Proposed Testing Method for Foam Padding

by

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ABSTRACT

One very basic necessity for foam padding testing technology is the ability to test two different padding samples and compare the results. The current standard for testing is to use a steel anvil backing for the padding, create an impact and record the parameters of the collision. The standardized method of testing with a steel anvil backing may not truly depict which foam or padding is actually the most protective, and this project aims to demonstrate how using a more humanlike backing produces more accurate test results. The experimentation setup used a projectile shot with a known velocity at various padding samples, where both a steel anvil and urethane foam are used as separate backings for the experiment. The steel anvil represents the current industry testing standard, whereas the urethane foam is meant to physically replicate the characteristics of human flesh. Using a load cell which is calibrated with an oscilloscope, a curve of the force applied over time will be recorded for each test run. From this force curve, the peak force, total impulse, and energy dissipated were calculated for each collision. By comparing these metrics across different foam padding specimens using the two padding backings across different velocities, the effect of varying the padding backing are demonstrated in the experimental results. Although using the steel anvil backing lead to generally similar recommendations for the best padding, it does not capture a lot of the details which are necessary to truly understand how different foam specimens compare with each other. Two main conclusions are drawn regarding the difference between the steel anvil and urethane foam setups: the difference in the shape of the force over time curves and the significance of changing the velocity of the impact. Using the urethane foam backing also established two different regimes which define whether or not the padding user would feel a significant impact. The parameters of these regimes provide the best data for deciding on appropriate foam specimens. The steel anvil backing lacks any capacity to test or predict which impacts are severe enough to cause serious injury.

Thesis Supervisor: Kim B. Blair
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There are a number of people who were essential in completing this project. Without them, this research could not have been completed.

Kim Blair, the thesis supervisor, has been a helpful asset this past year for a number of different reasons. He originally set up the contact with Rogers Corporation, ultimately revealing the possible problem with the current standard for testing foam padding. He also kept the project on schedule and provided guidance in formatting and editing the actual thesis.

Dave Robertson provided very useful information regarding all of the electronics used in the experimental setup. He specifically instructed how to build a power box for the light gates and was also routinely available to troubleshoot any electronic malfunctions.

Todd Billings also contributed to the project’s efforts by helping with the hardware aspects of the experimental design. His main contributions were machining a number of screws which were necessary for assembling the impact system. He also loaned the steel anvil used for the experiment, and he helped assemble a mounting system for it.

Dick Perdichizzi was important in getting the project off the ground. Without his help, there would not have been an area available to perform the testing.

Finally, the project’s partners at Rogers Corporation first articulated the industry query as to why steel anvil testing was the only standardized method, and helped generate the idea to do this project. Additionally, they served as resources on current standards for testing and also provided foam samples both for padding specimens and urethane backings.
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Introduction

Background
Testing the performance of protective foam padding is a major priority in the sports technology industry. As the athletes are becoming bigger, faster, and stronger, regulations and standards become stricter to try to keep the athletes safe. Without proper testing methods though, these preventative measures will not actually help protect the athletes.

One very basic necessity for foam padding testing technology is the ability to test two different padding samples and compare the results. The current standard for testing foam padding is to use a steel anvil backing for the padding, create an impact and record the parameters of the collision (ASTM International, 2008); (British Standards Institution, 1997). Although it is accepted that the absolute results from testing in front of a steel anvil is inconsistent with those of a human backing, this method is currently used to compare different types of padding. If one type of padding is more effective in front of the steel anvil, it is assumed to be more effective in protecting a human body. However, because steel alloys have vastly different physical characteristics than the human body, this assumption may not be accurate. A certain padding sample may perform better in front of a steel anvil than a different sample, but actually not protect the human body as sufficiently. In order to truly evaluate the two different samples, the testing may need to be conducted in front of a material reflective of how the human body would behave.

Project Significance
The standardized method of testing with a steel anvil backing may not truly depict which foam or padding is actually the most protective. The industry was so focused on setting parameters to make the testing repeatable that they may have overlooked making sure the results from testing with these parameters portrayed results relevant to the true applications of the product.

If successful in designing a testing mechanism which is simple enough to be standardized yet accurate enough to produce results which truly represent the most protective paddings and foams, there is a potential to fulfill a real need in the sports technology industry. Understanding which padding samples provide the most protection is very important for not only the sporting manufacturers, but also the players, parents, and coaches.

Conceptual Experimental Design
In order to test the overall protection of the padding samples, golf balls will be shot at them out of an air cannon from a short distance at high velocities. A ball will pass through a light gate system to measure its velocity before impacting a target attached to the load cell which will record the curve of force over time. The target is a 6 inch square piece of plastic which the foam padding samples can be attached to. This experiment will be run using a number of different types of padding with a steel anvil backing and a humanlike urethane foam backing. Comparing
the force data between the different padding samples and using the different test backings will check the assumption that padding that performs best in front of a steel anvil also performs best in front of the human body. A picture of this setup is shown in Figure 1.

![Figure 1: Overall setup of experimental design.](image)

**Literature Review**

**Current Testing Standards**

Published papers of foam padding’s protection describes in great detail the current standard by which padding needs to be tested to meet national standards (ASTM International, 2008). A lot of these different tests involved different geometries and force magnitudes in order to emulate the different impacts the padding is meant to protect against. One parameter which remained constant throughout all of these testing standards was the backing the padding was attached to for the impact testing. For every standard researched, a steel anvil is used (ASTM International, 2004); (British Standards Institution, 1997). In the literature describing testing standards they do not discuss the reasoning behind this material. It is very specific, though, how the steel is to be treated to ensure that there is no discrepancy in the hardness or strength of the steel between testing setups, implying the steel may have been chosen to ensure repeatability. There is no discussion regarding how the steel anvil affects the results of the testing or if it would be more beneficial to test the padding on a more humanlike material.
Other documents discussed briefly the theory behind using the steel anvil as a backing for impact testing; for example, a paper discussing collapsible impact energy absorbers discusses how several theoretical methods for dynamic crushing use the simplified rigid-plastic method of analysis (Alghamdi, 2001). The document also presents arguments for how to compensate for the effect of strain-rate on increasing the yield stress and why the inertia effects can be neglected for low velocity impact, converting all the kinetic energy into plastic work. The paper also discusses the strain-rate and strain-hardening effects which would obviously be very important to consider if the material was to be considered as the standard for impact testing backing.

**Foam Characterization**

Another document describes the characterization polymeric structural foams under compressive impact loading (Avalle, Belingardi, & Montanini, 2001). Although the purpose of most of these papers is to describe how the foam performs as a protective material, the results can also be applied to considering how the material would react if used as the backing for impact testing of other equipment. The aim of packaging or shock absorbing with this foam is to dissipate the kinetic energy of the impacting mass while keeping the maximum acceleration below some limit. Although these papers provide quantified results of impact testing, these results were all obtained using standard testing with a steel anvil backing and thus the results cannot be used as absolute measurements. Another paper discusses the possibility of using other forms of backing for testing, comparing the advantages and drawbacks of the different materials (Henry, Johnson, Shih, & Hile, 2001).

**Metallic Foams**

The possibility of using closed cell or hollow sphere metallic forms as a replacement for the steel anvil pops up in other documentation (Sanders, 2002). Metal foams are low density materials which provide the strength to be a possible backing for the padding testing, but are also slightly softer and therefore may provide more applicable results for human protective equipment. However, currently the mechanical properties being displayed in testing are not acting as the theory describes they should. Physically, the closed-cell foams are much weaker than predicted most likely due to defects such as cell wall curvature, cell wall corrugation, and density variations. Also, there is concern that even if the mechanical properties were consistent on the first impact, this metallic foam would deform and not provide repeatable testing. The current methods by which the metal foams are treated before being used in testing is not currently standardizing the material, and this would need to be corrected before it could be used as the standardized backing to be used for impact testing.

**Commercial Applications**

Papers also described examples of products which have used the standardized testing methods to do impact testing on different products and materials (Loveridge & Mills, 1993); (Sasaki, Saito, & Abe, 1999). All of these products described the steel anvil used in their testing for backing, yet none of them discuss how the steel could be affecting the results compared to the human
flesh which the product would actually be protecting. All of them use the steel anvil because that is the test that their results are to be standardized against. These products and materials included polymer foams, helmet liners, and other cushioning or energy dissipation products.

**Description of Experiment**

**Experimental Overview**
In order to properly assess the importance of the backing for foam padding testing, the experimentation required a projectile to be shot with a known velocity at various padding samples, each tested with different backings. Keeping these specifications in mind, the technical approach of this experiment required five physical subsystems: projectile launch, velocity measurement, impact recorded over time, foam padding, and padding backing. A high-pressure air cannon was used to launch identical golf balls at the padding samples at various velocities. The velocity was measured using a system of light gates, and the impact of the collision was measured using a load cell attached to the foam padding and backing apparatus.

For a given impact velocity, the testing results for two different foam padding samples could be compared when a steel anvil was used as the backing as opposed to a more human resembling material. By comparing this data gathered with the different backings, whether or not using a humanlike backing is necessary for comparing the effectiveness of different foam padding samples can be assessed.

**Description of Test Apparatus**
As described above, the test apparatus for this experiment included five key components: a pressurized air cannon which launched the golf balls, light gates for measuring the impact velocity, a load gauge for generating the force curve, the foam padding sample, and the backing for the padding in each test run. Together, these components allowed examination of how different types of backing affected the comparison of different foam padding’s protection effectiveness.

**Pressurized Golf Ball Cannon**
An existing air cannon in the Neumann Hanger on the campus of MIT was used to shoot the golf balls at the foam padding samples. A picture of the air cannon set up in the laboratory is shown in Figure 2.
In order to control the experiment, a system of valves on the air cannon needed to be operated so that the internal pressure could be specified. A detailed picture of these valves is shown below in Figure 3.

**Figure 3:** Top view of the air cannon with labeled valves.
A direct air line is connected to the back of the cannon in order to generate air pressure within the chamber. It was very important to be able to control the internal pressure within the cannon so that the velocity of the golf ball collision could be controlled. The two aspects of the cannon that make this possible are the pressure gauge and the adjustable valve. The pressure gauge displays the interior pressure of the cannon which would be calibrated with the exit velocity of the golf ball using the light gates. The adjustable valve controls the interior pressure within the chamber and is used to set the desired pressure, in turn setting the desired exit velocity. In order to actually shoot the golf ball, the trigger is flipped, quickly releasing the air pressure.

**Light Gates**

In order to accurately analyze the results of the collision, the velocity of the golf ball needed to be measured. In order to measure this parameter, a system of Pasco Accessory Photogates (Model ME-9204B) is used. These light gates are hooked up to an oscilloscope such that anytime the light beam is broken by an object, a voltage jump can be seen. A picture of the setup is shown in Figure 4.

![Light gates setup in front of air cannon.](image)

**Figure 4:** Light gates setup in front of air cannon.

In order to calculate the velocity of a golf ball traveling through the light gates, an oscilloscope is used to measure the amount of time that elapses between when the beam of the first light gate is broken to when the beam of the second gate is broken. Using this time along with the distance between the light gates, the velocity of the ball is calculated. A picture of these readings for a specific test run is shown in Figure 5.
Once the velocity can be measured, a correlation can be found between the internal pressure of the air cannon and the exit speed of the golf ball. Instead of measuring the velocity with the light gates on every test, the pressure gauge of the air cannon is used to determine the velocity of the collision.

**Impact System**

The load cell, foam padding, and padding backing are all parts of the load cell apparatus from which the data will be collected. The load cell actually records the curve of force over time for the collision, while the foam padding and padding backing characterize the environment of that specific test. A schematic of the load cell apparatus as it was setup for this experiment is shown in Figure 6.
Figure 6: Schematic depicting the impact system.

A picture of this apparatus put together in the laboratory without the urethane foam backing is shown in Figure 7.

Figure 7: Picture of impact system with steel anvil backing.
This setup was used to do the traditional industry testing of foam padding with a steel anvil backing. A picture of the impact system put together including the urethane foam backing to better replicate the human body is shown in Figure 8.

![Image of impact system](image)

**Figure 8:** Picture of impact system with urethane foam backing.

**Load Cell**

The load cell is a crucial aspect of the experimental design as the curves evaluating force over time are the key data for relating the different foam specimens with respect to the testing backing that was used. For this experiment, the load cells used were Interface Force Transducers (Model SM-1000). Given the physical parameters of this system, a 1000 lb load cell was selected. Using a Measurement Group – Instruments Division Amplifier (Model 2160), the load cell was hooked up to an HP 54601A Oscilloscope where the output voltage was correlated to the force applied.

**Foam Padding**

Similar to standard padding testing, three different foam padding samples will be compared in this experimental design. Table 1 labels each of the three foam padding specimens with their respective product numbers.
Table 1: Foam Padding Specimens which will be tested.

<table>
<thead>
<tr>
<th>Specimen 1</th>
<th>XRD-15236-35-540-RR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specimen 2</td>
<td>XRD-15500-35-545-RR</td>
</tr>
<tr>
<td>Specimen 3</td>
<td>XRD-12500-35-545-RR</td>
</tr>
</tbody>
</table>

All three of these specimens are different types of Rogers’ strain rate dependent foam, varying in thickness, density, and other physical properties. This foam becomes stronger as the rate at which a force is applied increases.

The molecular specifics of these foams are not relevant for the experiment since the goal of the testing is to compare the difference in padding samples when different backings are used. There are three main physical results that will be compared from the experiment: the peak force from the impact, the time elapsed during the collision, and the total impulse of the collision. Holding all of the other parameters of the system constant, such as golf ball size and velocity, these physical results can be used to rank the performance of each padding sample.

Padding Backing
For this experiment, two different types of backings will be used, the steel anvil and a urethane polymer foam. The steel anvil backing is the same as what is currently used in foam padding standardized testing. Although it bears no physical resemblance to the human body, the material is very easy to replicate and durable enough to run repeated impact tests. The urethane foam, however, more accurately represents the human body physically, although it may be more difficult to replicate as a testing setup.

The purpose of this testing is not to determine which of the padding samples being used is more effective, and the absolute data from each backing being used is not relevant either. For example, it can be assumed that given a certain padding specimen and impact velocity, the peak force using a steel backing will be higher than the peak force using a urethane foam backing. The goal of this testing is to see if the comparison between the different padding samples are consistent regardless of what backing is used.

Ball Containment System
The ball containment system had only one requirement: to successfully contain every launched ball without damaging the experimental infrastructure or injuring anyone. To meet this requirement, a diamond-patterned net was draped over twine that was attached to opposite walls in the chamber, fully enclosing both the golf ball cannon and the load cell apparatus. Two pieces of plywood were also used to provide side walls for the experiment. A picture of the containment system is shown in Figure 9.
This containment system worked sufficiently, not allowing any golf ball launches to exit from the system.

**Test Methodology**

In order to run the experiment consistently enough to provide accurate, repeatable results, a set methodology was used before performing each test.

**Pressurizing Air Cannon**

In order to shoot the golf ball at a given desired velocity, a specific pressure within the chamber needed to be obtained. This pressure was calculated using the calibration data involving the air cannon and light gates. Once the direct air source was hooked up to the cannon, the adjustable valve was used to obtain the desired internal pressure. Once the adjustable valve was set, the trigger was flipped to release the air in the chamber. Next, the trigger is moved back, and the golf ball is loaded, ready to be fired. It is necessary to release the current air in the chamber anytime the adjustable valve was changed as it would alter the firing power of the cannon with respect to the expected shot based on the pressure gauge reading.

**Shooting the Golf Ball**

Once the cannon was filled with the appropriate amount of pressurized air, the trigger was used to rapidly release this pressure, thereby accelerating the golf ball out of the cannon. It was crucial to the accuracy of the experimenting that the trigger be released extremely quickly on every test run. If the trigger is not released quickly, the calibration results become irrelevant and the golf ball is shot at an unknown velocity.
Hitting the Target
In order for the load cell to yield accurate data, the golf ball needed to collide with the shooting target perpendicularly and very close to the center. To ensure both of these criteria were met, only tests in which the golf ball rebounded perpendicular to the shooting target were recorded. Any other tests were disregarding as inaccurate data acquired by performing a “poor shot” of the air cannon.

Calibration
In order to calculate the physical parameters of the collision using the equipment at hand, the equipment being used needed to be calibrated. For the load cell, the voltage on the oscilloscope needed to be correlated to the actual force. The other calibration was associating the internal pressure of the air cannon with the exit velocity of the golf ball.

Load Cell
In order to calibrate the load cell, known weights were placed on the load cell and the voltage output on the oscilloscope was measured. Since the maximum force of the load cell is 1000 lbs and the maximum output voltage is 10 V, the gain needed to be set so that the maximum resolution could be reached without flat lining the output voltage. Assuming a linear correlation, the optimal equation relating the output voltage to the applied force is as follows:

\[ F_{\text{applied}} = 100 \cdot V \] (1)

When the gain was set to 160 on the amplifier, the following voltages were recorded with the associated forces in Table 2.

<table>
<thead>
<tr>
<th>Force (lbs)</th>
<th>Voltage (V)</th>
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<tr>
<td>25</td>
<td>.25</td>
</tr>
<tr>
<td>50</td>
<td>.50</td>
</tr>
<tr>
<td>75</td>
<td>.75</td>
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Table 2: Results of the load cell calibration.

This table demonstrates a linear correlation which corresponds with the equation listed above.

Air Cannon
Instead of using the light gates on every single trial to calculate the velocity of the golf ball as it exited the air cannon, a number of trials were run at different internal pressures in order to find the relationship between that pressure and the golf ball velocity.

First, the distance between the light gates was measured and recorded as 10.36 cm. In order to calculate the velocity, this distance was divided by the time elapsed between voltage blips on the oscilloscope. The internal pressure of the air cannon was measured using the pressure gauge on the outside of the chamber. Figure 10 illustrates the correlation found between the internal pressure of the air cannon and the exit velocity of the golf ball.
The fit curve demonstrates the following equation for correlated internal pressure to golf ball velocity.

\[ v_{golf \, ball} = 0.6783 \times P_{air \, cannon} - 16.531 \]  

(2)

This best fit curve has a correlation coefficient of 0.9538. Although there are slight fluctuations, this correlation certainly provides an accurate estimate of the exit velocity of the golf ball based on the reading of the pressure gauge on the air cannon.

**Comparison Criteria**

It is important to understand what physical properties of the collision will be used to compare the different backing materials based on the different foam padding samples. Using the load cell which is calibrated with the oscilloscope, a curve of the force applied over time will be displayed. A picture of a sample force curve from a collision with a steel anvil backing is shown in Figure 11.
From this curve, the key parameters of the collision can be recorded and calculated in order to compare them between the different testing setups.

**Peak Force**

One physical property of the collision is the instantaneous peak force. This value is measured very easily by simply finding the peak in the curve of force over time. It is an important parameter of the collision since it depicts the maximum force that would be felt by the individual wearing the padding.

**Time of Collision**

The total time of the collision is another physical property which characterizes the impact. This value is also easily measured by evaluating the force over time curve. It is an important parameter of the collision because as the time of the impact increases, the magnitude of the acceleration of the object decreases. The following kinematic equation shows why this is true given that the change in velocity is constant.

\[
\frac{dv}{dt} = a
\]

Acceleration and force can be correlated using Newton’s second law of mechanics.
\[ F = m \times a \quad (4) \]

Given that this experiment uses a constant mass, Equation 4 shows why increasing the acceleration increases the force applied. Therefore, increasing the time of collision decreases the average force of the collision.

**Average Force Applied**

Another physical property of the collision is the average force applied throughout the impact. In order to evaluate this parameter, the oscilloscope can be used to extract the average voltage throughout the collision. With the average voltage, the average force is easily calculated using the load cell calibration. It is an important parameter of the collision since it depicts the average force that would be felt by the individual wearing the padding.

**Total Impulse**

The total impulse generated from the collision describes the change in momentum of the projectile. Physically, impulse is defined as the integral of a force with respect to time, as shown in the following equation.

\[ I = \int_{t_1}^{t_2} F(t) \, dt \quad (5a) \]

Since the average force had already been measured, this equation can be simplified.

\[ I = F_{\text{ave}} \times t_{\text{collision}} \quad (6) \]

Knowing the total impulse helps understand the impact of the golf ball in terms of its total momentum changed by the collision.

**Energy Dissipated**

The amount of energy dissipated in the collision is an extremely important physical property characterizing the impact. Depending on the application of the foam padding, it can either be beneficial or disadvantageous to have a lot of energy dissipated by the padding. In sporting goods products, it is often advantageous to dissipate a lot of energy in order to reduce the velocity of the projectile. In more dangerous collisions, though, dissipating too much energy in the impact can lead to more serious injuries.

In order to calculate the amount of kinetic energy dissipated, we start with the equation for the kinetic energy of a moving object.

\[ E = \frac{1}{2} m v^2 \quad (7) \]

The mass before and after the collision remains constant, and the initial velocity is known from the light gates. To calculate the change in energy, we manipulate the impulse equation in order
to calculate the velocity after the impact. To start, we rewrite Equation 5 substituting for the force as a rate of change of momentum.

\[ I = \int_{t_1}^{t_2} \frac{dp}{dt}(t) \, dt \]  

(5b)

Using the constant average force for the time of the collision, this integral can be simplified to the following expression.

\[ I = \Delta p = m(v_2 - v_1) \]  

(8)

From Equation 8, we can calculate the velocity of the golf ball after the collision, allowing us to then determine the change in energy before and after the collision using Equation 5.

**Results and Discussion**

The results of this experiment show that although testing with a steel anvil generally demonstrates which padding specimen is more protective than the other, it conceals a lot of the physical characteristics of the foam padding. Using urethane foam as a backing for testing to replicate the human body more clearly depicts the force the person will feel as a result of an impact.

**Analysis of Results**

Three separate metrics were used to summarize how protective each padding specimen was given the other system parameters, golf ball velocity and padding backing. The three different metrics were peak force, total impulse, and energy dissipated. Each of these three metrics were compared across the different specimens under different velocities in order to evaluate how changing the padding backing affected the results of the experiment. The method by which these metrics were calculated are enumerated in the section labeled Comparison Criteria.

**Peak Force**

The most straightforward metric for evaluating the protection of the different padding specimens is simply recording the maximum force recorded by the load cell during an impact event. After taking many samples, the average peak force was calculated for each foam specimen given a specific impact velocity and type of padding backing used. The results of these measurements are summarized in Figure 12.
Looking at this graph, it is clear that the steel anvil and the urethane foam both rated the three specimens in the same order for each velocity. Although foam specimen 1 always recorded the highest peak force and foam specimen 3 always recorded the lowest, the urethane backing provides a more detailed outlook on the differences between the specimens. The steel anvil made it appear as though the difference between each padding specimen at each of the velocities is fairly similar. However, the urethane backing illustrates that specimens 2 and 3 are quite similar, and that as the impact velocity increases the differences between the more protective padding samples and specimen 1 diminishes.

**Total Impulse**

Another parameter which characterizes the collision is the total impact. This calculation quantifies the force versus time curve of the impact, rather than just highlighting the specific maximum force at one instant in time. The average total impulse was calculated for each foam specimen given a specific impact velocity and type of padding backing used based on the average force of the collision and the time elapsed during the collision. The results of these calculations are shown in Figure 13.
Figure 13: Graph plotting total impulse versus impact velocity for each padding specimen.

Similar to the peak force graph shown in Figure 12, the ordering of the specimens based on the magnitude of total impulse was similar between the steel anvil and the urethane foam. However, this graph also demonstrates how the steel anvil testing portrayed very little difference between the three specimens in terms of total impulse. The tests run using urethane foam showed very different patterns between the specimens.

In order to explain these different patterns for the different specimens, the actual force curves needed to be examined. Figure 14 is an example of a force curve for specimen 1 in front of urethane foam backing shot at a high golf ball velocity.
In this force curve, it is very evident where along the curve the foam is compressing before finally the urethane backing is fully compressed, causing the load cell to spike as it experiences the rest of the impact. This is what the curve looked like for all of the urethane backing impacts where the golf ball velocity was high enough to fully compress the backing. It is very obvious how this force curve is different from the steel anvil testing results displayed in Figure 11.

For some of the low velocity testing in front of urethane foam, though, the collision did not cause the foam to fully compress. An example of the curve of force over time from one of these tests is seen in Figure 15.
This force curve shows no significant spike, which means the urethane foam backing never fully compressed. Looking back at Figure 13, the extreme variance in data points between different velocities and specimens can now be explained. For specimen 2, the lowest velocity impact did reach full compression, and for specimen 3, only the highest velocity achieved full compression. This is a whole different aspect of the collision which the steel anvil testing neglects.

**Energy Dissipated**

The final metric by which the different specimens were compared for the different padding backings was the energy dissipated by the collision. Using the change in kinetic energy, the energy dissipated by the foam padding can be calculated. The results of these calculations are summarized in Figure 16.
Figure 16: Graph plotting energy dissipated versus velocity for each padding specimen.

This graph illustrates that for this metric, there is no difference between testing using a steel anvil backing and using a more humanlike material such as urethane foam.

Discussion of Errors

Although the experimental testing was designed to eliminate external variables in order to have completely controlled results, there were some aspects of the setup which may have caused some variance in the results.

One possible cause of variance was the velocity at which the golf ball was actually shot out of the air cannon on each test run. There was a slight leak in the direct air line, so the adjustable valve had to be altered frequently in order to obtain the exact internal shooting pressure for a specific velocity. Shooting at slightly different velocities could have affected the output readings of the load cell.

Another source of experimental error may have resulted from not hitting the target in the exact same location on every test. The trajectory of the rebound of the golf ball was used to assess whether or not the shot had been a good hit. Any data gathered in tests where the golf ball bounced off of the side of the target were eliminated, but there still could have been a difference in the results between hitting the target exactly in the middle and missing by an inch or two.

Finally, due to a faulty output port from the amplifier, the load cell needed to be switched to a different channel. Because the gain of the amplifier was not equal across both channels, the testing apparatus needed to be taken apart so that the load cell could be recalibrated. Although
the load cell was calibrated using the same method both times, there may have been some unforeseen inconsistencies with how the impact system was put back together, resulting in a slight offset between the results before and after second calibration.

Summary and Conclusion
The results discussed earlier show that the approach taken for this experiment show some improvements over industry methods for testing foam padding samples. Although using the steel anvil backing lead to generally similar recommendations for the best padding, it does not capture a lot of the details which are necessary to truly understand how different foam specimens compare with each other.

Summary of Findings
The primary findings of this experiment were in regards to the differences found between testing padding with a steel anvil backing versus testing padding with a more human behaving backing. Based on the graphs of the three metrics used to characterize the protectiveness of the padding specimens, two main conclusions are drawn regarding the difference between the steel anvil and urethane foam setups: the difference in the shape of the force over time curves and the significance of changing the velocity of the impact. Although the steel anvil testing is generally accurate in ranking the foam specimens based on the three metrics used, these other more detailed analysis shed more light on the physical properties of the collision.

Difference in Force Curves
When looking at the visual curve of force over time displayed by the oscilloscope, the physical difference between the steel anvil backing and the urethane foam backing is more obvious. In the case of the steel anvil, the force curve is symmetric before and after the instantaneous peak force, regardless of the impact velocity. This force curve is exemplified by the oscilloscope output shown in Figure 11.

When the testing was done in front of the more human behaving urethane foam, the force curve is more complex. Not only is it more than just a simple peak which rises and falls almost linearly, there are also two different regimes dependent on whether or not the impact reaches a critical threshold. The first regime is defined as the impacts in which the foam backing does not fully compress, and an example of this force curve is shown in Figure 15. This type of impact can be related to an impact on the human body where the skin slightly deforms, but no significant load is exerted on the flesh underneath.

Once the impact is great enough to reach the second regime, a spike in the force curve resembling shape of the steel anvil test results is seen after the foam is compressed. An example of this force curve is shown in Figure 14. In this case, the human body would feel a significant force.
With this in mind, whether or not the second regime is reached is a vital characteristic of the collision. It defines whether or not there is potential to do significant damage to the human body given the other parameters of the collision. The steel anvil backing lacks any capacity to test or predict which impacts are severe enough to cause serious injury.

**Increasing Velocity**

Because the steel anvil characterizes every collision with a similarly shaped force curve, it fails to demonstrate how increasing the velocity affects the key metrics of the collision. In this experiment, increasing the velocity was the method for increasing the overall impact. For all three metrics, increasing the velocity increased the values for each of the three specimens approximately the same amount.

When looking at the urethane foam testing, though, more detailed results of how increasing the velocity affects the results of the collision are shown. This is a direct result of the analysis on the different impact regimes previously described.

This new testing system is most applicable for determining which type of padding is best suited to provide sufficient protecting given a specific impact. For example, Figure 12 illustrates how the steel anvil testing correctly depicts that given a certain impact, specimen 1 will result in the highest peak force, followed by specimen 2, followed by specimen 3. However, the urethane foam testing provides further insight. Specimen 2 and specimen 3 yield much lower peak forces than specimen 1 at lower velocities, yet as the velocity increases their differences moderate.

Using a padding backing which more accurately represents human flesh allows the testing to give more detailed results, and these detailed results allow the user to best choose which specimen is most suitable given the known application of the padding.

**Assessment Concerning Hypothesis**

The hypothesis of this experiment states that comparing different samples of foam padding in front of a humanlike backing will yield more accurate relative results than if they were tested in front of a steel anvil.

Given the detailed results of this project’s experimental testing, the hypothesis stated above has been demonstrated, but not proven. All of the data collected lends itself toward agreeing that the urethane backing provides more accurate and detailed results than the steel anvil, but more data would be necessary to verify the hypothesis.

**Suggestions for Future Work**

As mentioned previously, the experimental testing for this project shows promising trends, but more research would be necessary to make final conclusions. Doing similar testing with many more foam specimens would allow for greater confidence in the theory behind using padding backing with more humanlike physical characteristics.
There are many other aspects of the data collection which could be broadened to provide more insight on the effect of changing the padding backing. For example, instead of shooting projectiles to generate an impact, a mass and pendulum approach could be taken which would be even more accurate given that the kinetic and potential energy of the system would be very controlled. Also, changing specific parameters such as the mass of the projectile and the effective area impacted would further validate the experimental results.

Another specific aspect of the experiment which could have been improved was the exact measuring of the force curve on the oscilloscope. This project did not yield enough time for this, but using a numerical software program to analyze the curve of force over time would have allowed for more detailed analysis of the results, such as curve fitting. This curve fitting could provide even more insight of how changing the padding backing affects the overall testing results of different foam specimens.
List of References


