Kevlar and Blunt Force Trauma

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1. Overview

This project started because I wanted to find an easy way to determine the blunt trauma forces on a person wearing a Kevlar vest when struck by a projectile. In order to do this I needed a pressure sensor to measure the forces, so I decided to use eggs. Eggs are very convenient because they break at a fairly consistent pressure, and give a very good indication when that pressure has been reached. What I discovered was that the force required to break an egg was not something I could simply look up on the Internet, but something I had to determine for myself.

To determine how much force is required to break an egg, I built an egg crusher from wooden boards and dowels. Once I knew how much force was needed to break an egg on its own I needed to test how much force would be needed to break an egg embedded in ballistics gel. The egg needed to be embedded far enough back so that the projectile wouldn't just break the egg on impact but would break from the shockwave. The problem was that the egg crusher wouldn't create a shockwave, so it couldn't be used to measure the forces.

To test the forces to break an egg in ballistics gel I first tried dropping heavy weights on the gel block, but I quickly learned that I couldn't get the velocity needed to break the egg. I then decided to try using a large slingshot. This allowed me to shoot a lighter weight at high velocities, which gave higher kinetic energies and more closely matched a bullet. However I soon discovered that how forces and pressure waves travel through ballistics gel is not very well understood. So I came up with an idea to treat the ballistics gel like a spring being compressed from one direction. I then built a box to hold it and keep it from expanding laterally. Then if I had the Young's modulus I could compute the potential elastic energy necessary to stop the slingshot projectile of a given kinetic energy by the gel. I was able to use the egg crusher to compute the Young's modulus of the ballistics gel.

I realized then that I needed to build a frame to protect the box holding the gel, because otherwise if I missed the gel and hit the box it would shatter. Using the velocity and mass of the projectile I could get the kinetic energy and then I was able to calculate the force of impact using the elastic potential energy formula to get depth of penetration.

After I had collected all of this data I discovered how difficult it is to compare these forces to injury on a person. I tested using Kevlar in front of the gel to calculate how much energy different numbers of layers dissipated. I then looked up bullet masses and velocities to see if Kevlar would stop the force. I finally found papers that showed how to determine likely injury from non-penetrating projectiles. These papers showed the likelihood of serious injury based on the force and diameter of the projectile as well as the weight of the impacted target. They also showed that seven layers of Kevlar would be sufficient to stop a .38 caliber bullet.

2. Determining the Force Required to Break an Egg

2.1. Introduction

When I first started testing the plan was to put the egg in between the two boards and then slowly pour water into the jar until the egg broke. Then all I would have to do is measure the combined weight of the board, masses, and the jar of water. The problem that I found was that if I kept pressure on the egg for a long period of time, the egg would slowly warp shape and it would take a lot of force to break the egg. This meant that the force required to break an egg with the weight slowly being added would take a lot more force to break then if the force was added all at once.

Figure 1. Slow break method.

Because the purpose of this test was to find the amount of force that would be required to break an egg in a very short period of time, this test had to be changed. Instead of having the weight being held up by the egg and slowly adding to it, I would have to have the weight on the board and then place the whole thing onto the egg all at once. (See Figure 2.)

I could then simply change the amount of force for each test until I could zero in on the minimum amount of force required to break the egg instantly every time. I started with a baseline of the board and two weights, which was (25.71N), and found that they would break the egg in about three minutes. I added a jar of known mass and started adding water for each test until the egg started breaking in just a second or two, was at (35.66N). I then slowly dialed in to when the eggs would consistently break instantly, which was at (36.63N).

Because I didn't have a precision scale that could measure the large mass of the water necessary to break the egg, I had to find it's mass a different way. I took 100ml of water in a beaker and measured the mass. I then subtracted the mass of the beaker and divided the mass by 100 to get the density of the water. Then I could just measure the volume of the water in the jar to calculate the mass.

Figure 2. Fast break method.

2.2. Equipment

The device is basically a flat platform with fours rods sticking up at the corners, and a board that slides up and down freely. I made it by drilling four holes into one board and then four slightly larger holes in the other. The poles fit tightly into the smaller holes and slide freely in the larger ones. On the top board are some set masses and a jar that can be filled with water to change mass. The egg goes in between the boards and then weight is added until the egg breaks.

2.3. Procedure

1. Measure the mass of the top board and set masses.
2. Put the egg inside a Ziploc bag and seal it and tape the top to make sure it stays closed.
3. Put the egg on the bottom board.
4. Add the set masses and the jar to the top board as a baseline test.
5. Quickly lower the top board with masses and jar onto the egg to see if it breaks instantly.
6. If the egg takes more than a few seconds to break, repeat steps 1 – 5 using more water in the jar.
7. When have masses that consistently break the egg almost instantaneously, then determine the total mass of the water and weights.
8. Calculate the force in Newtons from the overall mass.

2.4. Terms & Formulas

F = force in Newtons = m*g

m = mass in kilograms

g = acceleration of gravity = $9.81 m/s^2$

d = density = m / v

v = volume in liters

2.5. Results

fixed mass (board + weights + empty jar) = 2.7149 kg		
measured density of water = 0.992 kg / L		
	Trial # 1	Trial #2
volume of water (L)	0.9	1.0
mass of water (kg)	.89298	.992
total mass (kg)	3.6348	3.7339
force (N)	35.6574	36.6296
break results	3 seconds	instant

Table 1. Force to break raw egg.

3. Determining the Force Required to Break an Egg in Ballistics Gel by Dropping Weights

3.1. Introduction

I am trying to find how much force in needed to break an egg in ballistics gel. Since I already know how much force it takes to break an egg on its own, I will be able to see how the force is transferred though the gel in the pressure wave.

3.2. Equipment

Egg, Ziploc bag, ballistics gel block (13cm, by 14cm, by 15cm), 10 lb kettle bell, large plastic container, towels or blankets, tape measure.

3.3. Procedure

I first cut a block of ballistics gel that was a bout a 14cm cube. I then took an empty asparagus can and used it to punch a cylinder to the center of the block out of the gel. The cylinder was about 5cm from the edge where the force would be applied. I put an egg inside a Ziploc bag to keep the gel clean when the egg broke, and put it into the hole in the gel. I cut a small piece off of the cylinder of gel to make room for the egg and put it back to that the egg was completely encased in the block. (See Figure 3.)

I then put the block into a large plastic container and filled in the area around it with towels and blankets. These would help to keep the block in place while not keeping it from expanding and changing shape on impact. They also helped catch the weight after it bounces off the gel to keep it from getting damaged. (see Figure 4.)

I put a piece of tape on the wall and marked out 2meters in 10centimeter intervals. I dropped the kettle bell from varying heights onto the gel to see at what point the egg would consistently break. (See Figure 5.)

Figure 3. Ballistics gel with egg enclosed

Figure 4. Plastic tub holding ballistics gel.

Figure 5. Dropping the weight on the ballistics gel.

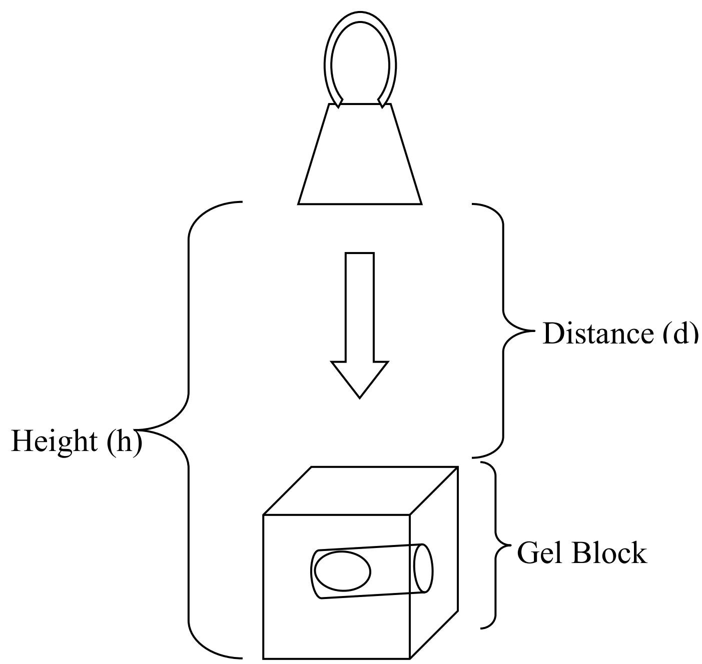

Figure 6. Diagram showing formula variables.

3.4. Terms & Formulas

$d = h - b$

- d is the distance the weight travels,
- h is the height above the ground,
- b is the height of the gel block. (See Figure 6)

$v = \sqrt{(2g \cdot d)}$

- v is the velocity of the weight when it hits the gel
- g is acceleration of gravity

$KE = \frac{1}{2}mv^2$

- KE is the kinetic energy of the weight on impact
- m is the mass of the weight
- v is the velocity of the weight on impact

3.5. Results

I dropped the kettle bell from various heights starting at 50cm and moving up 10cm at a time. The first egg I tested broke when the weight was dropped from a height of 120cm. however, with two more eggs tested dropping the weight from as high as 300cm, I was never able to repeat those results. The problem with dropping the weight is that simply through acceleration of gravity it can't build up enough speed to have the kinetics energy to create a powerful enough shockwave to break the egg. It doesn't work very well to emulate the impact of a bullet because the heavier mass moving slower actually has much less kinetic energy while also having more inertia. This means that the weight creates less of a shockwave in the gel, while causing the gel to deform more to the point that the weight simply crashes into the egg to break it. In order to break the egg with the energy wave in the gel, I will need to use a lighter mass at a higher speed that won't reach the egg, but will still have equal kinetic energy.

Height : h (m)	**Gel block : b** (m)	**Distance :d** (m)	**2g x d** (m^2/s^2)	**v** (m / s)	**KE** (J)
1	0.14	0.86	16.87	4.11	37.9647
1.5	0.14	1.36	26.68	5.17	60.0372
2	0.14	1.86	36.49	6.04	82.1097
2.5	0.14	2.36	46.30	6.80	104.1822
3	0.14	2.86	56.11	7.49	126.2547

Table 2. Kinetic Energy from falling weights.

4. Determining the Force Required to Break an Egg in Ballistics Gel by Crushing

4.1. Introduction

I had already measured the force required to break an egg using the egg crusher I made. However, in that test the egg was simply between two wooden boards, which means that the force was concentrated on a very small area on the egg. I decided to use the egg crusher with the egg in between two pieces of ballistics gel, which would spread out the force in much the same way as if the egg was inside a block of gel.

4.2. Procedure

I cut two pieces of ballistics gel 1.5cm thick to go above and bellow the egg in the egg crusher. I then added weight until the egg broke to find the amount of force needed.

Figure 7. Egg between ballistics gel in egg crusher.

4.3. Results

With the force spread out over a larger area on the egg it didn't break until I put 60lbs of weights onto the crusher. This is equivalent to 267 Newtons of force, over 7 times the force required to break the egg without the gel.

4.4. Conclusion

This test shows why it was so difficult to break the egg encased 5cm in the ballistics gel block. If all the force on the egg is concentrated on a single point of contact, then the egg will break fairly easily. However, the ballistics gel surrounds the egg and spreads the force over the entire egg, which combined with the domed shape of the egg, makes it extremely difficult to break.

Figure 8. Ballistics gel surrounding egg.

5. Determining Young's Modulus of Ballistics Gel

5.1. Introduction and Formula

I needed to know the Young's modulus of the ballistics gel we were using in order to calculate things like deformation on impact. To measure this we found a formula on Wikipedia[1] that gives the force required to cause an indentation by a sphere into a surface of given Young's modulus. The equation gives the force as a result of the effective elastic modulus (E^*), the depth of deformation (d), and the radius of the sphere (R)

$$F = 4/3\ E^*\ R^{1/2}\ d^{3/2}$$

(Eqn. 1)

The E^* is a function of the Young's modulus of both the surface being indented (E_1) and the sphere (E_2), and the Poisson's ratios of the surface (v_1) and the sphere (v_2).

$$1 / E^* = ((1 - v_1^2) / E_1) + ((1 - v_2^2) / E_2)$$

(Eqn. 2)

I used a chromium steel sphere to make the indentation and looked up its properties.[2]

$$v_2 = 0.3 \qquad E_2 = 200 \times 10^9 \text{ Pa}$$

This makes the second fraction of equation 2 essentially zero, so I was able to ignore that part of Eqn 2. and solve for E_1, the Young's modulus of the ballistics gel like this.

$$E^* = E_1 / (1-v_1^2)$$

(Eqn. 3)

Now recognizing that the force in Eqn 1 is simply F = mg, and substituting Eqn 3. Into Eqn 1. Solving for E_1 gives the formula

$$E_1 = 3mg\ (1-v_1^2) / 4\ R^{1/2}\ d^{3/2}$$

The Poisson's ratio (v_1) for gelatin = 0.5. And for the rest of this paper, the Young's modulus of the ballistics gelatin will be noted as E_y and its Poisson's ratio as v_p.

[1] "Contact Mechanics." *Wikipedia*. http://en.wikipedia.org/wiki/Contact_mechanics

[2] "Materials: Metal Alloys: Properties." *Materials: Metal Alloys: Properties*. EFunda. http://www.efunda.com/Materials/alloys/alloy_home/show_alloy_found.cfm?ID=AISI_50100&show_prop=all&Page_Title=AISI%2050100

5.2. Setup

For this test we got out the egg crusher again so that we could easily add a known mass. On the bottom of the crusher we put a one-inch slab of ballistics gel, the two inch steel ball went on top of that, and the top board of the crusher went on top of that. This allowed us to easily add together the masses of the ball, board, and any other weight for the test.

5.3. Procedure

Once the rig was set up I held the ball and board so that they were just at the surface of the ballistics gel and marked on the vertical polls the original position of the board. Then we added five pounds of weight to the top board causing the ball to sink into the gel, I then marked the final position of the board and measured the difference to give the depth of penetration.

5.4. Results

	Board+Ball	**Weights**	**Total**
m (kg)	0.865	2.2906	3.1556
V_p			0.5
R (m)			0.0254
d (m)			0.01
g ($kg*m/s^2$)			9.81
$R^{1/2}$			0.1594
$d^{3/2}$			0.001
$1-v^2$			0.75
E_y (Pa)			109258.875

Table 3. Data for calculating Young's Modulus of ballistics gel.

6. Slingshot Test

6.1. Testing and Assumptions

I will be testing if I can break the egg inside the ballistics gel, and how much kinetic energy is needed to do it. I will be assuming that all kinetic energy is converted to potential energy on impact. I will also assume that the egg doesn't affect the overall elastic modulus of the ballistics gel block.

6.2. Setup

I made a box out of plywood to hold the gel and be clamped down. The slingshot was made using quarter-inch surgical tubing, an old wallet for the pouch, and two trees. The projectile is a 2 inch steel ball that weighs .535kg. The velocity of the ball will be measured with a chronograph just before it impacts the gel.

Figure 9. Plywood box for holding ballistics gel.

6.3. Procedure

The steel ball weighs .535kg. I will shoot the ball out of the slingshot, over the chronograph, and into the gel. When I find the point where the egg breaks, and I will see the velocity. That and the mass will give me the kinetic energy, which I can assume converts to potential energy. I can then use that and the gel's elastic modulus to find the deformation of the gel. Then this combined with kinetic energy will give us the force on impact. I will then be able to see if this is anywhere close to the force tested in the egg crusher.

6.4. Slingshot Calibration

I decided to calibrate my slingshot so that I could more easily do tests at different velocities. To do this I tied a string to the tree so that I could mark at the correct distances for the slingshot to fire at a certain velocity. I shot the slingshot over the chronograph until I could consistently match the intended velocity and then I marked the string at that distance. This way if I want to fire the ball at 60fps, I can simply pull the slingshot to the 60 mark, and it will fire at that speed.

Figure 10. Calibration string for the slingshot.

6.5. Formulas

$KE = \frac{1}{2}mv^2$

- KE is the kinetic energy of the ball on impact with the gel
- m is the mass (kg) of the ball
- v is the velocity (m/s) of the ball on impact with the gel

$PE = (E_y * A * \Delta L^2) / 2L_i$

- PE is the elastic potential energy[3] of the gel when pushed in by ΔL
- E_y = Young's elastic modulus of ballistics gel (109,259 Pa)
- A = area of front of block where the ball is impacting
- L_i = length from front to back of ballistics gel block
- ΔL = deformation of the gel on impact (m)

I am assuming all of the kinetic energy is transferred to potential energy. So,

$$KE = PE$$

$$\frac{1}{2} mv^2 = (E_y * A * \Delta L^2) / 2L_i$$

I then solve for ΔL.

$$\Delta L = [(\frac{1}{2} mv^2 * 2L_i) / (E_y * A)]^{\frac{1}{2}}$$

And then finally I compute the force of impact by dividing KE by ΔL.

This works because the work done by the ball on the gel is equal to the PE and W = F * d. Since the distance the ball deforms the gel (ΔL) is equal to distance (d), F = W / ΔL. And since Work equals PE and PE equals KE,

$$(F = KE / \Delta L)$$

6.6. Results

On the first shot with the slingshot I managed to hit the block in the center at a speed of 48.3fps. The egg broke and everything seemed to work very well. However, the table with the ballistics gel box moved back several inches, meaning that a fair amount of the KE was lost to making it move. This is a problem because I am making the assumption that all of the KE of the ball is being transferred to the ballistics gel block. For the next test I added weights to the front of the table to keep it from moving.

On the second test the slingshot fired at 53.3fps but was slightly off on my aim and clipped the edge of the box before hitting the gel. The egg still broke, but the test is unreliable because the ball would have lost velocity when hitting the box. However the table stayed in place, meaning it is ready for future tests.

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[3] "Elastic Potential Energy." *Wikipedia*. http://en.wikipedia.org/wiki/Elastic_potential_energy

I continued taking shots, slowly reducing the speed until I found the speed that would no longer break the egg. Once I found that, at 32.6fps, we could find the absolute minimum force required to break the egg at that depth with just the gel.

Egg 5 cm Deep inside Ballistics Gel								
v (m/s)	m (kg)	KE (j)	A (m^2)	Li (m)	ΔL^2 $(m)^2$	ΔL (m)	Force (N)	Break?
16.25	0.535	70.6367	0.0195	0.1429	0.0095	0.0973	725.6544	Yes
14.72	0.535	57.9615	0.0195	0.1429	0.0078	0.0882	657.3312	Yes
11.95	0.535	38.1997	0.0195	0.1429	0.0051	0.0716	533.6351	Yes
10.1	0.535	27.2877	0.0195	0.1429	0.0037	0.0605	451.0221	Yes
9.95	0.535	26.4832	0.0195	0.1429	0.0036	0.0596	444.3238	No
9.6	0.535	24.6528	0.0195	0.1429	0.0033	0.0575	428.6943	No

Table 4. Slingshot data for egg 5cm deep inside ballistics gel.

I did the same exact thing with the egg 10cm in the gel. I shot it at 72fps and then slowly reduced the speed until the egg would no longer break. I found that the speed when the egg wouldn't break was right around 57fps.

Egg 10 cm Deep inside Ballistics Gel								
v (m/s)	m (kg)	KE (j)	A (m^2)	Li (m)	ΔL^2 $(m)^2$	ΔL (m)	Force (N)	Break ?
21.95	0.535	128.8822	0.0213	0.1461	0.0162	0.1272	1013.1517	Yes
19.45	0.535	101.1959	0.0213	0.1461	0.0127	0.1127	897.7586	Yes
17.37	0.535	80.7093	0.0213	0.1461	0.0101	0.1007	801.7515	No

Table 5. Slingshot data for egg 10 cm deep inside ballistics gel.

6.7. Conclusion

These tests show me the minimum force on impact required to break an egg at each depth without anything in front of the gel. This gives me a consistent control to compare other tests to. Now when I test with Kevlar sheets in front of the gel I will be able to find the minimum force to break the egg then, and compare that to the gel without Kevlar. This will tell me exactly how much the Kevlar helps.

7. Testing Kevlar with the Slingshot

7.1. Introduction

The purpose of Kevlar is not just to stop the bullet but also to dissipate the bullet's energy so that it doesn't cause as much damage. In order to test Kevlar's ability to dissipate energy, I had to shoot at gel with Kevlar in front of it and compare against gel without Kevlar. I can take the difference in energy to see how much the Kevlar helps, and even compare different numbers of layers.

7.2. Equipment

The equipment is the same as in the previous test only with the addition of the sheets of Kevlar 29 style 735.

- Sling shot,
- Chronograph,
- weighted stand,
- ballistics gel block,
- box to hold gel,
- shield to protect box,
- sheets of Kevlar 29 style 735.

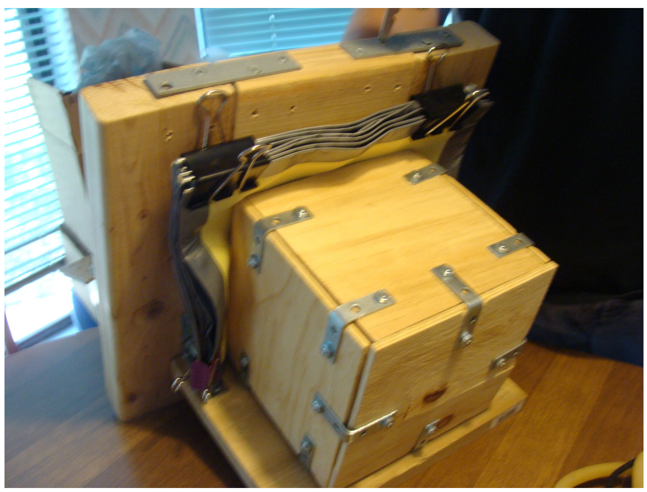

Figure 11. Kevlar layers placed between box and shield.

7.3. Procedure

The procedure is almost exactly the same as before the only difference being the addition of Kevlar. The tests will include increasing increments of four layers of Kevlar (4, 8, 12, etc) in front of the gel.

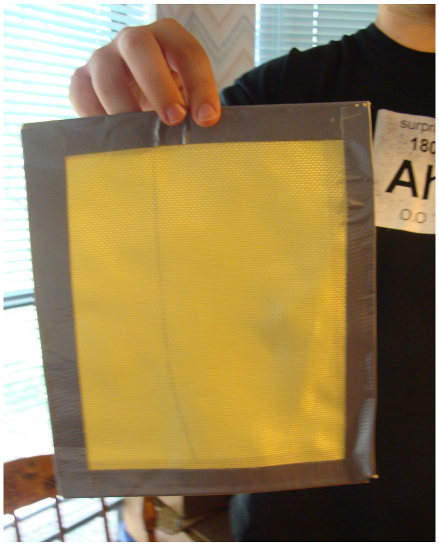

Figure 12. One layer of Kevlar.

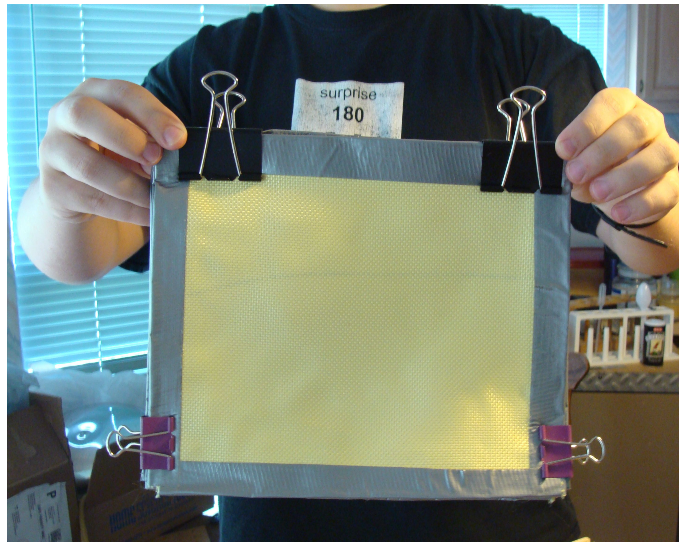

Figure 13. Eight (8) layers of Kevlar.

7.4. Formulas

The percentage of energy dissipated (KE_d) will found by the equation

$$KE_d = \{[(KE_k - KE_g) / KE_k] * 100\%\}$$

Where

- $KE_k = ½ mv_k^2$ = minimum energy to break egg in gel with Kevlar
- $KE_g = ½ mv_g^2$ = minimum energy to break egg in gel without Kevlar (See Table 4.)

7.5. Results

4 Layers of Kevlar & Egg 5 cm Deep inside Ballistics Gel					
m (kg)	v_k (m/s)	KE_k (J)	KE_g (J)	KE_d (%)	Break?
0.535	19.05	97.0764	27.2877	N / A	Yes
0.535	17.45	81.4544	27.2877	N / A	Yes
0.535	15.02	60.3481	27.2877	54.7829	Yes
0.535	14.63	57.2549	27.2877	N / A	No

Table 6. Energy dissipation of 4 layers of Kevlar.

8 Layers of Kevlar & Egg 5 cm Deep inside Ballistics Gel					
m (kg)	v_k (m/s)	KE_k (J)	KE_g (J)	KE_d (%)	Break?
0.535	20.55	112.9659	27.2877	75.8443	Yes
0.535	19.49	101.6126	27.2877	N / A	No

Table 7. Energy dissipation of 8 layers of Kevlar.

12 Layers of Kevlar & Egg 5 cm Deep inside Ballistics Gel					
m (kg)	v_k (m/s)	KE_k (J)	KE_g (J)	KE_d (%)	Break?
0.535	23.6	148.9868	27.2877	81.6845	Yes
0.535	23.48	147.4755	27.2877	N / A	No
0.535	21.82	127.3600	27.2877	N / A	No

Table 8. Energy dissipation of 12 layers of Kevlar.

7.6. Conclusion

These tests show that Kevlar not only helps to stop a projectile, but also does a very good job of dissipating the energy to keep it from damaging internal organs. The Test with four layers of Kevlar dissipated 54.78% of the energy on impact, the eight layers dissipated 75.84%, and the twelve layers dissipated 81.68%. This means that when struck by a projectile like a bullet, most of the energy is spread out protecting vital organs that could be damaged by the shockwave.

8. Determining Blunt Trauma

8.1. Introduction

My aim with this project was to test the effectiveness of Kevlar in dissipating energy to prevent blunt force trauma. I found the energies of the projectile and the force on impact, but these numbers don't really tell me what kind of injuries a person would sustain. I wanted to analyze my data to see how much blunt force the projectile would actually cause to a person. However, there is no magic number of newtons or joules that is the threshold because it depends a lot on the size of the person and where they were hit.

After some research I found a paper published in 1976 by some scientists and engineers doing research for the Department of Justice on blunt trauma and body armor at the Edgewood Arsenal.[4] These scientists shot large blunt projectiles at goats and noticed a connection between several factors and were able to derive an equation that predicted the level of injury from an impact. The model assumed a direct hit over the liver, as the liver is very large and a likely organ to be damaged by blunt trauma. If the model value is less than 414 then the person has a 0% chance of serious injury. If the value is between 414 and 1451 then the person has a 50% chance of serious injury. If the value is greater then 1451 then the person has a close to 100% chance of serious injury. In the case of the liver, serious injury can range anywhere from a bruised liver to a bleeding liver, both of which are bad.

The year before (1975) another scientist also working for the Departments of Justice at Edgewood Arsenal showed that seven layers of Kevlar 29 would stop a .38 caliber round.[5] I will do my tests with a 380 auto round, which has an equal diameter and very similar power to the .38

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[4] United States. National Institute of Law Enforcement and Criminal Justice. Department of Justice. *Body Armor: Blunt Trauma Data*. By Victor R. Clare, James H. Lewis, Alexander P. Mickiewicz, and Larry M. Sturdivan. 1976. Print

[5] United States. National Technical Information Service. Department of Commerce. *A Method for Soft Body Armor Evaluation: Medical Assessment*. By Michael A. Goldfarb. 1975. Print.

round used in those tests. I will also be doing my tests using eight and twelve layers of Kevlar, which should be plenty to stop the rounds.

8.2. Formulas

- $KE = {}^{1}/_{2}\, mV^2$
  - m = mass of projectile in kilograms
  - V = velocity of projectile in m/s
- $Tr = trauma = MV^2/WD$
  - M = mass of projectile in grams
  - D = diameter of projectile in cm.
  - W = weight of target in kg
- $Tr = 2 * 1000 * KE /WD$
  - $Tr < 414$ = 0% chance of serious injury
  - $414 < Tr < 1451$ = 50% chance of serious injury
  - $Tr > 1451$ = 100% chance of serious injury

8.3. Results

First I calculated the trauma that would be produced by a projectile just fast enough to break the eggs without the Kevlar. I used W = 77 kg which is about the mass of an average-sized male. (See Table 9.) For comparison, I also computed the trauma for an average-sized female using W = 55kg. (See Table 10.)

Male Blunt Trauma with no Kevlar				
egg depth (cm)	**KE (J)**	**MV^2**	**$Tr = MV^2/WD$**	**Injury? (Probability)**
5	27.2877	54575.35	279.0436	0%
10	101.1959	202391.8375	1034.8289	50%

Table 9. Male blunt trauma probability from breaking egg, no Kevlar.

Female Blunt Trauma with no Kevlar				
egg depth (cm)	**KE (J)**	**MV^2**	**$Tr = MV^2/WD$**	**Injury?**
5	27.287675	54575.35	390.6611	0%
10	101.1959188	202391.8375	1448.760469	50%

Table 10. Female blunt trauma probability from breaking egg, no Kevlar.

Both male and female have near 0% chance of serious injury if hit by a projectile with enough energy to break the egg at 5cm, without Kevlar. However, the female is much closer to the border of the 50% likelihood region. At 10cm the male is pretty close to the center of the 50% region. However, the female is right at the border of the two regions, which means that there is a very high probability of serious injury. This shows how a projectile can injure one person much more than another because the trauma it produces depends on the person's weight.

Next, I calculated the blunt trauma caused when shooting projectiles fast enough to break the egg under various layers of Kevlar. (See Table 11.) To do this, I first considered the minimum energies required to break an egg with different layers of Kevlar (See Tables 6, 7, and 8). I calculated how much energy was hitting the Kevlar and how much damage this would cause to a person if the Kevlar did not dissipate any of the energy. I only did the egg at 5cm because I could not generate fast enough velocities with the slingshot to break the egg at 10cm behind Kevlar.

Breaking Egg at 5cm Under Kevlar				
	KE (J)	**MV^2**	**$Tr = MV^2/WD$**	**Injury?**
4 Layers				
Male	60.3481	120696.214	617.1194	50%
Female	60.3481	120696.214	863.9672	50%
8 Layers				
Male	112.9659	225931.8375	1155.1889	50%
Female	112.9659	225931.8375	1617.264406	100%
12 Layers				
Male	148.9868	297973.6	1523.5382	100%
Female	148.9868	297973.6	2132.953472	100%

Table 11. Blunt Trauma : Kevlar Not Dissipating Energy.

What this shows is that these projectiles would cause serious harm to a person if the Kevlar were not dissipating their energies, but since these are the lowest energies that break the egg, we know only about 27J (KE_R)[6] is actually getting through the Kevlar to the ballistics gel, and 27 J was not enough to cause serious injury (See Tables 12). So the Kevlar is preventing serious injury.

[6] $KE_R = KE \times (1 -$ fraction dissipated by Kevlar layers)

Breaking Egg at 5cm Under Kevlar					
4 Layers :					
	Fraction dissipated	**KE (J)**	**KE_R (J)**	**$Tr = MV^2/WD$**	**Injury?**
Male	.547829	60.3481	27.2877	279.0436	0%
Female	.547829	60.3481	27.2877	390.6611	0%
8 Layers					
Male	.758443	112.9659	27.2877	279.0436	0%
Female	.758443	112.9659	27.2877	390.6611	0%
12 Layers					
Male	.816845	112.9659	27.2877	279.0436	0%
Female	.816845	148.9868	27.2877	390.6611	0%

Table 12. Blunt Trauma : Kevlar Dissipating Energy.

I wanted to compare my results to the scientists who claimed that Kevlar would stop a .38 bullet. I wondered how much trauma would be caused by a .38 bullet impacting layers of Kevlar.

One consideration was that the trauma model depends on the diameter of the projectile, but since the Kevlar is dissipating the energy over a larger area, the diameter that is striking the ballistics gel is much bigger than the projectile. In the original goat paper, the scientists did a first test with clay behind the Kevlar and measured the crater created, and used that as the diameter when they shot the armored goats.

In the previous tests with the slingshot and egg I found the amount that varying layers of Kevlar dissipated energy on impact. Since I cannot test the dissipated diameter on impact the way the scientists did, I will have to instead use the original diameter of the projectile and the dissipated kinetic energy. Both of these methods should work equally well because according to the formula, doubling the diameter or halving the kinetic energy should do the exact same thing.

.38 Blunt Trauma Predictions : 90 grains; KE = 270.907 J				
Kevlar (layers)	**Fraction dissipated**	**KE_R (J)**	**$Tr = MV^2/WD$**	**Injury?**
4	.547829	122.4960	3528.5735	100%
8	.758443	65.4403	1885.0481	100%
12	.816845	49.618	1429.27634	50%
.38 Blunt Trauma Predictions : 95 grains; KE = 258.0765 J				
Kevlar (layers)	**Fraction dissipated**	**KE_R (J)**	**$Tr = MV^2/WD$**	**Injury?**
4	.547829	116.6945	3361.4564	100%
8	.758443	62.341	1795.7702	100%
12	.816845	47.2680	1361.5842	50%

Table 13. Slingshot Model Using Dissipated Energy and Diameter of .38 bullet.

This top (Table 13) is what we got based on dissipated energies using the diameter of the projectile. The bottom (Table 14) is theirs using the increased in diameter.

.38 Blunt Trauma Predictions : 90 grains				
Kevlar (layers)	Expanded Diameter (cm)	KE_R (J)	$Tr = MV^2/WD$	Injury?
4	6.45	270.907	1090.937274	50%
8	8.93	270.907	787.9670117	50%
12	9.62	270.907	731.4496273	50%
.38 Blunt Trauma Predictions : 95 grains				
Kevlar (layers)	Expanded Diameter (cm)	KE_R (J)	$Tr = MV^2/WD$	Injury?
4	6.45	258.0765	1039.269272	50%
8	8.93	258.0765	750.6480185	50%
12	9.62	258.0765	696.8073602	50%

Table 14. Trauma Model Using Full Energy and Expanded Diameter

There is a very significant difference between the two sets of data, but this is probably just because my dissipated energies were not completely accurate. I think the problem is due to the increased mass, and therefor increased momentum, of the steel ball I fired from the slingshot. This most likely cause the projectile to push far enough into the ballistics gel to physically crush the egg, instead of breaking the egg with the pressure wave. This would cause the dissipation values to be too low and therefor our blunt trauma to be too high.

8.4. Conclusion

These results tell us quite a few things. They show that injury from blunt trauma is very dependent on the weight of the person getting hit. They also show how good Kevlar is at taking otherwise potentially lethal impacts and making them far less damaging. But most importantly they show how our tests with 5cm and 10cm gel blocks compare to actual impacts on people. The truth is, they aren't perfect; the 5cm block egg is too easy to break, and the 10cm egg is too hard to break. The ideal depth for these tests would probably be somewhere around 7cm, but due to the limited power of out slingshot, we have no way to test this. Our best bet for testing with a .38 caliber bullet is to use the 5cm block with 8 and 12 layers of Kevlar. If my hypothesis is correct, the 8 layer test should break the egg, but the 12 layer test might protect it.

9. Kevlar Bullet Tests

9.1. Hypothesis

It takes 27J to break the egg in the 5 cm block and 101 J to break the egg in the 10 cm block. Based on the data in Table 13, using the dissipated energies, the 95 grain .380 bullet should allow enough energy through at 8 and 12 layers to cause the egg to break in the 5 cm block but dissipate enough energy to not break the egg in the 10 cm block.

9.2. Procedure

My father fired 95 grain .380 bullets from a pistol at our ballistics gel rig with the egg embedded inside. The distance from the pistol to the rig was 10 feet. Kevlar sheets clipped together were placed in front of the gel block as in the slingshot tests.

9.3. Results

The first shot at the 5 cm block with 12 layers of Kevlar was low and did not break the egg, but the second shot was centered over the egg and broke it.

Figure 14. .380 bullets after impact with 12 layers (left) and 8 layers (right) of Kevlar.

Using the energy dissipation fraction for 12 Kevlar layers I found in the slingshot tests (See Table 8) this confirms my prediction, as nearly 43J of the bullets energy made it through the Kevlar and hit the gel, enough to break the egg at 5 cm.

.380 95 grain bullet; 12 Layers of Kevlar & Egg 5 cm Deep inside Ballistics Gel				
m (kg)	**v_k (m/s)**	**KE_k (J)**	**KE_R (J)**	**Break?**
.0061	277.37	234.65	42.99	Yes

Table 15. .380 Test of Kevlar dissipation with 5 cm block.

The first shot at the 10 cm block with 8 layers of Kevlar was centered over the egg but did not break it. This too was expected since only 56 of the 101 joules necessary to break the egg passed through the Kevlar. The bullet also did not penetrate the Kevlar, confirming that 8 layers will stop a .380.

.380 95 grain bullet; 8 Layers of Kevlar & Egg 10 cm Deep inside Ballistics Gel				
m (kg)	**v_k (m/s)**	**KE_k (J)**	**KE_R (J)**	**Break?**
.0061	276.97	233.97	56.53	No

Table 16. .380 Test of Kevlar dissipation with 10 cm block.

We also tested the hypothesis that 7 layers of Kevlar were needed to keep the bullet from penetrating by firing at 6 layers of Kevlar with a hollow-point bullet. The hollow-point bullet did penetrate the 6 layers of Kevlar but it went under the egg, so it was not broken.

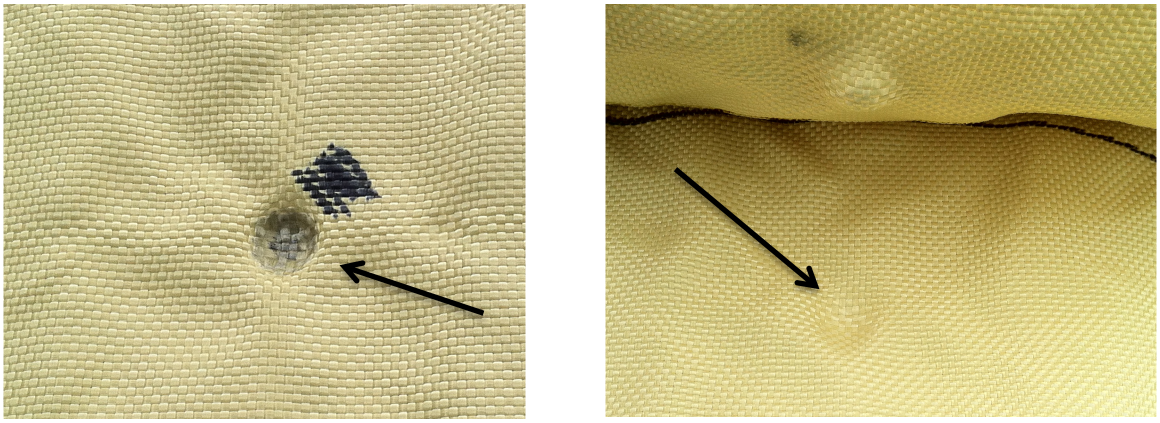

Figure 15. Impact crater on outer layer (left) and inner layers of (right) of Kevlar.

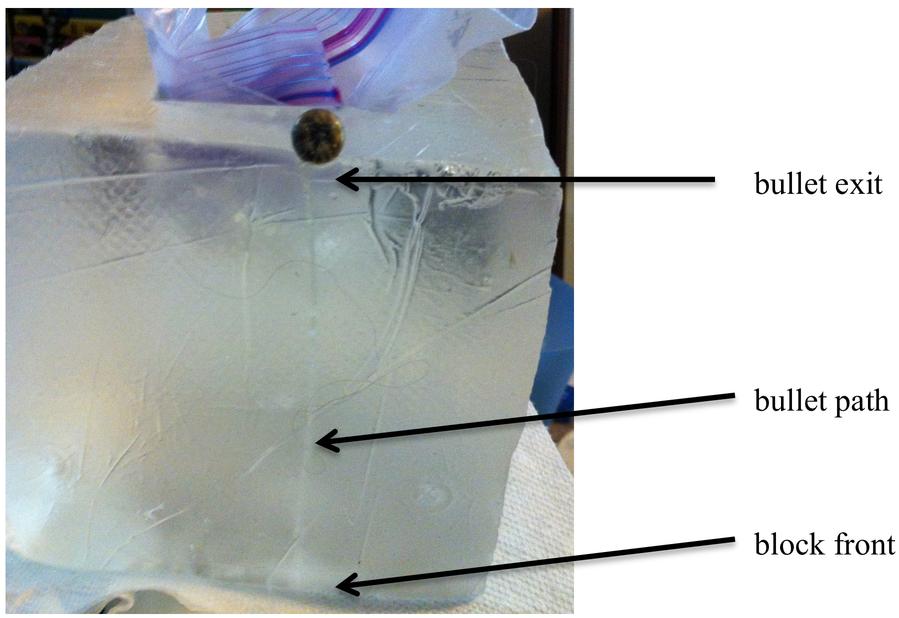

Figure 16. Path of .380 hollow-point bullet through ballistics gel.

Figure 17. The .380 hollow-point bullet plugged with Kevlar (right) and did not mushroom as much as the .95 grain .380 bullet.

9.4. Conclusion

My hypothesis was proven correct which validates my results for how much Kevlar dissipates energy.

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