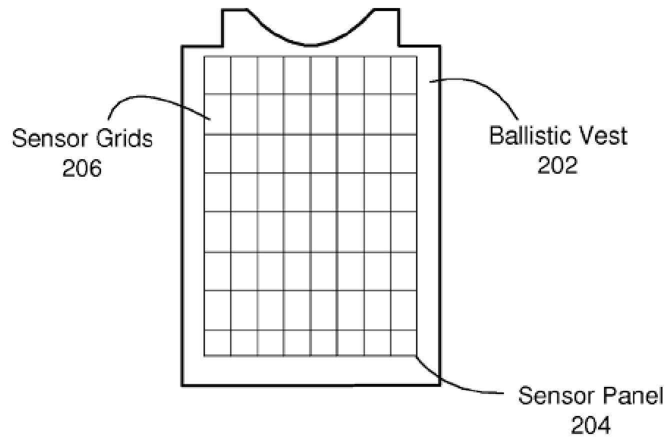


Figure 2-7: Ballistic Vest Sensor Grid

This patent includes only a bullet detection system without a GPS. Therefore, if an officer is shot at an unknown location, paramedics will only know he has been shot, but not be able to do anything about it since they do not know exactly where the injured officer is located.

3.0 Design and Implementation

The goal of this Major Qualifying Project is to improve upon the current ballistic vest in multiple aspects to provide as much aid to a wounded police officer before emergency personnel arrive and acquire as much information as possible to send to EMTs. To achieve this goal, our objectives are as follows:

1. Implement a Traumagel mold to quickly stop bleeding,
2. Identify where the vest was impacted, and
3. Send the bullet impact information and GPS location to emergency services.

We developed these objectives after thorough research and interviews with local first responders. These interviews helped us gain an understanding into police operations to determine the most suitable design. The transcripts for these interviews can be found in **Appendix E: Interview Questions** and **Appendix F: Interview Transcripts**.

3.1 Objective 1: Implement a Traumagel Mold

Our first objective within this project is to create a housing to hold Traumagel. This pouch will have to release Traumagel onto the officer's wound upon impact in order to slow or stop the bleeding. To develop this Traumagel pouch, we went through a variety of calculations, tests, and iterations.

3.1.1 Determining the appropriate size of the Traumagel mold.

To determine the dimensions of these gel molds, we first performed a TOPSIS analysis for optimal gel locations. TOPSIS stands for the Technique for Order of Preference by Similarity to Ideal Solution, a multicriteria decision-making method based on the concept that the best alternative should have the shortest geometric distance to a positive ideal solution and the geometric farthest distance from a negative ideal solution (Celikbilek, 2020). Please refer to Celikbilek's article published in the Journal of Management Analytics listed in the references page for a more detailed description of this topic. The areas a standard bullet-proof vest protects include the abdomen, heart, lungs, stomach, sides, liver, upper back, and lower back. Although the ballistic plate acts as a protective barrier for the entire torso area, the goal of hemostatic gel is to slow external bleeding, so the officer does not bleed out onsite. Since the gel would add too much additional weight to the vest if applied to the entire surface area, our team needed to determine the best areas to concentrate the gel.

Three factors taken into consideration were the likelihood of being shot, fatality likelihood through hemorrhage, and vulnerability ranked on a scale of one to ten. The likelihood of being shot was based on the information provided from the FBI data for officers feloniously killed, with lungs being ranked the highest. It is important to note that the fatality through hemorrhage likelihood only considers the risk of bleeding out when shot, so although the lungs have the highest likelihood of being shot, an officer is not likely to die due to bleeding out if shot only in the lungs. This takes into account where the hemostatic gel most benefits the officer, as gel being applied to a gunshot wound to the lungs will not save an officer's life, but gel applied to a stomach wound greatly increases the officer's chances of survival. Finally, vulnerability was taken into account because the ballistic plates in the vest do not fully cover the entire torso area, primarily the abdomen and sides.

Due to the hemostatic gel only having properties to help an officer in danger of bleeding out, the factor of fatality through hemorrhage likelihood was weighted the highest with 0.75. The likelihood of being shot is weighted 0.2 because an area which is more susceptible to bullet wounds should be protected. The remaining weight of 0.05 is applied to the vulnerability of an area. Although the variable of vulnerability is important to consider, it is the lowest priority because it does not directly compare to how a hemostatic gel will help. The rankings for each factor as well as the overall rank are listed in Table 3-1.

Table 3-1: Rankings of Where to Put the Gel through TOPSIS Analysis

weight	**0.2**	**0.75**	**0.05**	
	Likelihood of being shot	Fatality through hemorrhage likelihood	Vulnerability	Rank
Abdomen	8	6	10	**3**
Heart	3	10	6	**2**
Lungs	10	4	6	4
Stomach	8	9	6	**1**
Sides	2	1	10	8
Liver	4	3	6	5
Upper back	6	1	6	6
Lower Back	5	1	6	7

The highest-ranking areas of where to place the gel were the stomach, heart, and abdomen. Based on these results, the next step was to determine the size of the gel pockets. A diagram representing approximate gel pouch sizes can be seen in Figure 3-1.

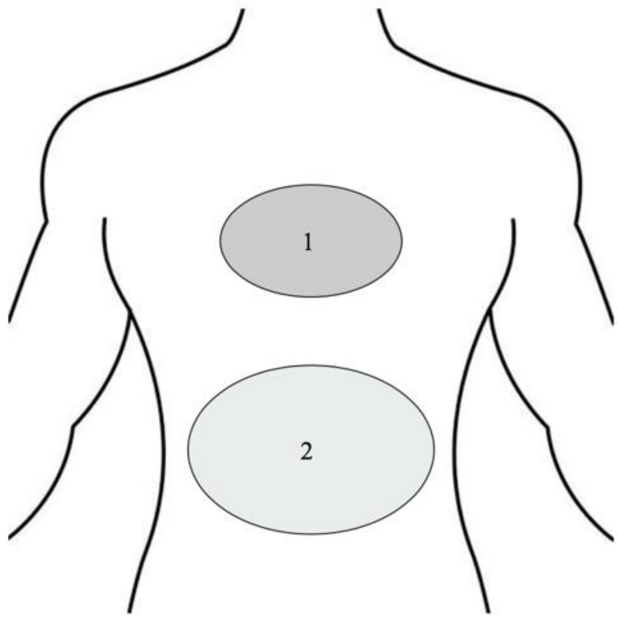


Figure 3-1: Diagram of Gel Pouch Approximate Size and Location

The dimensions of the hemostatic gel pouches are:

Table 3-2: Gel Pouch Dimensions

	Pouch 1	Pouch 2
Dimensions	5in x 3.5in x 1/16in or 12.7 cm x 8.89 x .159 cm	8in x 4in x 1/16in 20.32 x 10.16 x .159 cm
Volume of Gel	17.92mL	32.77mL

For gel pouch 1, the average dimensions of a human heart are 11.41cm long, 8.21wide, and 6 cm front to back, so we added a little extra length to both dimensions to hold more gel and cover the entire area of the heart (Mohammadi et al., 2016). For gel pouch 2, it is estimated that the adult stomach at its widest point is 6 inches across (15.24cm) and is in total 10 inches (25.4cm) long (Frothingham, 2018). In order to cover the complete area of the stomach and ensure there would be enough gel to cover a wound, we added about 2 inches (4cm) to the length and estimated a 4 inch (10.16cm) width since the stomach's primary length is horizontal.

Since the Vetigel costs $30/ 5mL, the cost for this gel addition to the vest would be about **$300** in total. However, the thickness of the pouch can be easily altered depending on the results of future testing. Table 3-3 shows varying costs for the vest dependent on the thickness of the gel pockets.

Table 3-3: Cost for Varying Gel Pouch Thicknesses

Gel Pouch 1						
thickness (in)	thickness (cm)	length (cm)	width (cm)	volume (mL)		cost
1/8	0.318	12.7	8.89	35.847	$	215.08
1/16	0.159	12.7	8.89	17.923	$	107.54
1/32	0.079	12.7	8.89	8.962	$	53.77

Gel Pouch 2						
thickness (in)	thickness (cm)	length (cm)	width (cm)	volume (mL)		cost
1/8	0.318	20.32	10.16	65.548	$	393.29
1/16	0.159	20.32	10.16	32.774	$	196.64
1/32	0.079	20.32	10.16	16.387	$	98.32

Total Cost		
1/8	$	608.37
1/16	**$**	**304.18**
1/32	$	152.09

As noted in Table 3-3, varying the thickness of the gel pocket to utilize more or less gel, significantly changes the price. For testing, we planned to use the 1/16 in. thickness; the intermediate thickness and price shown in the table.

3.1.2 Testing TraumaGel Substitutes

In order to simulate the gel application method and practicality of the gel in the vest, it was important for us to understand the gel's ability to seep into the wound. Since we initially planned to place the gel packets underneath the kevlar plate, the gel would need to seep through the thin, inner fabric of the vest and the wearer's undershirt. A diagram of the bullet movement can be seen in Figure 3-2.

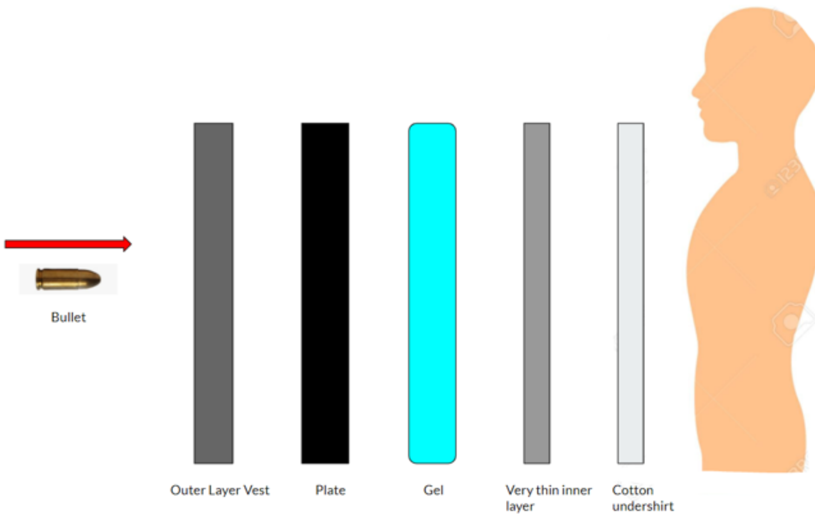


Figure 3-2: Layers of our Ballistic Vest Design a Bullet Will Travel through

Due to the fact that we were not able to obtain hemostatic gel and there were very limited material properties of the gel listed online, we used our best judgement to infer the consistency of it through videos. We decided to test five different substances with varying viscosities to observe their material properties and test their ability to seep through a cotton undershirt, the final layer before the skin. The testing results of five different substances can be shown in Table 3-4.

Materials:

Table 3-4: Substance Testing to Mimic the Viscosity of Hemostatic Gel

Substance	Rank of Viscosity (most viscous to least viscous)	Observations
Hot/ Cold Gel Pack	1	We think this is the closest substance to the TraumaGel, kept its form while on the plate.
Aftersun Aloe Vera Soothing Gel	2	The aloe veras were both pretty similar in consistency. It seemed that this one was a bit thicker while running a toothpick through the gel.
99% Aloe Soothing Gel	3	Out of the 5 substances, this seemed to rank right in the middle.
Liquid Soap	4	After around 4 minutes, the soap expanded on the plate.
Foam Bath Soap	5	Very liquid, immediately expanded when squirted on the plate.

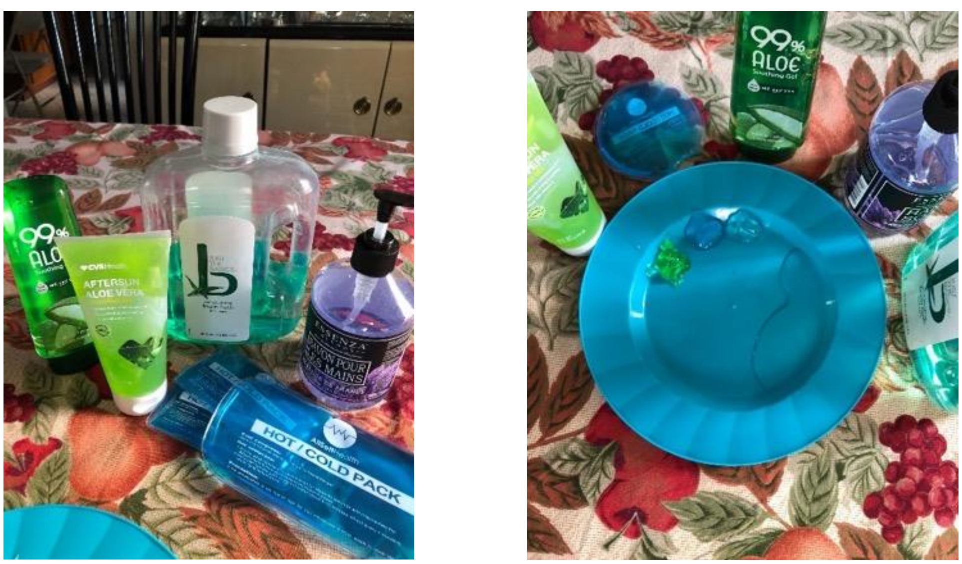


Figure 3-3: Tested Gel Substances

The setup of this experiment included a cotton shirt tied around the top of a glass cup. A glass cup was utilized to clearly see if any liquid was to drip through. 1.5 mL of each substance was then inserted into a plastic bag. Once a small hole was cut at the bottom of the bag, the bag was squeezed to release the gel on the cotton shirt. A timer was used to record the amount of time it would take for a drop of gel to drip through the fabric. It is important to note in this test, there was no hole in the shirt, we simply wanted to see if the substances would seep through at all.

Figure 3-4: Liquid Soap in Bag and Shirt with Liquid Soap

The first substance that was tested was the liquid bath foam, the least viscous substance. After application of the gel, the gel sat on top of the shirt and did not drip until minute 6. From this test, it was assumed that the other substances, due to their thicker properties, would have taken longer to seep through the shirt into the glass.

The test was then repeated with the only differences being that there was a “bullet-sized” hole in the cotton shirt to mimic the bullet hole, and the substance tested was aloe vera to more closely match the consistency of the gel.

Figure 3-5: Aloe Vera Testing through a Cotton Shirt with a Hole

When aloe was released from the plastic bag, some seeped through the hole in the fabric, but it never dripped to the bottom of the cup. When the gel was pushed through the hole using a piece of cardboard, some aloe plunged through and dripped to the bottom of the cup.

After this testing, it was concluded that the gel would not seep through the cotton shirt to release enough gel to effectively stop the bleeding of a wound. Since the gel would not be able to seep through the undershirt effectively, we decided to incorporate the Traumagel pouch into the officer's undershirt. This way, when the pouch was broken, the gel would seep out of the pouch directly onto the skin and would not have to seep through an additional layer of clothing.

An updated diagram of the bullet movement can be seen in Figure 3-6.

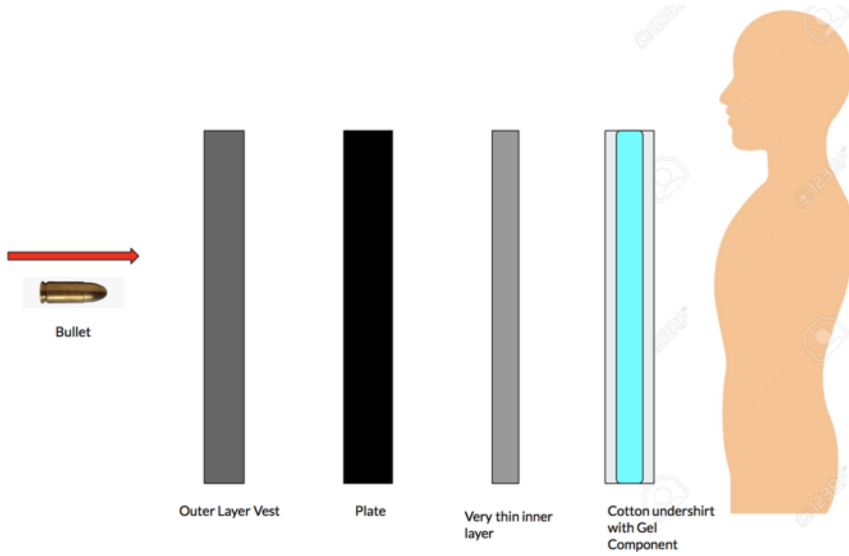


Figure 3-6: Updated Layers of our Ballistic Vest Design a Bullet Will Travel Through

3.1.3 3D Model of Gel Implementation in Undershirt

A 3D rendition of the design was created in ZBrush. This was created to help visualize our design and the sizing of our parts on a human. In the model, both the heart and stomach gel pouches can be seen embedded on the officers tight undershirt. The sizes of the pouches demonstrated in the illustration correspond with the pouch sizes determined in Section 3.1.1. As depicted in Figure 3-7, the heart gel pouch is smaller than the stomach gel pouch.

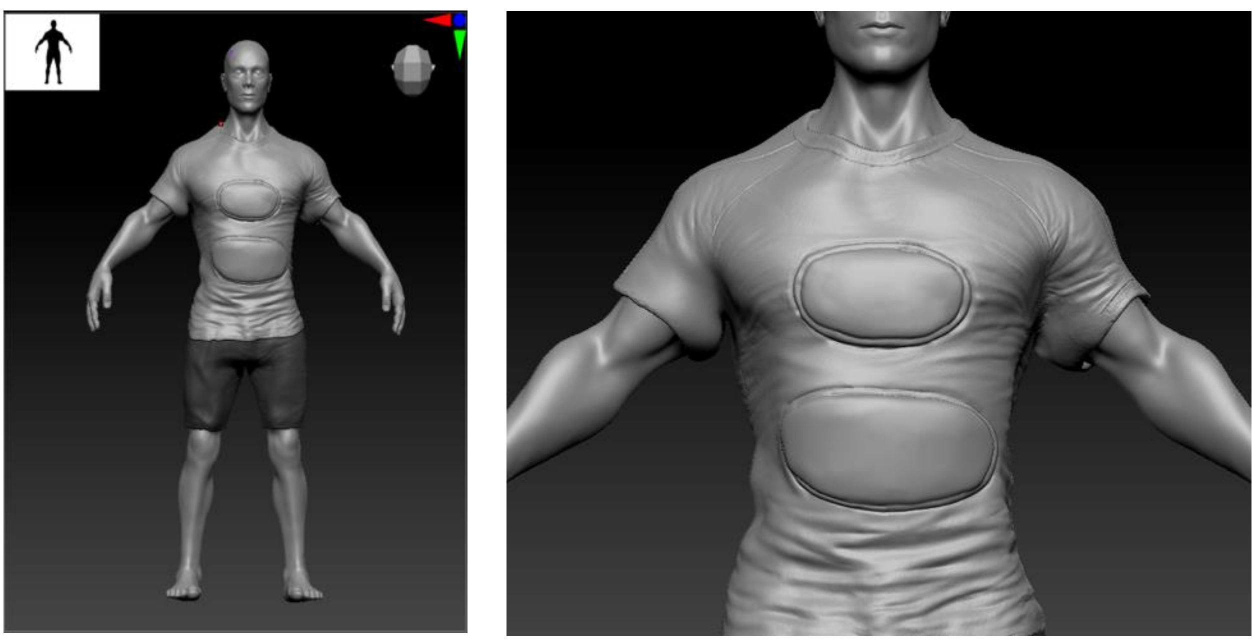


Figure 3-7: ZBrush Model

3.1.4 First Iteration: Silicone Mold

The first Traumagel pouch was designed using SolidWorks computer aided design software. The mold for this was 3D printed using PLA, with liquid silicone being poured into the mold to create the pouch.

The pouch was designed to have a hollow core to allow for the hemostatic gel to be inserted. It needed to be relatively thin so as to not be bulky or uncomfortable to the officer. We chose to use silicone since it is a lightweight and flexible material. Additionally, its poor adhesive properties are beneficial for molding processes as it is easy to remove the casing from the mold.

The initial CAD design featured a two-piece mold that had a rectangular shape. The gel container wall thickness is 0.5 inches.

After analyzing the rectangular pouch, we then decided to pursue an oval shape for the pouch as opposed to the rectangular center in an attempt to allow better gel flow when punctured, as we did not want the Traumagel to become stuck in the corners of the rectangle. Instead, a curved center that got thinner towards the edges would allow as much gel as possible to exit through the bullet hole instead of remaining in the pouch.

The improved 3D model included 3 parts for easy removal: a hollow body, broken into two halves, and an insertable piece to be plunged inside once silicone was applied to the mold. The model is shown in Figure 3-8. The space inside the pouch allotted for a 1/16" layer of gel within the mold; this was calculated based on the assumptions that 17.92 mL of hemostatic gel will be needed for the area covering the officer's heart.

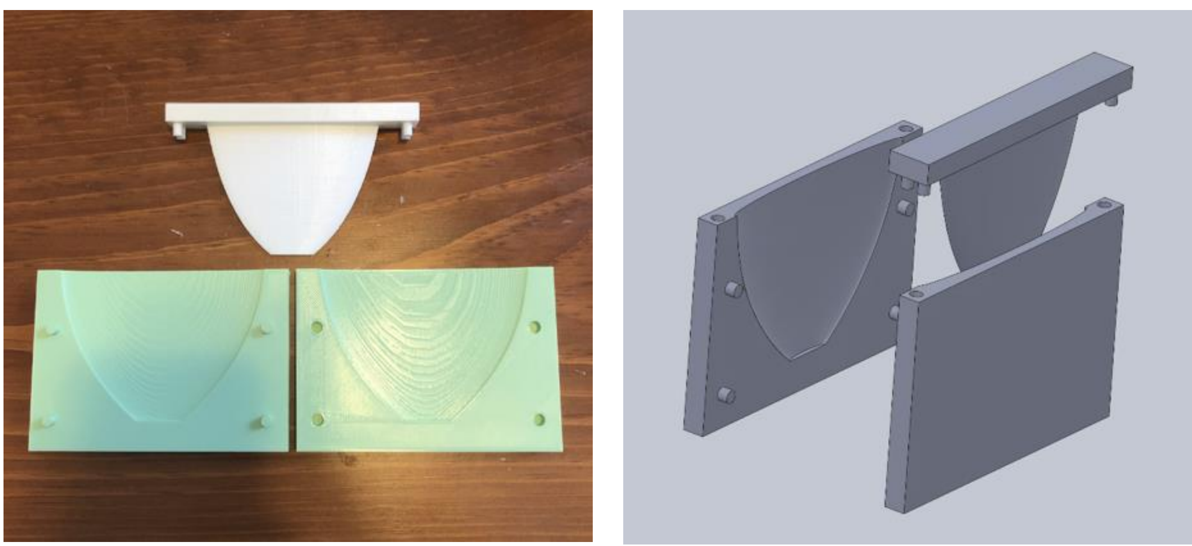


Figure 3-8: Silicone Mold 3D Printed Model and CAD

The two green mold halves were put together and liquid silicone was poured into it. The white plunger piece was then placed inside and sealed, to create a hollow half pouch shown in Figure 3-9. The cure time for the liquid silicone our team used was 16 hours, so we printed multiple molds to more efficiently create the pouches. Once two halves were made, gel was inserted and liquid silicone was used to seal the two halves together.

Figure 3-9: Silicone Pouch

To test the silicone pouch, we used a spring powered airsoft sniper rifle and shot 2 inches away from the pouch. The plastic airsoft BBs are 6mm in diameter and are shot from the rifle at speeds up to 500 feet per second (152.4 m/s). After a few trials with the gel-filled pouch, our team realized that the silicone was not a viable material. Although flexible and would be comfortable for an officer to wear, the hole in the pouch was only the size of the BB which did not allow the gel to seep out. This result is displayed in Figure 3-10.

Figure 3-10: Airsoft Rifle Trial on Silicone Pouch

3.1.5 Testing the First Oval Mold Using ANSYS

Following the redesign of our mold from rectangular to oval, we tested its strength using ANSYS. A hollow body in the oval shape was able to be developed through ANSYS and run through an explicit dynamics simulation. The pouch was given the material properties of “Rubber, Silicone (VMQ),” which is a standard silicone material, and the top and bottom of the pouch design were fixed in place. A 9mm bullet was also added to the simulation sent through the pouch (from right to left) at speeds replicating that of an actual bullet.

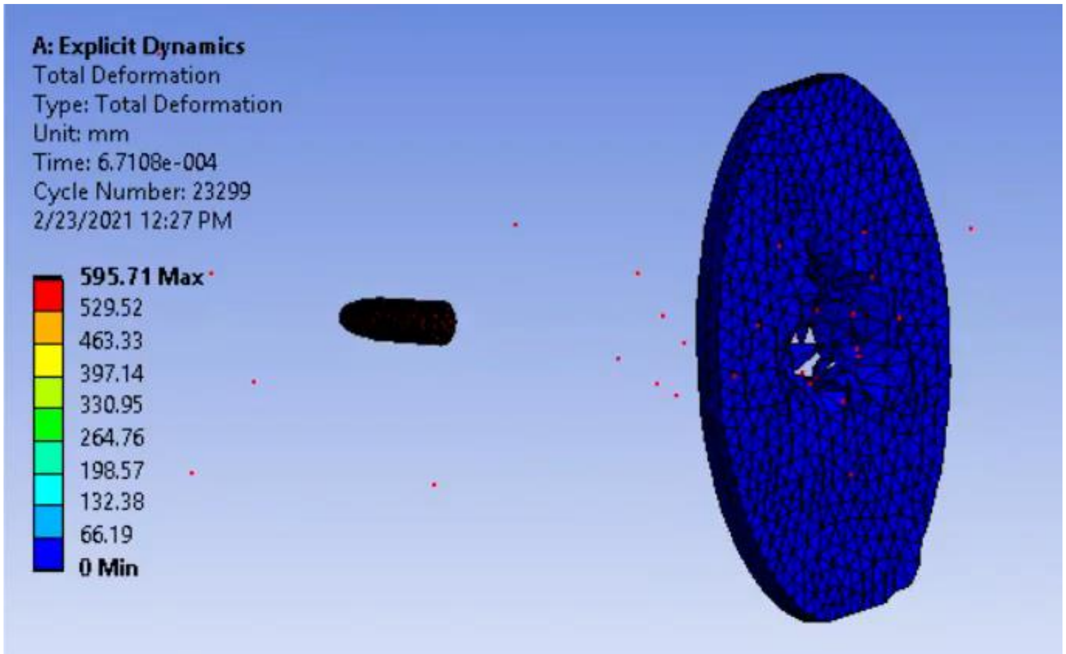


Figure 3-11: Explicit Dynamics Total Deformation of Bullet-Pouch Impact with Hollow Body

Figure 3-11 depicts the impact of the simulated bullet and the resulting total deformation. While the value 595.71mm of maximum deformation was not used in our analysis, it was a good comparison to other testing done to the same pouch without a hollowed center. The total deformation for a non-hollow pouch fixed at the top and bottom was 575.59 mm. Our following iteration featured only one wall that a bullet would need to penetrate. Because of this, it was important to minimize the hole produced on the initial impact and maximize the exit hole. This testing showed us what we could expect the entry hole size to be. This resulting hole is approximately 25 mm in diameter.

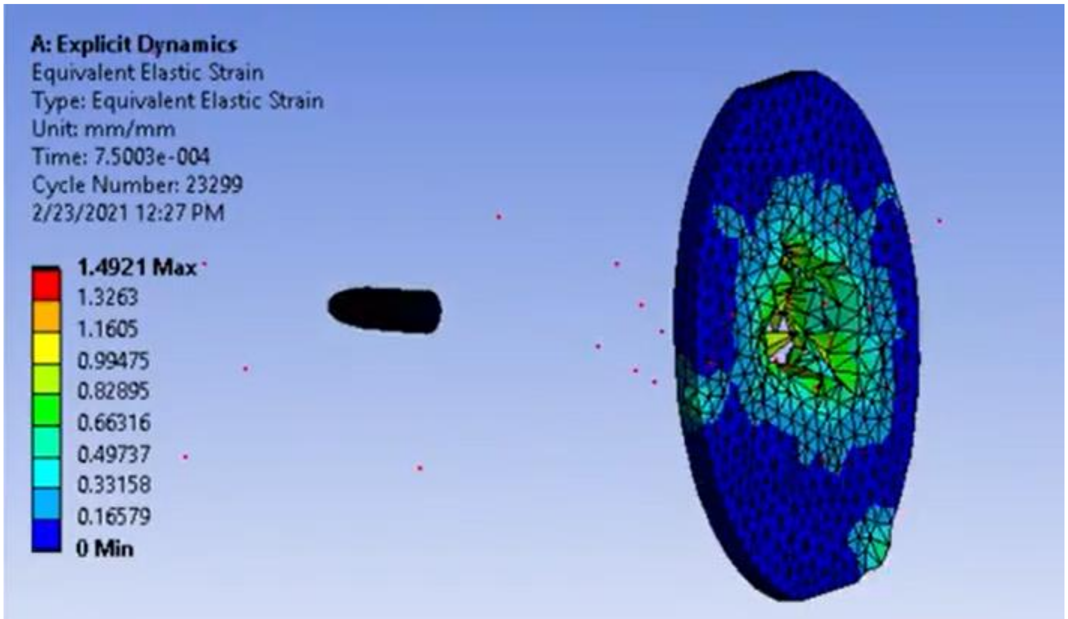


Figure 3-12: Explicit Dynamics Equivalent Strain of Bullet-Pouch Impact with Hollow Body

Figure 3-12 depicts the equivalent elastic strain of the impact between the bullet and silicone pouch within the explicit dynamics simulation run on ANSYS. The maximum strain occurs at the impact site and reaches a value of 1.4921 mm/mm. This gives us a better understanding of the relative deformation of the material under the given forces. Figure 3-13 shows us the stress on the pouch in the impact between the bullet and silicone pouch within the explicit dynamics simulation run on ANSYS. The maximum stress found for the impact was 3189.8 Pa.

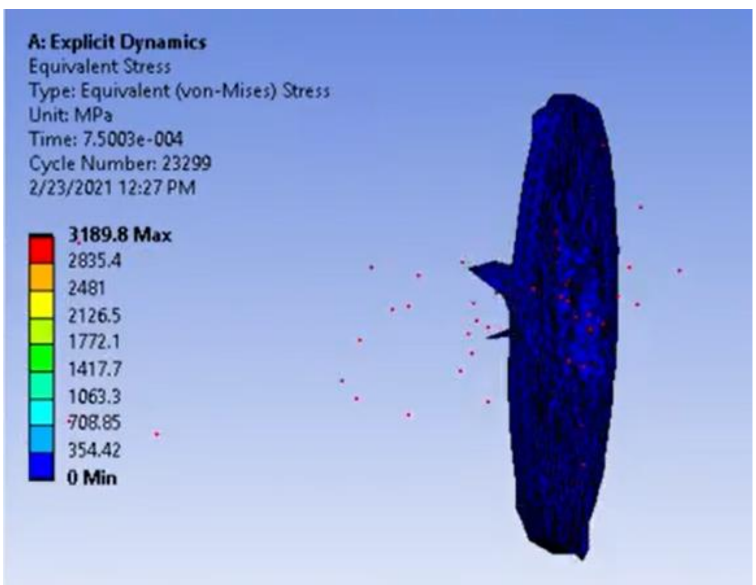


Figure 3-13: Explicit Dynamics Equivalent Stress of Bullet-Pouch Impact with Hollow Body

Figure 3-14 outlines the material properties for the silicone we selected within our ANSYS simulation. This silicone rubber features extreme flexibility in a large temperature range from -50 degrees C to +232 degrees C (-58 to +450 Fahrenheit) and was thought to be perfect for the application of a vest worn in all types of climates and temperatures. However, because our team continued with another design iteration following this hollow oval pouch, materials such as PLA and Tangoplus later replaced the silicone due to rigidity and ability to maintain its shape as the elastic material held the TraumaGel inside. We recommend that any future team working on this project explore ANSYS modeling of PLA and Tangoplus to determine the best outcome. Specifically, Tangoplus as its properties can be adjusted easily using the PolyJet rapid prototyping machine to become more elastic or more rigid.

Rubber, silicone (VMQ)

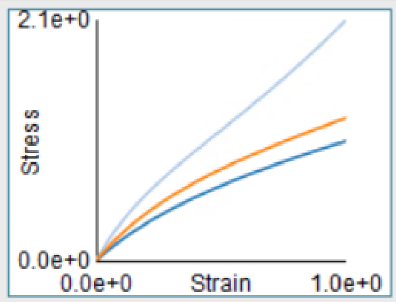
Density	1.116e-09 tonne/mm³
Structural	
Isotropic Secant Coefficient of Thermal Expansion	0.0002739 1/°C
Mooney-Rivlin 2 Parameter	
Tensile Ultimate Strength	8.972 MPa
Tensile Yield Strength	8.972 MPa
Thermal	
Isotropic Thermal Conductivity	0.0002449 W/mm·°C
Specific Heat Constant Pressure	1.075e+06 J/tonne·°C
Electric	
Isotropic Resistivity	1.225e+15 ohm·mm

Figure 3-14: Rubber, Silicone (VMQ) Properties

3.1.6 Gel Release Mechanism

After testing the silicone pouch with the airsoft gun, we realized that gel was not flowing out of the pouch as intended. However, a critical component we had to consider while designing the hemostatic gel containers was how the gel would be expelled out of the pouch and onto the wound after being pierced by the bullet. If the gel was not successfully expelled from the pouch onto the wound, the pouch would be useless.

One initial concept was to design some sort of mechanical plunger, as seen in Figure 3-15, that would extend a plate against the pouch and compress it to release the gel out of the hole created by the bullet. However, we quickly realized that any mechanical pushing mechanism would be impractical, as it would likely get damaged by the bullet or upon impact in the case of a fall or other force.

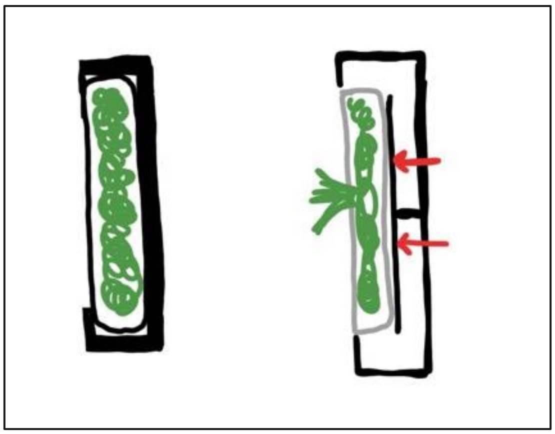


Figure 3-15: Mechanical Plunger Concept for Gel Release

After ruling out the possibility of a mechanical release due to the likelihood of the mechanism failing upon bullet impact, we decided to pursue a material route. We wanted to find a material that when punctured, would expand to be much larger than the size of the puncture in order to expose a greater area of Traumagel to the skin. We thought about the similarity of how a balloon expands when popped by a needle. We wanted our material on the pouch to mimic this behavior and expand after being pierced by the bullet.

In this balloon concept, an elastic material will be tightly stretched over a piece of thicker, more durable material. This durable material will have a pocket in which the calculated amount of Traumagel will be inserted. The elastic material side will be directly on the chest of the officer, and the side opposite of that will face outwards. That way, when the bullet punctures through the durable side to the balloon side, the small hole created by the bullet in the balloon will expand due to tension to create a bigger opening for the Traumagel to close the wound.

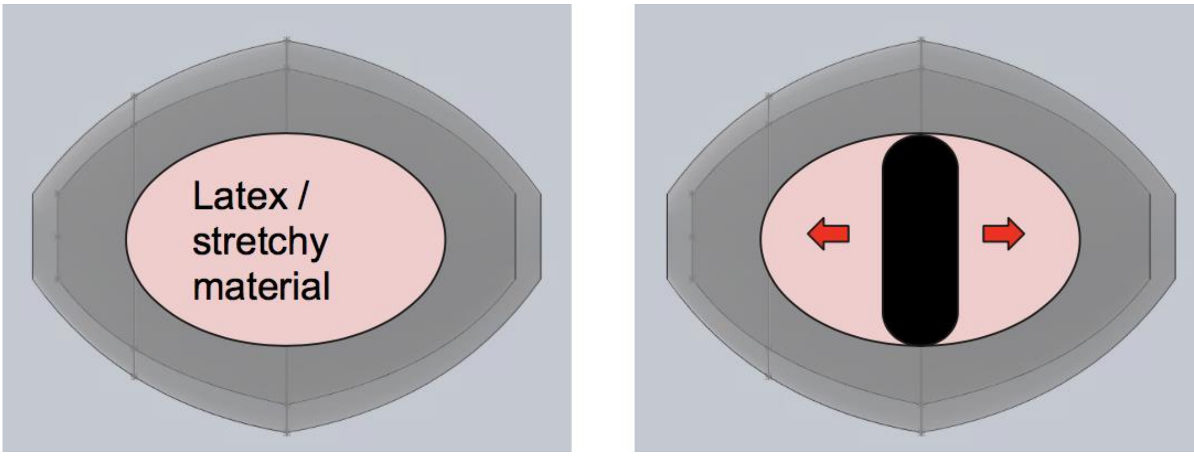


Figure 3-16: Balloon Design Concept

3.1.7 Elastic Pouch

Our first iteration of the pouch was created using PLA and a latex balloon. We chose to use PLA for the pouch material because of the convenience and quick turnaround with printing the parts with a 3D printer. When designing the SolidWorks model, we made sure to size the pouch according to the dimensions we calculated in our background research, also making sure that enough gel could be held in the packet.

For ease, we only modeled, printed, and tested the heart pouch (pouch #1). Since the stomach pouch (pouch #2) would be created the same way as the heart pouch, just with bigger dimensions, we assumed that the stomach pouch would produce the same results in testing.

Figure 3-17: First Solidworks Iteration Balloon Pouch, Rear View

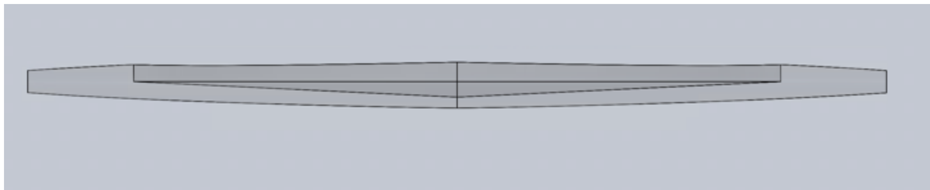


Figure 3-18: First Solidworks Iteration Balloon Pouch, Side View

In order to cover the PLA tightly with the balloon, we tried two different methods. The first method was to simply snip off the opening of the balloon and manually stretch the material over the PLA. The second was to blow up the balloon and then compress the PLA to the balloon tightly while letting out the air of the balloon. That way, the latex would form tightly around the PLA. The first printed pouch with a manually stretched balloon is shown in Figure 3-19.

Figure 3-19: First Pouch Iteration Printed Model

We noticed that Method 1 (manual stretch method) was able to produce a tighter fit compared to Method 2 (blowing up the balloon then compressing the pouch against it). Therefore, in future iterations we used the manual stretching method to secure the balloons. We gathered that the tighter the balloon, the bigger the opening when punctured.

We then ran a series of tests with the same airsoft gun used in the first iteration silicone pouch testing. The pouch was shot at a 2-3 inch distance from the airsoft gun in every test. After each test, observations and results were recorded and new iterations of the pouch were created. We did this a series of times until we created a model (refer to section 3.1.7) that we thought would yield the best results in a live fire shooting test.

Figure 3-20: Setup of Airsoft Rifle Test

Figure 3-21: First Pouch Iteration Test with Airsoft Rifle

There were many observations that were recorded after our first airsoft rifle test. First, we realized that there was not enough gel in the pouch because the pocket within the pouch was not deep enough. In our next iteration, we made a deeper pocket. We also noticed that the hole created was not as big as expected. This is because the balloon was not tight enough. In our next iteration we used a heat gun on the latex to tighten the material. In addition, our model had a small inner crevice pocket that gel was getting stuck in. In our next iteration, we eliminated this inner crevice.

Figure 3-22: Second Pouch Iteration Airsoft Rifle Test

As shown in Figure 3-22, our second iteration was much more successful, yielding a larger hole for the Traumagel to seep out of and close the officer's wound. We conducted a series of other tests as well, varying the method in which we apply the balloon, and the amount of time the heat gun was used for.

We also wanted to create pouch models using alternatives to the PLA and the latex. In a real-world situation, the PLA on the chest and stomach would not be very comfortable. We wanted to pick a material that would be soft enough to conform to the officer's body, but also strong enough to withstand the tension from the balloon. In addition, we realized that latex would not be the most practical material as there are many people that are allergic to latex, and the friction of the latex created on the chest may be uncomfortable.

Our inspiration for a latex replacement was a stress ball; a little toy we used to play with in our youth. Stress balls are created from a special rubber called closed-cell polyethylene, which allows for its extremely stretchy and soft feel. In addition, polyethylene is extremely susceptible to heat, and so it will easily rip if exposed. We thought the heat of the bullet might tear the stress ball even further upon bullet impact.

To further increase the comfortability of the gel pouch, our team considered engineered resins instead of PLA. This material would simulate rubber and curve with the body in comparison to the stiff and brittle PLA. Using the rapid prototyping Form2 machine, Figure 3-23 shows the gel pouch design printed with “flexible” formlabs material. Although the latex and polyethylene material would not be as tightly stretched to the model as the PLA due to the applied force bending the resin, it appeared to be a more viable material in terms of functionality. An officer does not want to be on a call with a plastic piece attached to their chest, as this would add irritation to one’s uniform and possibly inhibit movement. The flexible resin is an alternate material which would complement an officer’s uniform.

Figure 3-23: "Flexible" Resin Model

3.1.8 Attaching Traumagel Pouch to the Shirt

After finding that the balloon mechanism could successfully open wide enough to expose the gel to an officer’s wound, we needed to find a way to attach the Traumagel pouch to his/her undershirt. We decided to create an additional part that would be sewn into the officer’s shirt and clip into the Traumagel pouch.

It was important to have a separate piece that would be in the shirt and attach to the pouch for multiple reasons. First, the balloon material needed to be able to stretch over the front and back of the pouch without any obstruction. If the pouch itself was attached directly to the shirt, it would be very difficult to secure the balloon. Additionally, it was very important for us to be able to exchange different pouches onto the shirt for our testing. We would only need to sew one attachment onto the shirt and once the pouch was broken, we could exchange it for a new one without having to sew a new part onto the shirt.

To do this, we needed to make slight adjustments to the design of our Traumagel pouch. First, we changed the shape of the pouch from having a rounded depth to a uniform height, as seen in Figure 3-24. In order for the clips to work properly, there needed to be holes on the undersides of the pouch. However, our initial design was too thin on the edges for this to work properly. The drawings of the final pouch design can be found in **Appendix G: Drawings of Final Gel Pouch**.

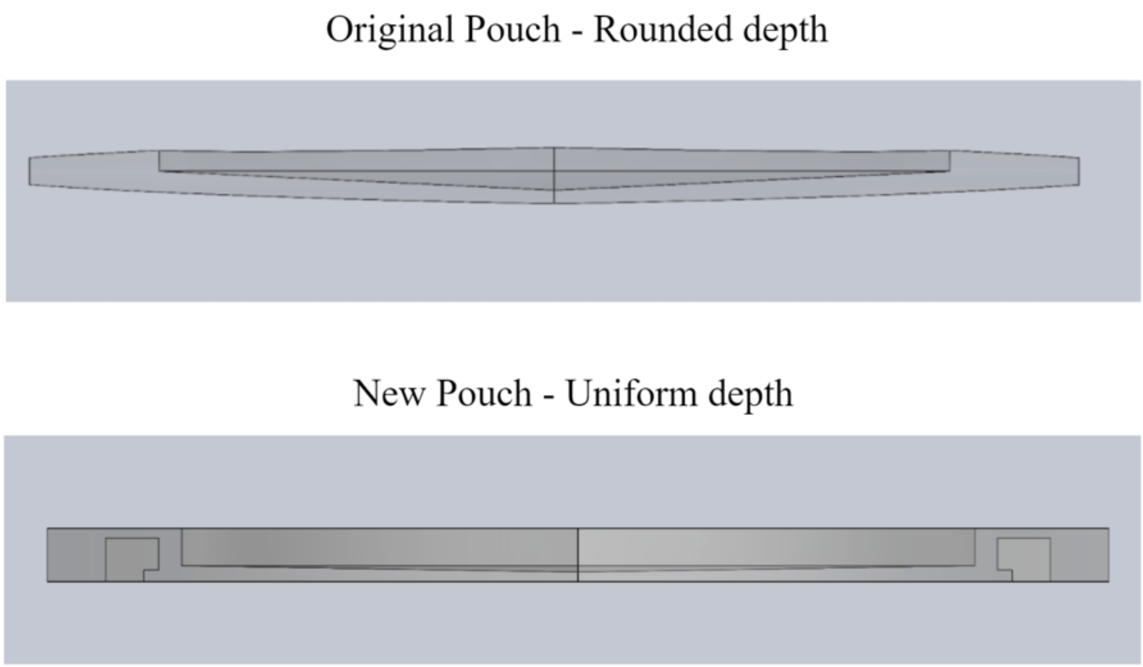


Figure 3-24: Comparison of Pouch Shapes

After adjusting the size of the pouch, the hole (or area that would hold the gel), was about 1.35 cubic inches, which is equivalent to about 22 mL of Traumagel. This was slightly higher than our initial plan of 17.9 mL for the chest pouch (as discussed in Section 3.1.1). The new gel amount would cost about **$131** for one heart pouch of this size.

We modeled the clipping mechanism after the clips shown in Figure 3-25. This clip is pushed down into the adjacent hole and then click into place. To release it, the user simply squeezes in the clip and pulls up.

Figure 3-25: Polaroid Camera Clip

After looking at this clip design, we modeled the Traumagel pouch and attachment piece shown in Figure 3-26 and Figure 3-27.

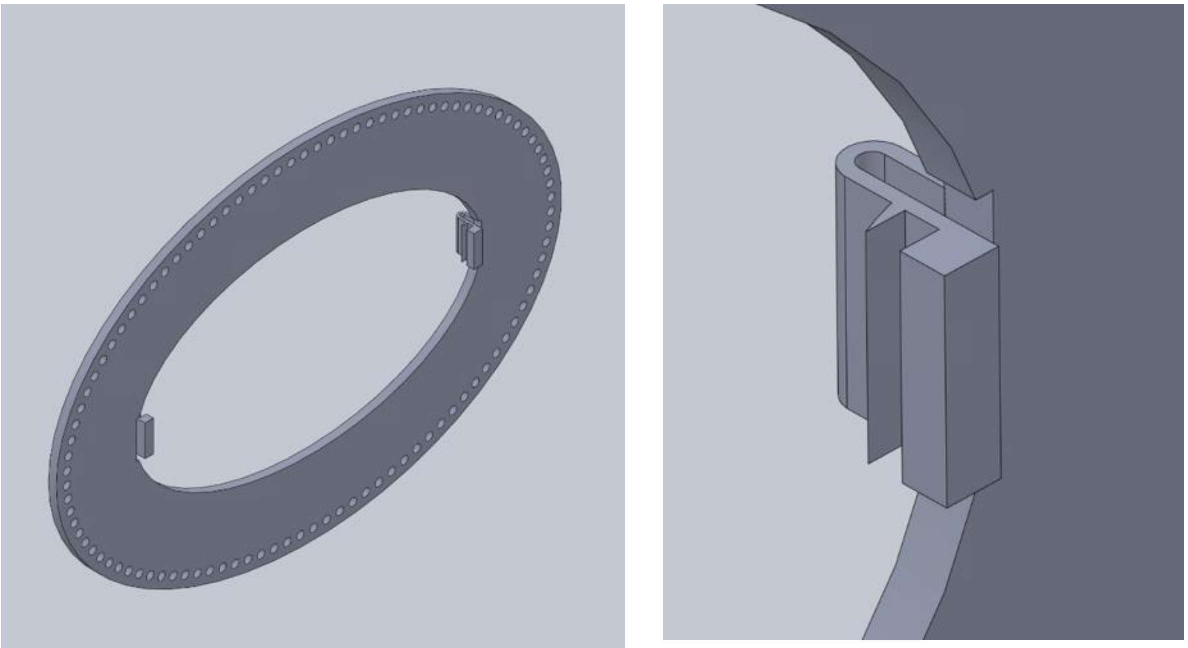


Figure 3-26: Pouch Attachment Piece Showing Clip Design

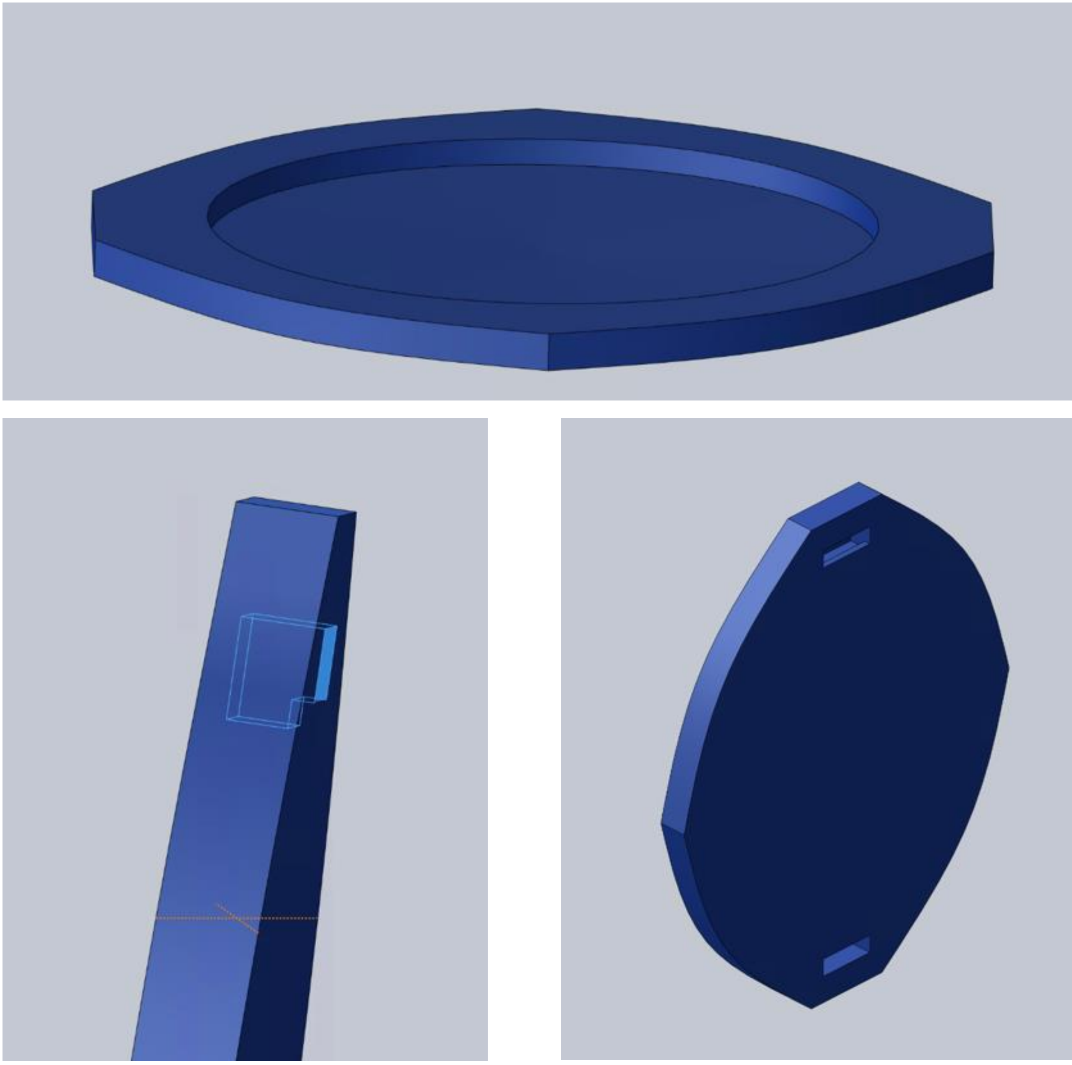


Figure 3-27: New Traumagel Pouch with Holes for Clips

As shown above, the attachment piece includes holes around the edge that are big enough for a sewing needle and clips in the center that will attach to the pouch. The assembly of the pouch and attachment piece are shown in Figure 3-28 and Figure 3-29.

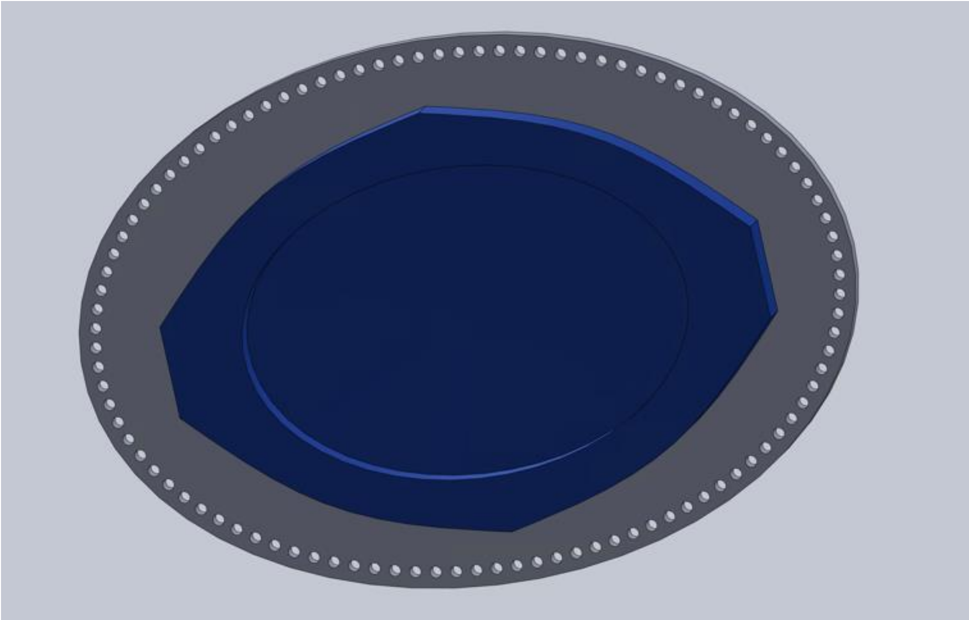


Figure 3-28: Solidworks Model of Pouch and Attachment Assembly

Figure 3-29: 3D Printed Pouch and Fin Assembly

Our first few attempts at printing the pouch and attachment piece were unsuccessful, as we ran into some issues with the fit. For example, the holes on the pouch were not deep enough and the clips on the attachment piece did not properly align with the holes on the pouch. We also noticed that the attachment piece stuck out from the pouch a bit too far, so in our next iteration we made the diameter of the attachment piece smaller as seen in the 3D printed model in Figure 3-30.

Figure 3-30: Second Iteration of Pouch Attachment

The drawings of the final attachment piece design can be found in **Appendix H**.

3.2 Objective 2: Implement a Bullet Detection and GPS System

The second component of our project was to develop a bullet detection system to identify when an officer has been shot or stabbed and allow for a distress signal to be sent to paramedics. To accomplish this, we tested different circuit configurations on a small scale, and then identified the best one to implement into our ballistic vest. We then modified and improved the configuration to get the best possible system for our needs.

3.2.1 Sensor Configurations

Resistance Change Sensor

The first method that we looked at to measure a bullet detection in the ballistic vest was to create a circuit where the resistance would change during the impact of the bullet. This change in resistance would be detected by an Arduino, which would trigger the emergency protocol. In order to create a circuit like this a piezoelectric material needed to be used. A piezoelectric material (i.e. Velostat) has the ability to convert a mechanical stress into an electric charge. To test the practicality of this idea we sandwiched a layer of Velostat between two layers of conductive material. We used an ohm meter to connect the two layers of conductive fabric which measured the resistance in our Velostat circuit. A cross-sectional view of our design is shown in Figure 3-31.

Figure 3-31: Resistance Change Circuit

The next step in the process was to experimentally determine how different stress events affected the resistance reading from the multimeter. To accomplish this, we conducted three tests using three different stress events, the first stress event was poking the strip with a finger, the second was stabbing it with a knife, and the third was smashing it with an entire hand, to simulate a punch. The results of the experiments are shown in Table 3-5.

Table 3-5: Resistance Change of Different Stress Events

Stress Event	Initial Resistance	Resistance After Stress Event	Change in Resistance (%)
Finger	2100 ohms	20 ohms	- 99.0%
Knife	770 ohms	30 ohms	- 96.1%
Punch	700 ohms	20 ohms	- 97.1%

These tests raised some concerns for the group if we were to move forward with the resistance change configuration. The goal of our project was to send data when an officer was in serious trouble and wounded. These tests showed a very similar change from a punch to a knife blow, so it is possible that if we went with this design our emergency alert could be inadvertently triggered when the officer is not in serious danger. For example, if the officer were to open the car door and hit the vest in such a way as to trigger the system it might be okay one time but if these instances piled up it would affect the reliability of the vest. Therefore, our team decided to utilize a different method for our bullet detection system.

Complete Circuit Break

The next circuit configuration that our team looked at would only be activated by a complete breakage in the wires. Therefore, the circuit would only be activated if the vest was in some way punctured. To accomplish this, we would connect a regular wire (around 16 gauge) to a power source and an Arduino. When the wire is broken the Arduino will identify the circuit has shut off and interpret that the officer has been shot. In this system the wires were laid out in a grid formation, shown below in Figure 3-32.

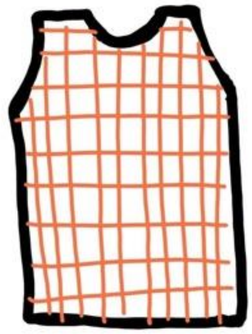


Figure 3-32: Grid Layout of Wiring on Ballistic Vest

The grid system allows for identification of the region of the bullet impact. When the vest is penetrated a horizontal and vertical wire will break. This code in the form of (column, row) allows for an accurate general location for the region where the ballistic vest was punctured. This information could also be passed on to paramedics so they would know ahead of time what equipment was required and how serious the injury is. The team decided to proceed with this design because of the benefit of only triggering when the officer was in serious danger.

3.2.2 Bullet Detection System Fabrication

The next step was to fabricate the bullet detection system. To conduct this the team first determined the best configuration for the wires. It was unfeasible to place and power each individual wire in the vest as shown in the previous section. Therefore, the team decided to bunch the wires together by creating wire strips. A single wire strip is shown in Figure 3-33.

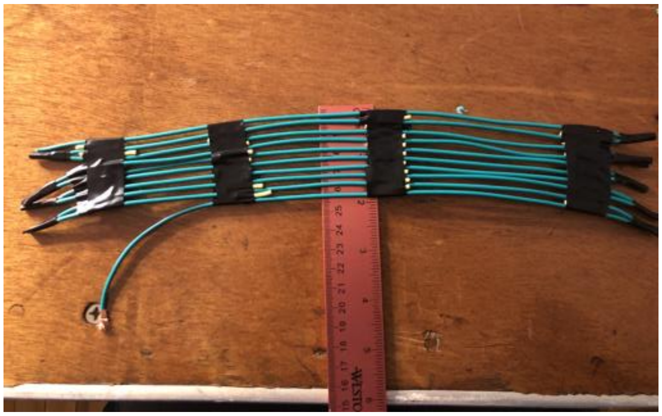


Figure 3-33: One Wire Strip

Each strip was composed of 10 wires. To space the wires out a small piece of 16 gage wire was placed in between each wire in four different spots along the strip to promote equal spacing. The spacing of the wires was absolutely crucial. If the wires were spaced too close together, there would be many unnecessary wires that would increase the weight and stiffness of the vest;

however, the further the wires were apart the greater the risk of a wire not breaking clean through. If the wire did not completely break then the vest would not detect the break and no emergency alert would be triggered. A zoomed version of the spacing is shown in Figure 3-34.

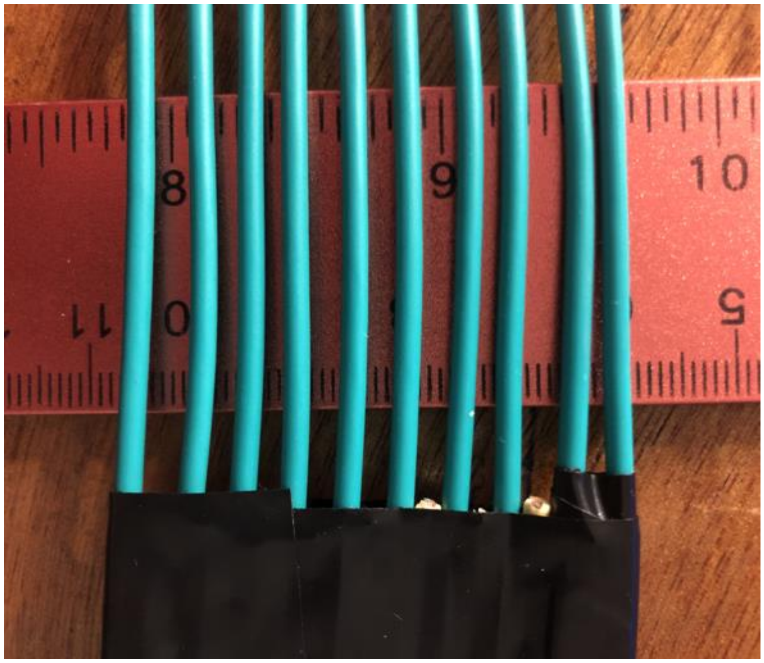


Figure 3-34: Wire Strip Spacing

The final end-to-end wire spacing was about 6mm. Meaning if a bullet struck the vest directly in between two wires as long as it was greater than 6mm in diameter it would break at least one wire. Wire strips were laid out horizontally and vertically. A diagram of the wire strips and their coding (letter or number) is shown in Figure 3-35.

Figure 3-35: Row and Column Coding

Rows were coded as numbers and were sequential from top to bottom, Columns on the other hand were coded as letters and were sequential from left to right. The final prototype consisted of six columns and seven rows and is shown in Figure 3-36.

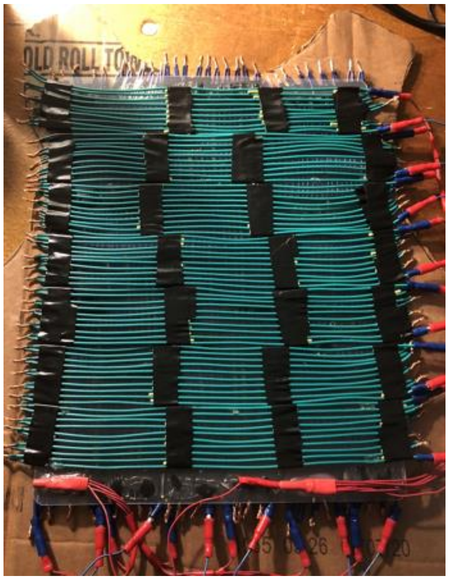


Figure 3-36: Bullet Detection Full Version

In the final version of the bullet detection system, each wire connection on the individual strips is soldered together to guarantee the best connection every time. In order to make the strips easy to connect and disconnect for preliminary testing, quick disconnect plugs were connected to the end of each strip. The positive side of the strip is connected to the 3.3 V power supply by a red wire as shown in the previous figure. The negative side of the strip is connected by a blue wire to an input pin on the Arduino. In order for the system to properly function each wire strip is connected to its own pin on the Arduino. When the connection to the pin was interrupted the Arduino would recognize that the signal had cut and output the letter or number of the wire which had broken. The completed bullet detection system added 630 grams, or about 1.4 pounds, to the total weight of the vest.

3.2.3 GPS System

The final step in the bullet detection system was the implementation of the GPS. The GPS was a vital aspect of our project because it allowed for an injured officer to be found in a timely manner. The GPS that we decided to use for our system was a u-blox NEO-6 GPS module and antenna. The GPS has a total of four pins and therefore requires very little wiring to get setup. The first pin is the input voltage which is connected to the 5V output on the Arduino. The next pin is the receive and transmit pin abbreviated as Rx and Tx, respectively, these pins are connected to two different digital input pins on the Arduino. The final pin is the ground pin which is connected directly to the ground on the Arduino. The wiring of the GPS module is shown in Figure 3-37.

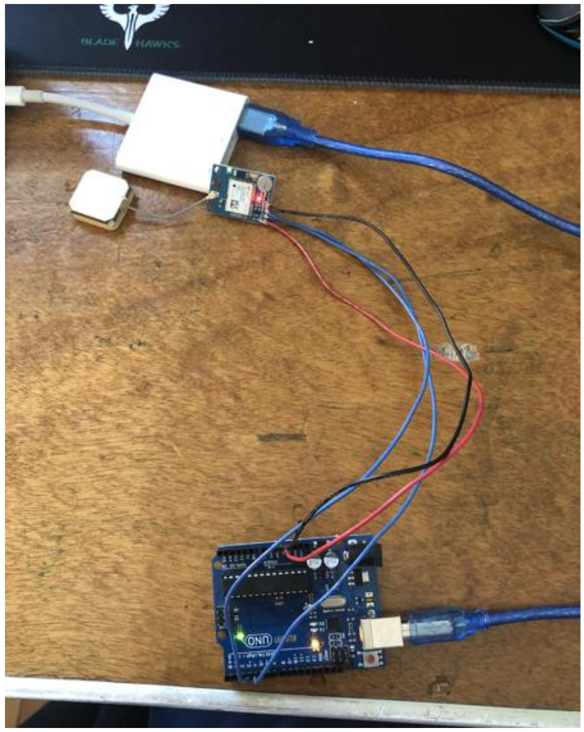


Figure 3-37: Wiring of GPS Module

The red wire represents the voltage, the black is the ground, and the blue wires represent the rx and tx pins. This GPS has the ability to collect two key pieces of information that can be used in the ballistic vest implementation. The first are the coordinates of the officer displayed as latitude, longitude. This information would be sent to the app where the physical latitude and longitude could be placed on a map. The second component that could be important is speed. If the officer is moving a couple miles an hour it could indicate to the paramedics that he is still moving under his own power. Which might suggest that the injury is not as serious as if the officer was incapacitated on the ground. The speed could even indicate if the officer is in a vehicle. All this information could be useful for the paramedics and other emergency services. The Arduino display information is shown in Figure 3-38.

```
14:01:08.461 -> Location: 42.274330,-71.803230   Speed:   2  Date/Time: 3/12/2021 19:01:08.00
14:01:08.531 -> Location: 42.274330,-71.803230   Speed:   2  Date/Time: 3/12/2021 19:01:08.00
14:01:08.598 -> Location: 42.274330,-71.803230   Speed:   2  Date/Time: 3/12/2021 19:01:08.00
14:01:09.131 -> Location: 42.274337,-71.803230   Speed:   2  Date/Time: 3/12/2021 19:01:09.00
14:01:09.201 -> Location: 42.274337,-71.803230   Speed:   2  Date/Time: 3/12/2021 19:01:09.00
14:01:09.341 -> Location: 42.274337,-71.803230   Speed:   1  Date/Time: 3/12/2021 19:01:09.00
14:01:09.446 -> Location: 42.274337,-71.803230   Speed:   1  Date/Time: 3/12/2021 19:01:09.00
14:01:09.517 -> Location: 42.274337,-71.803230   Speed:   1  Date/Time: 3/12/2021 19:01:09.00
14:01:09.588 -> Location: 42.274337,-71.803230   Speed:   1  Date/Time: 3/12/2021 19:01:09.00
14:01:10.107 -> Location: 42.274330,-71.803260   Speed:   1  Date/Time: 3/12/2021 19:01:10.00
14:01:10.212 -> Location: 42.274330,-71.803260   Speed:   1  Date/Time: 3/12/2021 19:01:10.00
14:01:10.352 -> Location: 42.274330,-71.803260   Speed:   2  Date/Time: 3/12/2021 19:01:10.00
14:01:10.420 -> Location: 42.274330,-71.803260   Speed:   2  Date/Time: 3/12/2021 19:01:10.00
14:01:10.530 -> Location: 42.274330,-71.803260   Speed:   2  Date/Time: 3/12/2021 19:01:10.00
```

Figure 3-38: Display of GPS Data Received

During the test in this image the team was walking down the street to test the capabilities of the speed and to make sure that the GPS was updating and sending appropriate coordinates. When the GPS system was integrated into the vest it was always on. By leaving the GPS always on we were able to avoid the startup time and significantly reduce the amount of time required before the GPS started to send coordinates. When the vest was punctured the first piece of information that was displayed was the column and row of the impact. Then the GPS would turn on and send data about every 150 ms to the Arduino and is accurate to about 2.5 meters.

3.3 Objective 3: Send the GPS Location upon Impact

In the case of an emergency event, our plan is to be able to activate a GPS sensor within the vest that will send the officer's location to emergency services. This should be easily achieved by connecting a GPS receiver module to an Arduino and using a GSM (Global System for Mobile Communications) module to send the signal to an app or other receiver module of the team's choice.

However, a mobile application also has its drawbacks. EMTs have stated that they are not typically using their phones and it may be counterproductive to have an emergency responder looking at their phone for information instead of preparing their gear or responding at the scene. Additionally, using a service like this would incur additional expenses for the police station and would require them to pay for cellular service on the vests as well as a database management system to send data about their officers to the application.

Despite these drawbacks, our team has begun to develop this application for use by emergency services. Even if the mobile application is not practical, the logic from this application could also be used on a tablet or screen displayed inside an ambulance to allow EMTs to continue using their hands to prepare for the scene while also being able to see the data they need.

The application uses the Google Maps API to display a map of the officer's location. This location is precise and takes in latitude and longitude coordinates that can be retrieved from our GPS sensor in future iterations.

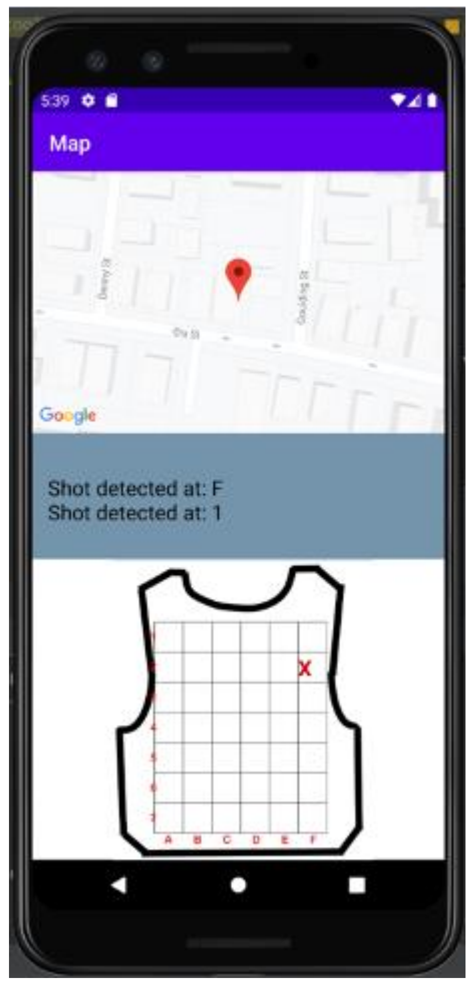


Figure 3-39: GPS and Bullet Detection Display on Mobile Application

The lower part of the application shows an image of the vest and where the officer was hit (indicated by an X). Our impact sensing should be able to detect which row and column of the vest was hit, and this row and column will be reflected on the application. Currently, the app is able to move the X to the correct position on the vest but does not interact with the Bluetooth module on the vest.

4.0 Live Fire Testing

In this chapter we will discuss the results of our live shooting tests on the vest prototype as well as our hypotheses and experiment design and protocols. Included will also be the results of the gel pouch testing using actual bullets and the transmission of data to the corresponding mobile application.

4.1 Live Fire Test Setup

The live fire test was conducted with Officer Fuller from the WPI police department. The tests were conducted on a Rubber Dummie designed for target practice. Our setup was in a sandlot with the dummy positioned in front of a sand pile as shown in Figure 4-1.

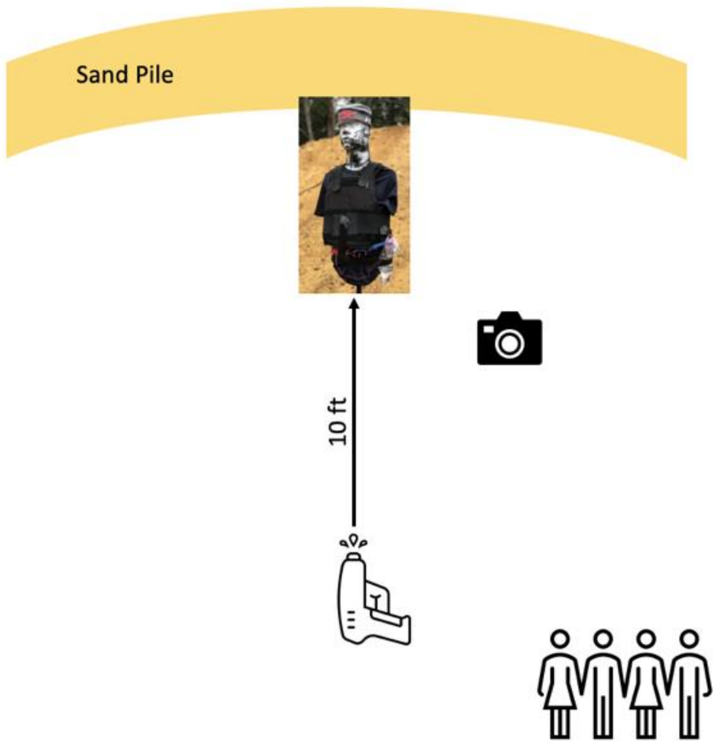


Figure 4-1: Live Fire Test Setup

In our gel pouch testing, we shot the gel-pouch undershirt on the dummy, without the bulletproof vest. We did this to isolate our gel-pouch results and to test our design materials. In addition, we only had one opportunity to test the wire grid, so we decided to test the two components separately. In the wire grid testing, we shot the bulletproof vest with the gel-pouch undershirt. Both of these setups are displayed in Figure 4-2.

Figure 4-2: Gel Pouch Testing Setup (Left) and Wire Grid Testing Setup (Right)

4.2 Design of Experiment

Prior to conducting testing, our team created a design of experiments to test the material components of the gel pouches. This included selecting isolated testing for the actual gel insert (PLA vs engineered “Flexible” resin) and the elastic material holding the gel in place (latex vs polyethylene). To determine the optimal combination of materials, we established measurable variables: size of hole each bullet made in each pouch and amount of gel secreted following puncture of the pouch.

Based on the advice of Deputy Marsh and Officer Fuller of the WPI Police Department, we developed our experiments based on an AR-15, as it is guaranteed to go through the vest. This is due to its high velocity, streamlined bullets that can easily penetrate the level IIA ballistic armor we were given to test. Although a gun with larger diameter bullets would do more damage to the gel pouches and yield better results, the bullets are not likely to penetrate the vest because the vest is designed to stop larger bullets.

Table 4-1 outlines all experiments conducted during our live fire testing. There were eight total tests done, using a combination of both a pistol and an assault rifle (listed on the table as AR-15) to shoot the PLA and resin pouches with both latex and polyethylene coverings. Each test was done by shooting the corresponding pouch from approximately 5 yards away center mass.

Table 4-1: Design of Experiments Testing Scenarios

	Material of Pouch	**Type of Gun**	**Material of Balloon**
Experiment #1	PLA	Pistol	Latex
Experiment #2	PLA	Pistol	Polyethylene
Experiment #3	PLA	AR-15	Latex
Experiment #4	PLA	AR-15	Polyethylene
Experiment #5	"Flexible" Resin	Pistol	Polyethylene
Experiment #6	"Flexible" Resin	Pistol	Latex
Experiment #7	"Flexible" Resin	AR-15	Polyethylene
Experiment #8	"Flexible" Resin	AR-15	Latex

Following the testing of the gel pouches, we shot our wire grid system to determine whether the bullet from the AR-15, or any of the other guns present would signal a breakage on our app, in turn activating the GPS.

4.3 Live Fire Testing: Gel Pouch Results

Each of the experiments listed above in Table 4-1 were carried out in the manner listed previously. We first tested the gel pouches without the presence of the ballistic vest and wire grid. Each pouch and elastic covering combination were shot and analyzed on site. To measure the chosen variables (amount of gel secreted and size of the hole created by the bullet), we weighed each pouch and all materials included before and after the bullet impact, allowing us to approximately calculate how much gel was secreted. We also used a set of calipers to measure the size of the opening produced by the bullet. As seen in Figure 4-3, the combination of PLA and Latex provided the most noticeable hole. However, the holes in the pouches remained relatively small as the velocities of the bullets were very high compared to the testing we had done prior with the airsoft gun.

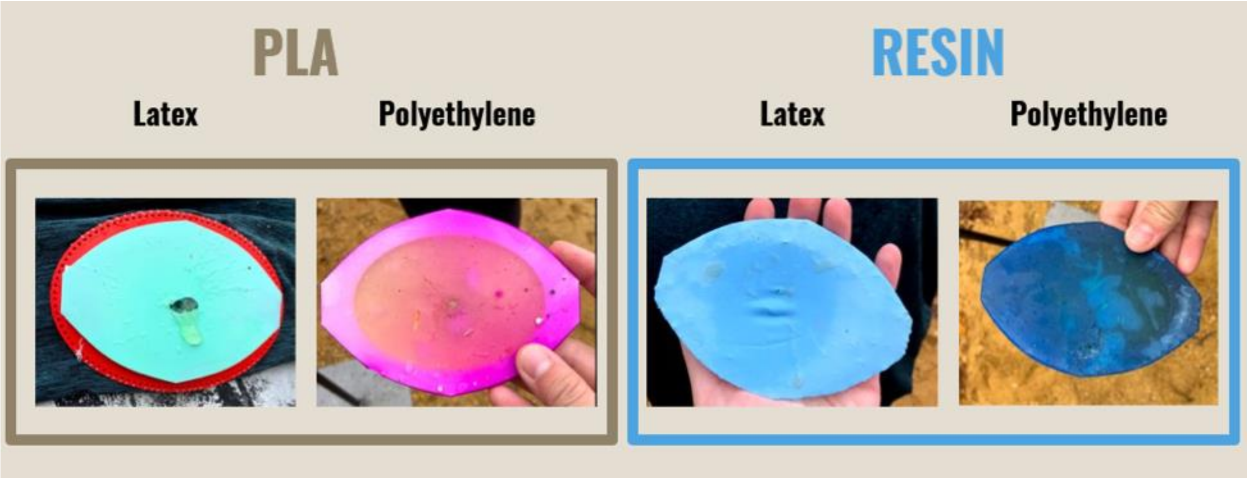


Figure 4-3: PLA vs Resin Gel Pouch Material with Altering Elastic Coverings

Table 4-2: AR-15 Test Results

Gel Pouch Insert Material	Elastic Covering Material	Hole Size (mm^2)	Weight Lost (grams)
PLA	Latex	100.81	9
PLA	Polyethelyne	10.08	6
Resin	Latex	0.00	2
Resin	Polyethelyne	10.08	0

As shown in Table 4-2. the combination of PLA and Latex created a hole with an area of 100 mm^2. It also secreted 9 grams of gel when shot. The second-best combination was the PLA with the polyethylene. This combination had the same hole size as the resin with the polyethylene, however, it secreted much more gel (6 grams vs 0 grams).

Figure 4-4 and Figure 4-5 graphically show the measured results of the gel pouch testing. You can see visually on the graph that the PLA and Latex combination has the largest opening and the largest amount of gel secreted.

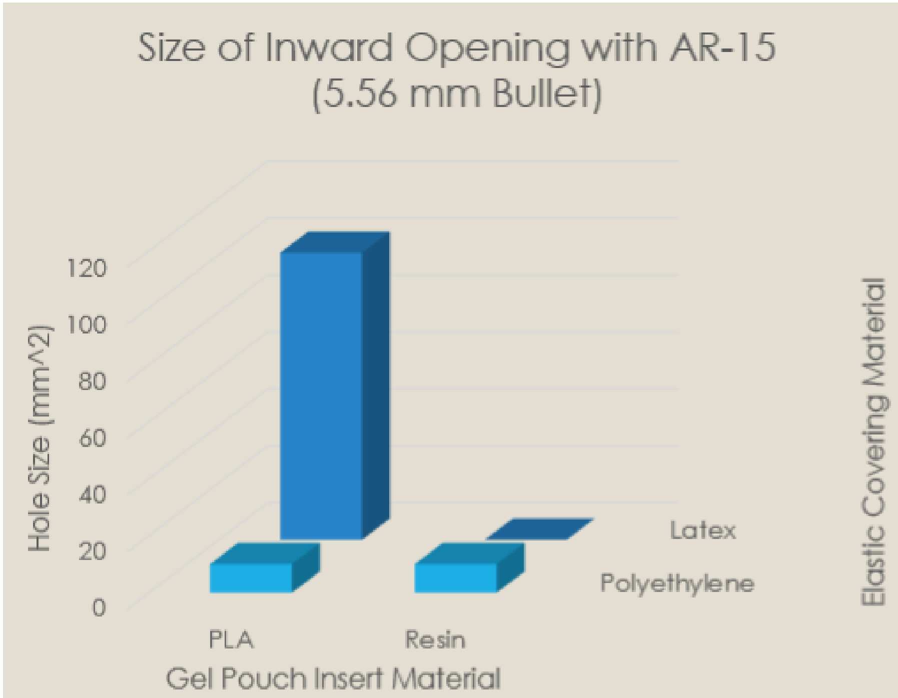


Figure 4-4: Size of Opening Produced in Gel Pouch by AR-15

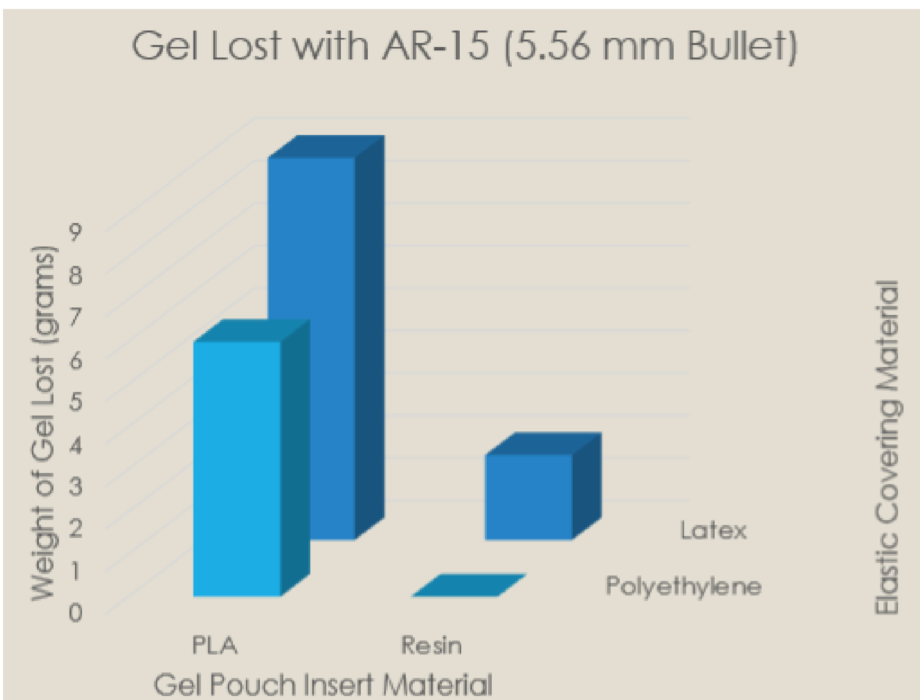


Figure 4-5: Gel Lost from Gel Pouch After Shot by AR-15

One of the contributing factors that could have caused the PLA to create a larger hole and secrete more gel than the resin, is because the PLA is very brittle. When the PLA is shot it fractures, which causes shards of PLA to break off, as seen in Figure 4-6. Therefore, when the bullet travels through the pouch material it takes some PLA shards with it, which could have caused a larger hole in the latex and polyethylene when compared to the resin. Although these shards could have given favorable results in our experiment, if an officer was wearing the vest these shards would be very unfavorable since they could get inside the officer's body and cause more problems.

Figure 4-6: Small PLA Shards on Dummy's Chest

4.4 Live Fire Testing: Wire Grid Results

Following the execution of our gel pouch testing, we then tested our wire grid system along with the application that records data taken from the attached Arduino and GPS module. Officer Stuart Fuller of the WPI Police Department was able to assist us in the testing. Although, we were able to shoot the vest with three different bullets: .22 LR, 9mm, and 5.56, only the 5.56 was guaranteed to go through the vest; therefore, for this portion of our results we will focus on the tests conducted with the AR-15 to test the wire detection system. Figure 4-7 shows a section of the resulting wires following our testing.

Figure 4-7: Wire Grid Breakage

As you can see in Figure 4-7, the wires broke upon impact from the bullet. However, because these wires were stranded instead of being one solid wire, if one of the small strands touches another piece of wire, the vest will not register that it has been shot in that location. Additionally, not every bullet fired from the assault rifle was detected by the vest. Some may have passed through the gaps between the wires as they were spaced approximately 6mm apart.

Figure 4-8 displays the application that the Arduino on the vest sends data to via a Bluetooth module. Another issue we encountered was that if the vest did register that a bullet hit the wire grid, only a row or a column were identified. No shots triggered both a row and a column to be broken.

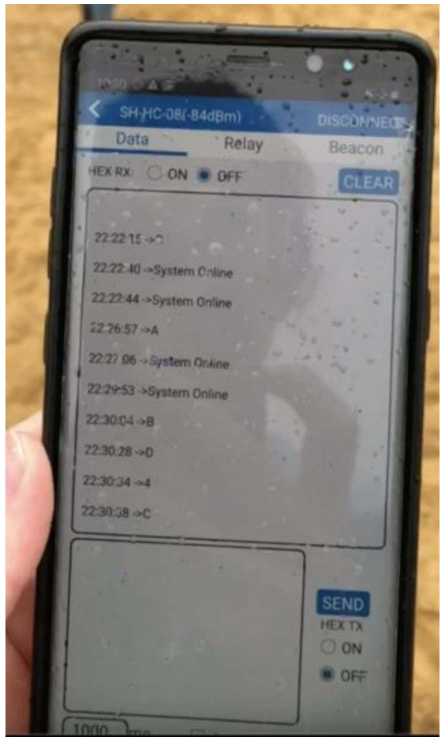


Figure 4-8: Close-up of Mobile Application Interface

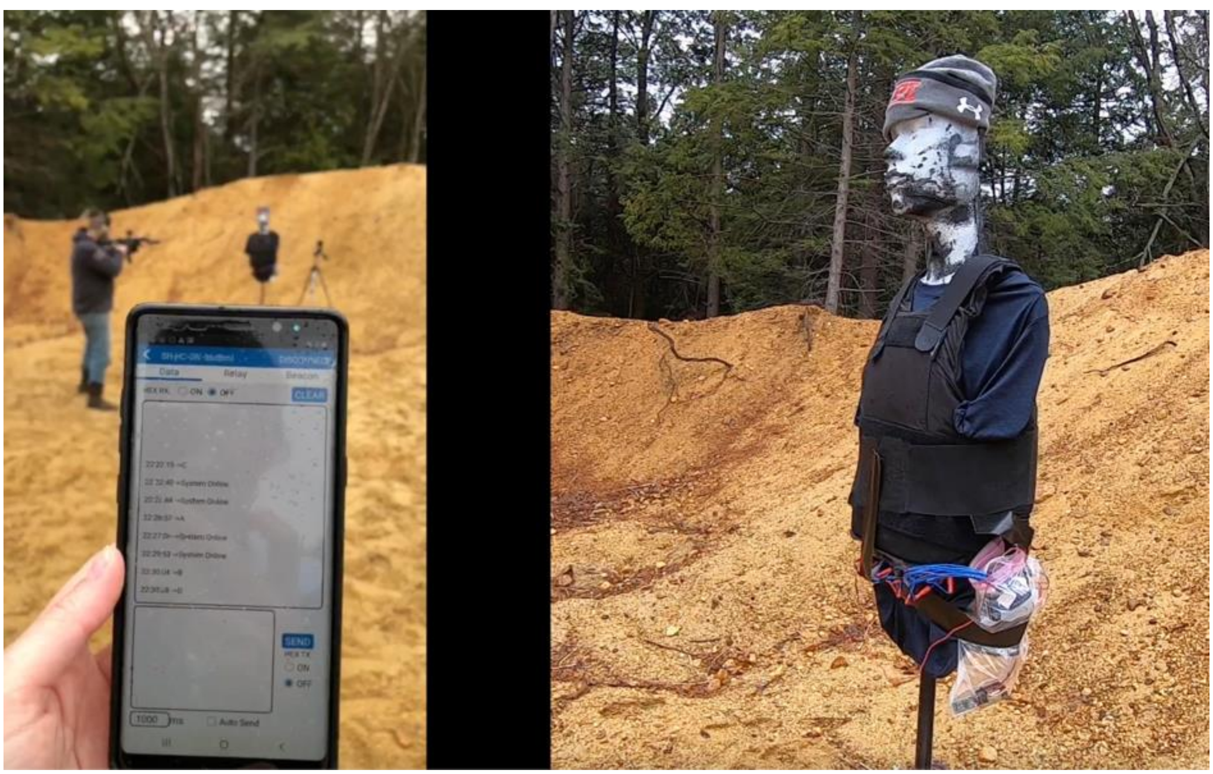


Figure 4-9: Application Interface and Vested Dummy

5.0 Conclusion & Recommendations

Following the results of our testing, there are several aspects of our project that we believe could be improved in future iterations. First, as mentioned previously, the wires we used during our testing of the wire-grid detection system were stranded. This resulted in defects in the detection system because even if two small strands were touching, the grid would not register a breakage. A solution to implement in a future iteration would be to use a solid wire. Additionally, some of the bullets went through the vest without hitting any wires. This could have been due to the fact that our wires were spaced 6mm apart. To improve this, our team suggests that wires have minimal spacing to eliminate this issue.

For our gel pouches, we recommend continuing searching for a material that can be both comfortable for an officer while also being able to create a large enough hole against a wound to secrete the appropriate amount of gel. Even though our tests concluded that PLA was the best at doing this, we do not see a practical application for it. As described in the background, PLA is a solid plastic that is quite brittle. This can prove to be quite uncomfortable if worn all day against the skin. Also, when broken, it could shatter, and shards could enter the resulting wound. This could lead to further complications of the injury, which we want to avoid. With the high cost to create a prototype implementing the hemostatic gel, our testing did not yield necessary results to consider this type of design. Since a large amount of gel is needed directly inside the area of the wound, the hemostatic gel would be most effective in the form of a syringe an officer carries on themselves until an electronic mechanism can be designed to appropriately apply the correct amount of gel to a wound. In addition, for ease of testing, we only tested the heart pouch, assuming that the larger stomach pouch would yield similar results. However, this may be an oversight and the larger pouch could yield different results.

Finally, during our testing, we used a Bluetooth transmitter to send the data from the vest directly to the mobile application. In the next iteration, we recommend the use of GSM Module to connect to a cellular signal for long range data transmission capabilities. In a working model, this would allow the data to be transmitted to appropriate first responders who are dispatched. In addition, we recommend that additional medical statistics such as an officers pulse, oxygen level, blood pressure, name, allergies, and important medical history be information that is recorded and sent to EMTs along with the location of the wound.

Finally, during our background research we noted that most officers died due to head injuries, compared to any other bodily injury. Although we wish this is something we are able to tackle this year, we did not have enough time to implement a design. Our team sees a huge gap in police helmet technology, and this is something we recommend a future MQP team to take on.

Overall, we believe that with some improvements to our design, it will be a useful device that could help modernize police technology and further protect our officers. Through the use of the wire grid, EMTs will be able to be notified of the exact location an officer has been shot on their torso. That way, EMTs can understand if any vital organs may have been hit before arriving at the scene. In addition, the GPS feature allows the EMTs to identify which officer has been shot, and their precise location so no time is wasted locating them when arriving on scene. Both of these designs allow the EMTs to have a general idea of which officer is in the most fatal position, who to assess first, and where they are. Furthermore, the TraumaGel can help to close off the wound and limit bleeding until the EMTs arrive at the scene. Our design focuses on minimizing the time it takes for EMTs to locate wounded officers and do their assessments, preventing bleeding in the meantime. The implication of this design is novel in the police and medical field and should be further explored in future years.

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7.0 Appendices

Appendix A: FBI Data for Officers Feloniously Killed

Circumstances of Officers Feloniously Killed											
	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	Total
Ambush Situations	15	15	6	5	7	4	17	5	11	2	**87**
Attacks During Arrests	14	23	12	6	4	5	9	4	3	3	**83**
While Investigating Suspicious Perososns	8	5	8	5	7	8	9	6	3	1	**60**
During Traffic/Foot Pursuits/Stops	7	11	8	2	9	6	4	11	10	12	**80**
Answering Disturbance Calls	6	7	4	4	11	3	13	3	6	7	**64**
Tactical Situations	3	9	5	4	4	7	6	6	6	9	**59**
Investigative Activity	2	1	1	1	5	1	5	6	12	9	**43**
Prisoner Transport	1	1	3			2		1	2		**10**
Mental Illness			1		3	2		1	1		**8**
Unprovoked Attack					1	3	3	3	1	5	**16**
Total	**56**	**72**	**48**	**27**	**51**	**41**	**66**	**46**	**55**	**48**	**510**

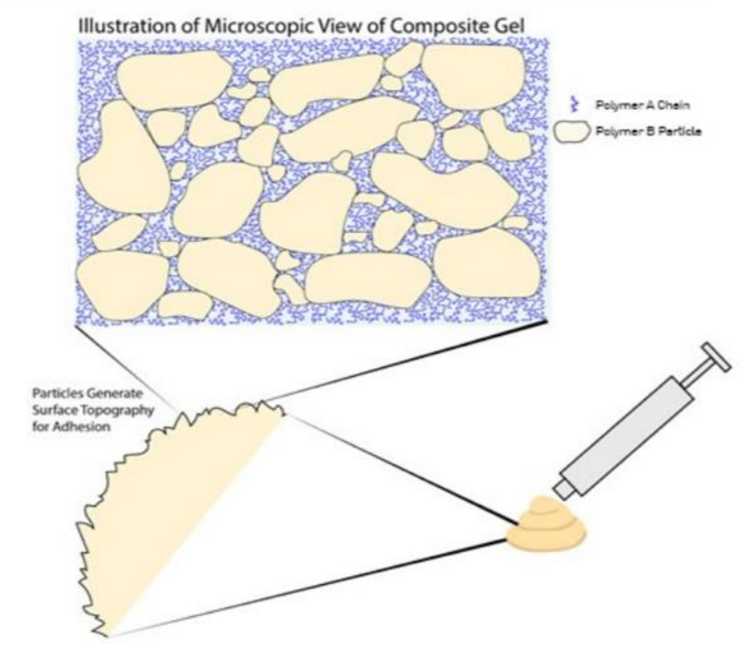
Officers Feloniously Killed With Firearms While Wearing Body Armor											
	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	Total
Front of Head	7	10	11	4	11	8	14	11	16	6	**98**
Side of Head	10	9	4	5	9	1	6	6	5	3	**58**
Rear of Head	3	8	1		2	4	2	1	4	2	**27**
Neck or Throat	5	2	4	3	3	3	3	3	6	2	**34**
Shoulder										2	**2**
Shot in Upper Torso/Chest	7	12	1	5	5	4	8	7	7	8	**64**
Front Lower Torso/Abdomen	3	1	1			1	2	1	1	2	**12**
Rear Upper Torso	2	3	1		4	2	1			1	**14**
Rear Lower Torso		1		1		1	2			2	**7**
Waist Groin										1	**1**
Below the Waist Front						1	1				**2**
Below the Waist Rear	1					1	1				**3**
Multiple Wounds/Not Reported					1	1	7	2	1		**12**
Total	**38**	**46**	**23**	**18**	**35**	**27**	**47**	**31**	**40**	**29**	**334**

Appendix B: Vetigel Chemical Structure

For Vetigel to achieve its unique chemical properties, it is composed of two plant-based polymers which react with each other to morph to the skin cells it is applied to. Referred to as polymer A and polymer B, both substances are naturally derived which provides natural variability based on source material.

As previously mentioned, polymer A is extracted from the cell wall of seaweed/algae, serving as the primary scaffolding component for polymer B. Polymer A has the ability to be crosslinked by a positively charged divalent cation, having polyanionic properties. This creates an attraction to polymer B, a polycationic particle, when dispersed in the solution. Essentially, polymer A chains are attracted to positively charged polymer B particles that are dispersed in the solution. This ionic interaction creates a mix of strong cohesive and adhesive properties, forming a robust seal.

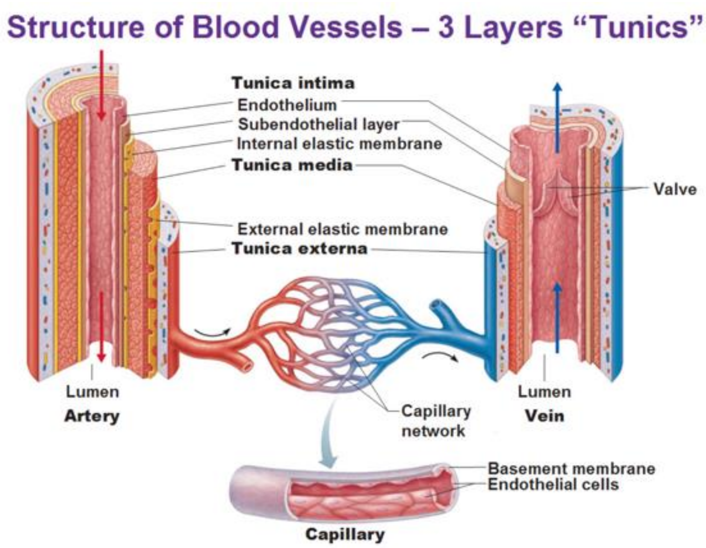
This process is referred to as dissolution, where a solute dissolve in a solvent to form a solution (polymer B dissolves in polymer A to form a hemostatic gel agent). The figure below shows the composition of Vetigel on a microscopic scale. To understand how polymer B creates the gel effect, the dissolution of polymer A by itself in water forms a viscous, polymer gel. This was not the desired viscosity and texture for the Vetigel product, but with the interaction of polymer B, a granular composite material is formed. This is best described as a flowable, thick paste that adheres to tissue and forms a physical barrier to stop bleeding.



Microscopic view of Vetigel with polymer A and polymer B.

To better understand the morphing of Vetigel to the body's tissue after application, it is necessary to look into how hemostasis is achieved. This is broken down into two sections: Primary hemostasis and Secondary hemostasis. The structure of blood vessels figure shows a diagram on the anatomy of blood vessels to better understand the process of hemostasis.

Primary hemostasis incurs an injury to the vessel wall, forcing the vessel to constrict in an effort to restrict blood flow. Presence of the sub-endothelial layer allows blood platelets to adhere and activate which forms a plug to recess the bleeding. In secondary hemostasis, coagulation cascade occurs. This initializes a series of biochemical reactions which leads to fibrin polymerization. The process of creating fibrin further stabilizes the initial plug.



Structure of human blood vessels.

Once Vetigel is introduced to the hemostasis process, the hemostatic gel agent acts as a catalyst. Upon application, Vetigel forms a fibrin patch over the wound and initializes fibrin polymerization within 15-20 seconds.

Appendix C: Manufacturing Processes

Additive manufacturing, or 3D printing, is the construction of a three-dimensional object by means of layering material on top of itself. This process is a less expensive alternative in the manufacturing space and can be used for designing, modeling, and prototyping for a variety of applications. Other benefits include the ability to manufacture complex structures, minimize waste, and prototype quickly (Ngo & Kashani, 2018). The most common method of additive manufacturing is known as fused deposition modelling. This method of 3D printing uses continuous filaments to print layers of material and includes several key benefits such as low cost and high speed. Its drawbacks, however, include weak mechanical properties, a layer-by-layer appearance, and poor surface quality (FDM).

Printing using additive manufacturing provides many options, from material to print, shape to model, machine to use, and much more. Common materials include polylactic acid (PLA), acrylonitrile butadiene styrene (ABS), PETG, ASA, and Polycarbonate. The table below documents the primary pros and cons of PLA (SIMPLIFY 3D, 2020), which is one of the chosen materials for this project.

PLA Pros and Cons (SIMPLIFY 3D, 2020).

	PLA
Pros	Low Cost
	Stiff/Good Strength
	Environmentally Friendly
	Dimensional Accuracy
Cons	Low Heat Resistance
	Can Be Brittle
	May need Extra Cooling Measures

In comparison, engineered resins encapsulate rubber-like qualities which are printed using rapid prototyping technologies. These technologies have the capability to produce complex shapes, smooth surfaces, and intricate details by layering liquid photopolymer and curing it using UV light. Our team focused on the Form2 machine which has a variety of material options through the Formlabs material website. Based on WPI's on-campus offerings, our team selected the Flexible 80A resin with material properties listed in the table below. As described on the Formlabs material website, the flexible material is the most stiff, soft-touch material they offer and simulates rubber or thermoplastic polyurethane (TPU). Important for testing purposes, the material is also described as being able to withstand bending, flexing, and compression, even through repeated cycles (Formlabs, 2021).

Formlabs "Flexible" Material Properties.

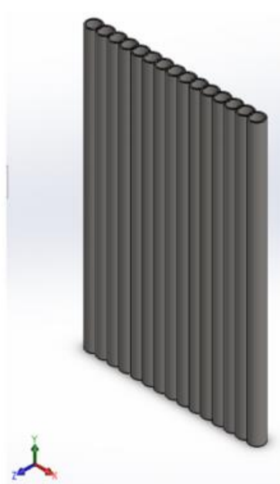
	METRIC[1]		IMPERIAL[1]		METHOD
	Green	Post-Cured[2]	Green	Post-Cured[2]	
Mechanical Properties					
Ultimate Tensile Strength[3]	3.7 MPa	8.9 MPa	539 psi	1290 psi	ASTM D 412-06 (A)
Stress at 50% Elongation	1.5 MPa	3.1 MPa	218 psi	433 psi	ASTM D 412-06 (A)
Stress at 100% Elongation	3.5 MPa	6.3 MPa	510 psi	909 psi	ASTM D 412-06 (A)
Elongation at Break	100%	120%	100%	120%	ASTM D 412-06 (A)
Shore Hardness	70A	80 A	70A	80 A	ASTM 2240
Compression Set (23 °C for 22 hours)	Not Tested	3%	Not Tested	3%	ASTM D 624-00
Compression Set (70 °C for 22 hours)	Not Tested	5%	Not Tested	5%	ASTM D 395-03 (B)
Tear Strength[4]	11 kN/m	24 kN/m	61 lbf/in	137 lbf/in	ASTM D 395-03 (B)
Ross Flex Fatigue at 23 °C	Not Tested	>200,000 cycles	Not Tested	>200,000 cycles	ASTM D1052, (notched), 60° bending, 100 cycles/minute
Ross Flex Fatigue at -10 °C	Not Tested	>50,000 cycles	Not Tested	>50,000 cycles	ASTM D1052, (notched), 60° bending, 100 cycles/minute
Bayshore Resilience	Not Tested	28%	Not Tested	28%	ASTM D2632
Thermal Properties					
Glass transition temperature (Tg)	Not Tested	27 °C	Not Tested	27 °C	DMA

Appendix D: Previous MQP Gel Casings

The previous 2019 MQP team researched previous MQP designs that have dealt with ballistic vests and chose to incorporate some of the features into their design. One of these additions was a hemostatic agent to induce blood clotting around wounds beneath an officer's vest, as previously mentioned in Section 2.4. To prevent all of the gel from escaping if the vest is punctured once, the team designed a multi-pocketed silicone container to store the gel. This design was originally based off of cylindrical bubble wrap, as seen in the figure below. The designed tubing can be seen below that in the Solidworks model figure.

Ten-Inch Long Bubble Wrap Tubes

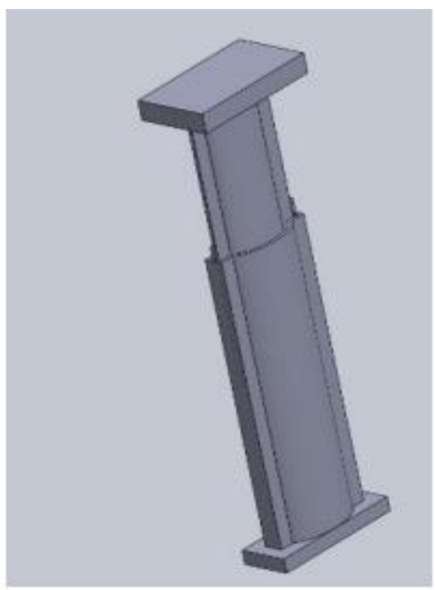
They assured the designed silicone tubing structure was strong enough so that if the wearer were to fall, the container would not rupture under the load.



SolidWorks Model of Multi Pocketed Gel Tubing

The gel container is made of liquid silicone that is molded and hardened. The mold was 3D printed due to cost effectiveness and ease of producing compared to machining a stock material. The tubes are designed to be replaced individually if they are damaged and are meant to fit in the area of the vest designed for the ballistic plate. The previous team chose silicone as the material for their container because it is light weight, yet has a yield strength that will not allow fractures under normal stresses. Additionally, it has poor adhesive properties which will be beneficial for molding processes as the team wants to be able to remove the casing from the mold with ease. If needed, a mold release can be applied to a mold before pouring silicone in. Mold release is an agent that coats the surface of the mold to prevent other materials from bonding to the mold surface. Silicone has great elasticity and restoring force, cures fast, has good heat resistance, tear resistance, and biocompatibility with resistance to bacteria growth (Simtec, 2020). The heat resistance of silicone ranges from -100 to 200 degrees celsius, and will not elongate at high temperatures while remaining flexible at low temperatures (Kim et al).

The 2019 MQP team’s first mold design was an insert to be put in another block, as seen in the Solidworks models below. This design was unsuccessful because the mold was hardened shut and they were unable to open it to retrieve their silicone container.



SolidWorks Model of First Iteration Gel Mold

Appendix E: Interview Questions

E.1 Questions for Police

- What is your name?
- What is your title? What department do you work for?
- Past officer history?
- What is the current procedure if you get injured (do they have an emergency button, just radio in?)
    - How do you contact to let people know
- Does your station require you to wear the vest at all times? If not when?
- Does your station require you to wear body cameras?
    - How is it attached? Straps? Integrated onto the vest?
- Tell me what your current vest is like
    - kevlar or other material?
    - Lightweight or heavyweight
    - Bulletproof and stab proof? *(need to look more into this bc I know they are different but idk if you can have both)*
    - Does it have a place for a body camera? How does it attach?
- Do you have any current problems with your vest? Things you don't like about it?
- What are things you would want on your vest?
    - Do you think it would be beneficial to add trauma-gel, heart rate sensors, oxygen sensors, gps?
- What is more important to you? Weight/comfort or extra technologies?
    - ___ extra pounds for the trauma-gel (hemostatic gel)? Would that be worth it?
- Would you / do you ever wear shoulder pads or a helmet?
    - What type of helmet would you prefer to wear, if/when you wear one?
- What is the procedure when leaving your designated county, town, etc?

E.2 Questions for EMTs

Paramedic/ EMT

- What is your name?
- What department do you work for? Past departments?
- How many years have you been working as a paramedic/ EMT?
- What is your protocol for different wounds?
    - Stab wound
    - Bullet wound
    - What about for different parts of the body?
- What are some important vital signs / information that would be helpful to know when arriving on a scene?
    - Heart rate
    - Oxygen
    - Location of the wound?
    - Are the other sensors we aren't thinking of?
    - Allergies?
- How do you identify a patient's medical history?
    - In a situation where a patient is unresponsive, what is your protocol for administering medication?
    - How/when do you get that info
- How do you prioritize which person you help first?
    - If you assess on scene, what information would be helpful
    - Would it be helpful to know beforehand, what and where the wounds were?
- Is there anything you wish you had?
    - Technology? Information?

Appendix F: Interview Transcripts

F.1 Interview with EMT Jon Vanderburgh

Paramedic/ EMT
What is your name?
- Jon Vanderburgh

What department do you work for? Past departments?
- EMT at Medstar Worcester

How many years have you been working as a paramedic/ EMT?
- 3 years

What is your protocol for different wounds?
- Stab wound
- Bullet wound
- What about for different parts of the body?
    - First do a full body assessment. Make sure only stabbed once. Apply direct pressure. Try to stop building. Use bandages, control the building and drive fast. For bullet wounds try to control the bleeding. If anywhere in the chest, look for bubbling which shows that a lung was punctured, Use an occlusive dressing so that the airflow doesn't cause bubbling and make it pop off. Never dealt with a gunshot, but in the case there would be a very rapid assessment and the other partner on duty handles coordinating the hospital.

What are some important vital signs / information that would be helpful to know when arriving on a scene?
- Heart rate
- Oxygen
- Location of the wound
- Are the other sensors we aren't thinking of?
- Allergies?
    - Pulse, respiratory rate and blood pressure. Those 3 are essentials. Depending on the situation will check pupil size if questioning head injury. Some trucks have pulsox that reads oxygen level. It would be nice. Make it a point to ask for medical history. What medication they take.

How do you identify a patient's medical history?
- In a situation where a patient is unresponsive, what is your protocol for administering medication?
- How/when do you get that info?
    - Ask any bystander if they know them. If not, continue to transport to hospital, if they've been to the hospital before that info can be pulled. Can take the patient to

any hospital they want. They can call medical control (doctor) if that would be advisable.

How do you prioritize which person you help first?

- If you assess on scene, what information would be helpful
    - Triage the patients. Ask if anyone can stand and walk, and if they can, they are at the lowend of priority, Make sure no head injuries and they are alert and oriented. If mass casualty, people who are unresponsive are given a black card are not a priority. Unresponsive child overrides an unresponsive adult. Never had to deal with that.
- Would it be helpful to know beforehand, what and where the wounds were?
    - It would be helpful to know where the wounds were. The one danger is tunnel vision. You would focus on that immediately and there could be tunnel vision. You would still perform a full assessment. You can mentally ready yourself.

Is there anything you wish you had?

- Technology? Information?
    - It would be helpful to know where the wounds were beforehand. The one danger is tunnel vision. You would focus on that immediately and there could be tunnel vision. You would still perform a full assessment. You can mentally ready yourself. A better understanding of the scene would be better. Usually given a very simple explanation. Location and chief complaint and sometimes male or female. It would also be helpful to where exactly the patient is and where to park. If the patient was dragged to a new area it would be helpful to know where. Every bit of information is good information. If I could locate the police officer, that would be amazing.
    - I would trust vest readings if the vest is shown to be accurate. They would still do assessment. But it would help. Especially blood pressure because it is so loud. If there is a wound in the chest, remove the vest. We were presented trauma gel, it would be fantastic if we had that, especially with the way things are going.

F.2 Interview with Officer Mike Capps - MA State Police Trooper

Name and work experience?

- Mike Capps
- 27 years with the MA State Police Department

What is the current procedure if an officer is injured on duty?

- Every officer in the state police rides alone for shifts
- They have to radio in to call for backup

Does your station require you to wear the vest at all times?

- Not required to wear a vest, it is optional. However, the officers who choose to wear the vest wear it in all scenarios while on-duty.
- About 70% of MA State Troopers choose to wear the bulletproof vest.

Does your station require you to wear body cameras?

- Depends on department for body cameras, as it is easier for smaller departments to fund body cameras whereas the large organization of state police is more difficult to incorporate.
- However, the state is in the works to get body cameras
- 2000 officers and it’s very expensive at the state level, so they are introducing a pilot program of 20-30 officers to start the process.

Tell me what your current vest is like. Do you have any current problems with your vest?

- Biggest issue is comfort!
- Kevlar is the ballistic material, carry is polyester
- Very hot in summer
- Nor stab proof
- Kevlar is stab resistant, but more designed for ballistics; could diminish penetration
- Switching over to external vest instead of wearing a vest underneath a uniform
  - Main reason in department during interrogation, you can take it off while doing paperwork so it's not as hot
  - More people would be apt to wear the vest so it’s less hot; hot in summer but also in winter doing paperwork
- Current vest weighs 3-4 pounds
- **Vest is bulky and traps sweat; not breathable is the primary issue, NOT weight**
- Adding the gel would be a very beneficial component and would be valued over weight

What things would you like to add-on to your vest?

- Some carriers have tails; no ballistic material in tail of carrier; helps keep the vest in place and is tucked into place

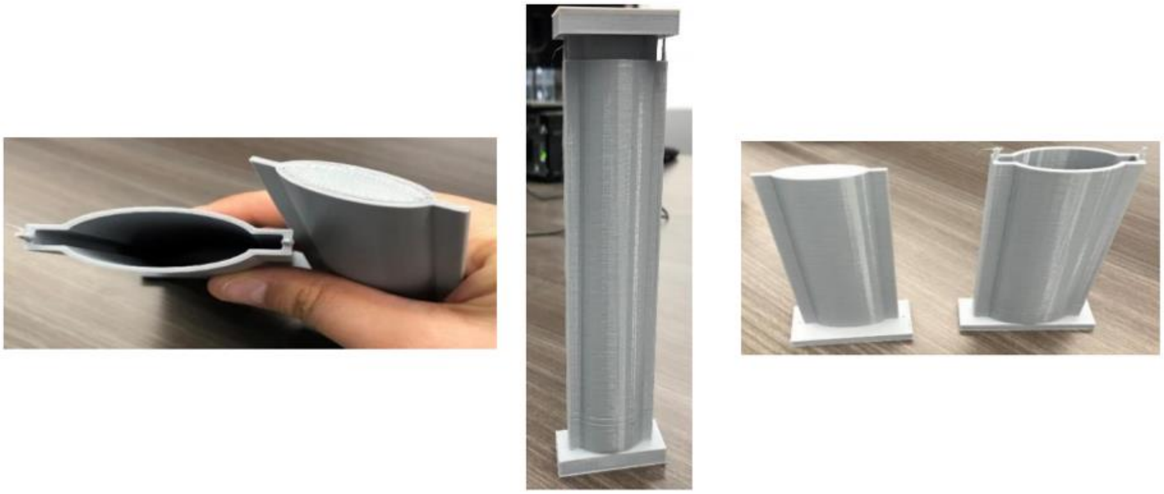
- A lot of people have been killed because bullet penetrates below vest area
- Put gel in thin layer within that tail to add a level of protection
- Bottom of vest cant be below where the belt is; only goes to belly button or inch below
- Mark Charbonnier (94) got killed wearing a vest getting shot around belt area and hit abdomen; bled out
    - https://www.odmp.org/officer/702-trooper-mark-s-charbonnier
    - https://www.upi.com/Archives/1994/09/02/Mass-trooper-fatally-shot/5184778478400/
- Vest carrier with gel layer could prevent this type of fatality

Are there any misconceptions about putting on a bulletproof vest?
- A lot of people think vest = good to go; safe mindset but this isn't the case, as a ballistic vest only offers limited protection
- Many vulnerable areas on a vest
- Front panel and rear panel meet there is a gap which is vulnerable
- Fit for an overlap, but enough space for a bullet to slide through
- Armpit straight down to hip is VULNERABLE
- Mike puts front panel OVER rear panel flap because most time facing the front in a shootout
- Other way the bullet could go under rear and slide through
- Concentrating gel in vulnerable areas could save lives which couldn't be protected by the bulletproof vest

Do you ever wear a helmet while on-duty?
- Only wears a helmet in riot situations
- Grab riot bag with helmet, baton, face shield, gas mask (for average trooper)
- Specialty teams have more advanced gear with paw platoons
- Helmets aren't used enough to focus on improvements
- Only a handful of times in 27 years he's put riot gear on
- Riot helmet that he has was given 27 years ago, and he hasn't gotten a new one
    - Every 5 years the department is issued new equipment, but the older equipment still works, just that the manufacturer doesn't guarantee this for liability issues
    - Most small departments don't have the resources or funds for new equipment, so they take whatever equipment they can get which is better than no equipment
- Motor vehicle crash can be attributed to head injury stat
    - Pursuit, going through a call, hit by another vehicle

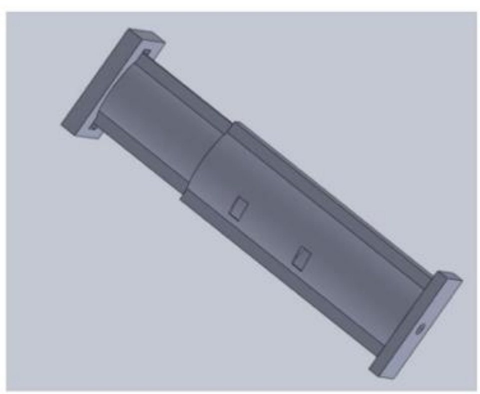
What is the procedure when leaving your designated site?
- Jurisdiction throughout the state
- Counties don't matter; NO county police force

- County sheriffs are correctional facilities; i.e. jail
- Worcester sheriff's department is strictly jail guards for Worcester county correctional facilities
- Dispatch calls to NH, once you cross over you can continue as a secondary vehicle
- NH vehicle would take over primary; will be in NH custody after arrest
- Charged in NH as a fugitive in NH and then released to custody in MA
- Pursuits are minimal and limited pursuit policy; MAJOR liability
- Even on State level; terminate pursuit anyway because it's not worth it
- Used to be lax, but over the years too many injuries so not worth it now
- Cameras help with identify people, so there is no need to risk a pursuit



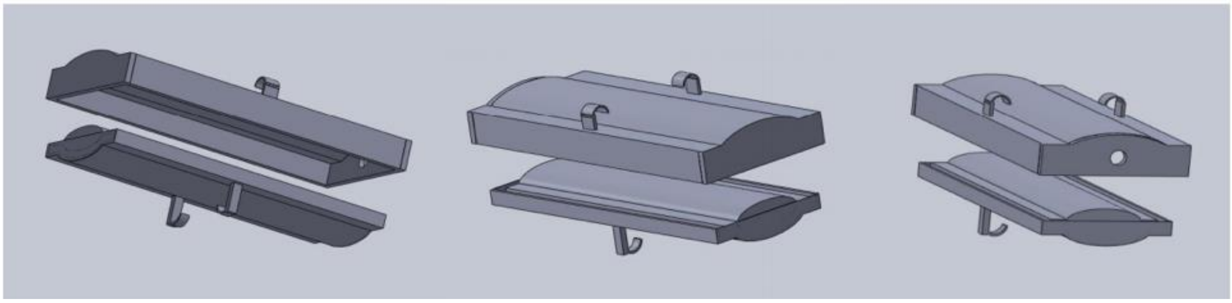
3D Printed Parts for First Iteration Gel Mold

The second mold design still used PLA as the material, as other MQP groups at the time had no issues with the PLA and silicone bonding to each other, but it was now a two part mold that snapped into place, as seen in the figure below. Their goal was to eliminate air gaps that could have been produced in the previous design. A hole was made at one end of the mold to provide a place to insert the gel with a syringe. Small holes were also added to the sides of the mold to reduce air bubbles in the silicone. The silicone hardened and the mold was not able to be opened without damaging the silicone. The team felt that the suction causing the mold to stick together was due to friction, so to reduce this, they increased the surface area where the two pieces came together.



Solidworks Model of Second Iteration Gel Mold

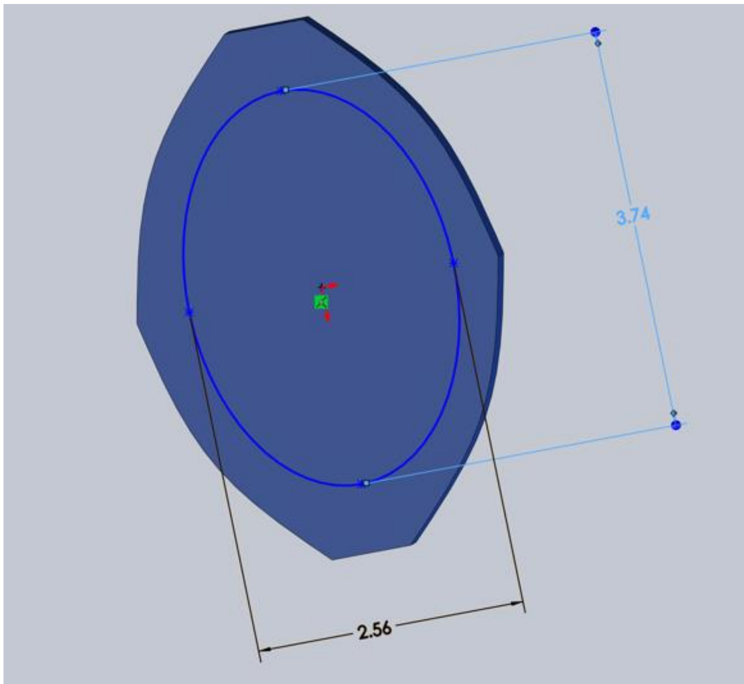
The third mold iteration had this increased surface area implemented, and they created a horizontal two part mold (seen below). Additionally, the side holes on the mold were removed because too much silicone would seep out. Handles were added as well to easily separate the mold once cured. However, due to COVID-19, the third iteration mold was never produced or tested.

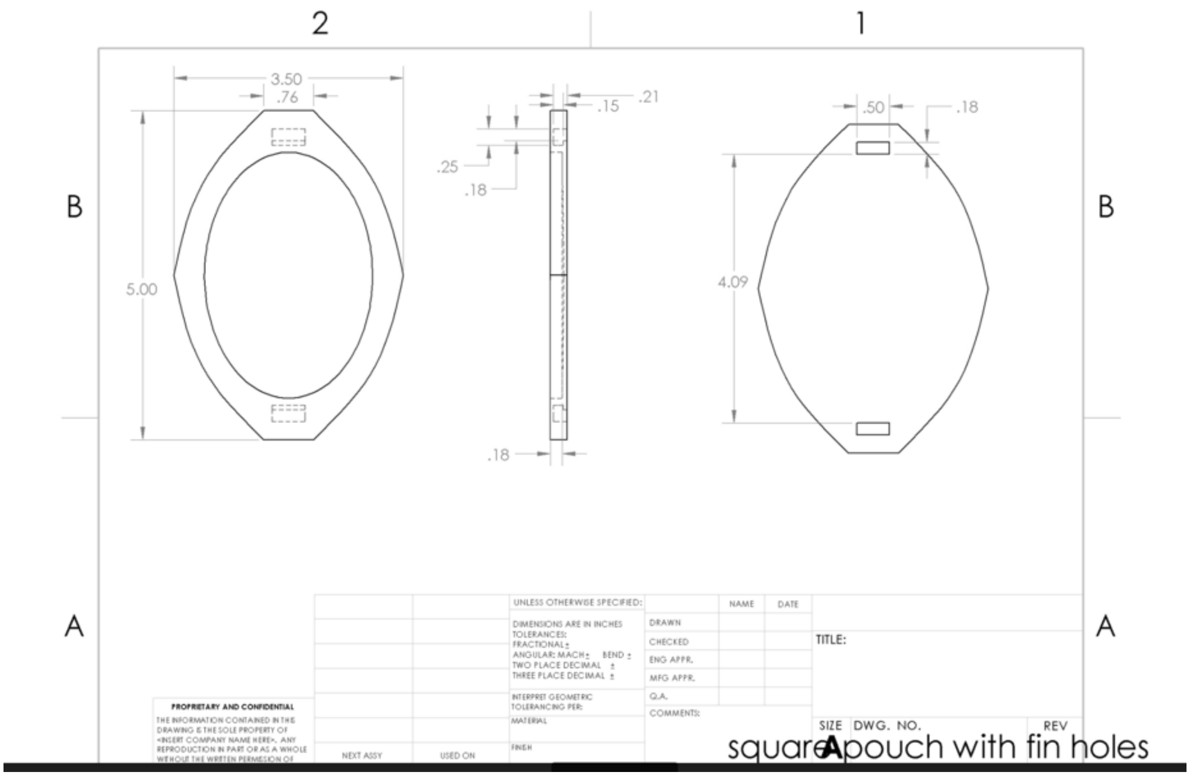


SolidWorks Model of Third Iteration Gel Mold

Once their silicone mold was formed, the previous team ran a series of tests to ensure functional requirements, such as withstanding body weight stresses and impacts, were met. Using ANSYS workbench software, the team was able to confirm the mold met their requirements. They conducted a test in which a uniform load was placed on the silicone container using two solid fixed plates on either side. These plates were each given 1000N of force in opposite directions. They assumed 1000N was the max that the container would typically see from a wearer. The team also planned to fire three rounds of simulation bullets from handguns and rifles to see how the mold would act from a bullet impact. The shots would be from 20, 40, and 60 yards. Overall, the previous team thinks the design, material, and molding process for the gel container can be improved upon if it is further researched.

Appendix G: Drawings of Final Gel Pouch





Appendix H: Drawings of Pouch Attachment Piece