Exploring the relationship between the pressure of the ball and coefficient of restitution.

When I started thinking about possible investigations I knew I wanted to create a lab that was related to sports. After a number of ideas, I thought that changing the pressure of the ball would be a good independent variable and the rebound height of the dropped ball would be a good dependent variable. This was very interesting to me because I had just started basketball season and it's always a struggle finding a good ball to use at practice. Some balls are too bouncy and others are under inflated. My sister and I are also very particular about our soccer balls. When the ball is over inflated it's harder to control, and when it is under inflated the trajectory of the ball is altered.

I finalized my investigation to deal with the rebound height of different size soccer balls when they rebound off of different materials with different pressures, and that I should test the rebound height of the ball when it is under inflated and over inflated.

After some research I discovered that the ideal pressure for a size 5 soccer ball is 6-8 Lbs. FIFA measures the pressure of the ball in bars but for this experiment I will use lbs. In physics we usually talk about air pressure in atmospheres, but for soccer balls the pressure is usually measured in Lbs. or bar.

<u>Coefficient of Restitution</u>

The coefficient of restitution is a mathematical way of showing the elasticity of a collision. It can be used when two moving objects collide or when a moving object hits a stationary object. In my investigation a moving object (a soccer ball) will collide with the ground. There are many formulas to calculate the coefficient of restitution depending on the data that you are given, but the one listed below specifically deals with the height of ball bounces.

$$C_R = \sqrt{\frac{\text{Rebound Height}}{\text{Initial Height}}}$$

If the collision is perfectly elastic, meaning that no energy is transferred, the coefficient of restitution will be 1. Collisions are not perfectly elastic because energy is lost on collision. If the coefficient of restitution is 0, the collision is completely inelastic and all energy is transferred from the ball to the ground, friction, sound, heat and other forms of energy loss. This would mean that when the ball drops, it doesn't bounce back.

<u>Energy Transfer in this experiment</u>

The soccer ball is first raised up to a specific height. In this action energy is being transferred from the person to the ball. When the ball is resting at its maximum height all of its energy is gravitational potential. As the ball is released, gravity accelerates it towards the ground. As it is accelerating, the energy is transferred from potential energy to kinetic energy. The instant it hits the ground all of the energy is kinetic energy but it is quickly transferred to elastic potential energy when the ball deforms. The elastic potential energy is then transferred to kinetic energy again when the ball rebounds back up. This kinetic energy is then transferred to gravitational potential energy. At any part in the path of the ball, the energy is a combination of kinetic and potential.

When the ball rebounds back up it will not reach its original height due to energy loss. The energy loss occurs when the ball hits the ground. Energy is loss to sound and heat. When the ball loses energy it is not able to reach its maximum height.

Research Questions: What are the optimal conditions for a bouncing soccer ball to achieve the maximum rebound height?

Independent Variable: In this experiment I will be testing the impact of three different variables on the rebound height of the ball. The most important variable that I will be changing is the pressure of the soccer ball. In order to enhance this experiment I will change the surface that the ball bounces on. The three surfaces that I will be using are grass, stone and dirt. I will also be investigating if the size of the ball affects the rebound height. I will be using size 1, size 3 and size 5 soccer balls.

Dependent Variable: The dependent variable in this experiment will be the rebound height of the soccer ball.

Control Variable: In this experiment there are many control variables that will be put in place to ensure our results are as accurate as possible. Control variables are used to ensure that only one variable is being changed in each experiment. Since this investigation deals with three independent variables, only one will be changing at a time. Here is a list of the control variables:

Height that the ball is dropped: The ball will always be dropped from 150cm above the test surface.

Surface that the ball is being dropped on: When I change the pressure of the ball the surface will remain the same for all trials.

Soccer ball: The size 5 soccer ball that is used will always be the same for every trial. The same goes for the size 1 and size 3 soccer balls.

Materials: Laptop, Vernier LabPro interface, Motion sensor, Meter stick, Air pressure gauge (measured in Lbs.), Air pump, Size 1 soccer ball, Size 3 soccer ball, Size 5 soccer ball, Grass area, Dirt area, Limestone Area, Pole (at least 1.5 meters high), Chair/table to help hold apparatus during data collection.

Procedure

1. Stick a pole into the dirt surface where you will be doing the first experiment.
2. Put tape on the stick 150cm above the ground.
3. Set up the motion sensor and Vernier to your laptop.
4. Using chairs/ tables place the motion sensor approximately 175cm above the ground. Make sure it is set up beside the pole. (I had to move my pole to make it work with the motion sensor.)
5. Inflate size 5 soccer ball to 12 Lbs.
6. Hold up the ball so the middle is at the tape (150cm).
7. Start collecting data with LabPro
8. Drop ball.
9. Stop data collection when ball has bounced and returned to the ground
10. Save data.
11. Complete 3-5 trials for each ball, pressure and surface.
12. Once all trials are completed, analyze data and record in data tables.

Safety/Setup Considerations:

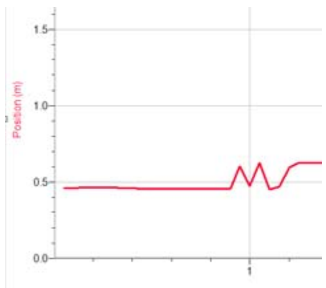
- Ensure the motion sensor is securely placed on the table. Use tape to keep it down if necessary.
- Place your laptop as far from the bouncing ball as possible to ensure it does not get hit by the rebounding ball.

Data and Processing:

I collected the data with the motion sensor and saved the data (data table and graph) on my laptop. Once I was finished collecting all the data for my investigation I analyzed each trial and recorded the initial and rebound height.

Here is a screen shot of what the graph looks like when a ball is dropped. This graph is one of practice drops, but it clearly shows what an ideal bounce would look like. The y axis shows the position of the ball from the motion sensor, not from the ground. In this example the ball starts 0.456 meters away from the sensor.

Beside seeing a visual of change in position, LabPro records the data (see next page) in a table and a graph (on the right).



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From 0.80 to 0.90 seconds, the ball is still at its original position. At 0.95 seconds the ball hits the ground, bounces back up at 1.00 seconds and returns to the ground at 1.05 seconds.

To calculate the distance it bounced up I looked at the position column. The ball starts 45.6cm from the motion sensor. It then hits the ground that is 60.2cm from the motion sensor. This means the ball dropped 14.6 cm (60.2-45.6). The ball then bounces back up where it is now 47.0 cm away from the motion sensor. The ball rebounded 13.2cm (60.2-47.0) after it hit the ground.

	Time (s)	Position (m)
16	0.80	0.456
17	0.85	0.455
18	0.90	0.454
19	0.95	0.602
20	1.00	0.470
21	1.05	0.623
22	1.10	0.449
23	1.15	0.469
24	1.20	0.595
25	1.25	0.626
26	1.30	0.626
27	1.35	0.626
28	1.40	0.626

The tables below show the data collected from my experiment. The processed data for this lab is the coefficient of restitution. I have included the coefficient of restitution in the raw data table so you can easily see how when the rebound height decreases, the coefficient of restitution decreases. I expected to see this relationship because a lower coefficient of restitution means the collision is more inelastic, and a lower rebound height means that more energy is lost during the collision.

Size 1 Soccer Ball

Stone	Pressure (+/- 0.5lbs.)				
Height rebounded	10.0	8.0	6.0	4.0	2.0
Trial 1(+/- 0.1cm)	110.3	87.4	43.0	20.4	6.2
Trial 2(+/- 0.1cm)	107.1	85.6	42.3	23.3	4.4
Trial 3(+/- 0.1cm)	108.6	87.8	44.7	24.8	6.0
Average (+/- 0.01cm)	108.7	86.9	43.3	22.8	5.5
Coefficient of restitution (+/- $3.8x10^{-3}$)	0.9	0.8	0.5	0.4	0.2

Dirt	Pressure (+/- 0.5lbs.)				
Height rebounded	10.0	8.0	6.0	4.0	2.0
Trial 1(+/- 0.1cm)	0.3	2.8	6.2	9.3	0.0
Trial 2(+/- 0.1cm)	0.0	0.0	4.7	11.5	0.0
Trial 3(+/- 0.1cm)	0.0	0.0	5.5	13.1	0.0
Average (+/- 0.01cm)	0.1	0.9	5.5	11.3	0.0
Coefficient of restitution (+/- 0.0)	0.0	0.1	0.2	0.3	0.0

Grass	Pressure (+/- 0.5lbs.)				
Height rebounded	10.0	8.0	6.0	4.0	2.0
Trial 1(+/- 0.1cm)	87.3	68.6	33.9	21.2	4.0
Trial 2(+/- 0.1cm)	79.1	71.1	32.3	18.4	7.6
Trial 3(+/- 0.1cm)	82.8	74.7	29.0	18.9	6.1
Average (+/- 0.01cm)	83.1	71.5	31.7	19.5	5.9
Coefficient of restitution (+/-$3.2x10^{-3}$)	0.7	0.7	0.5	0.4	0.2

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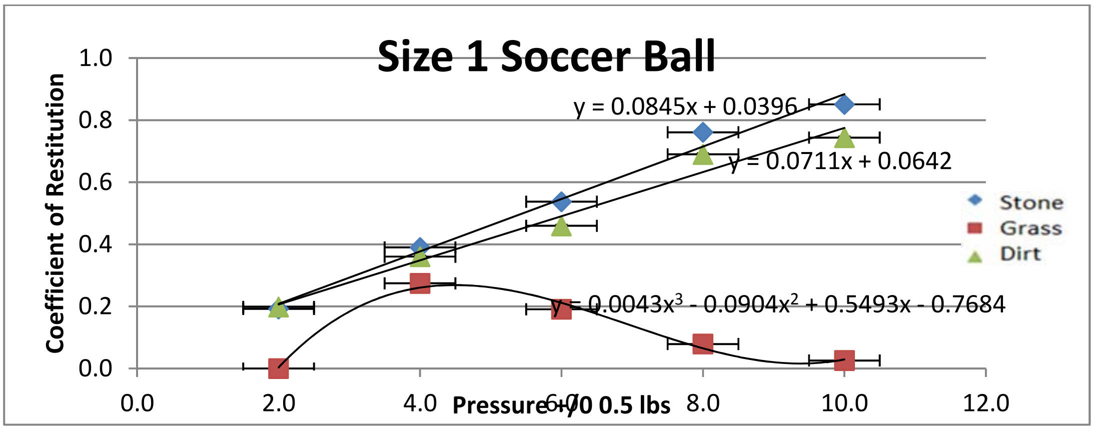


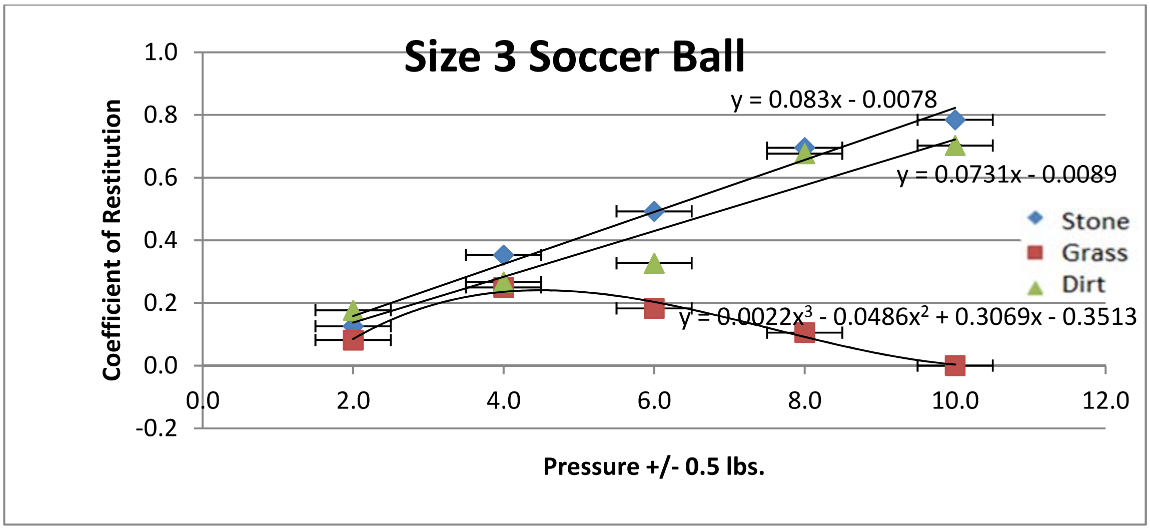
Graph 1: Coefficient of Restitution for size 1 soccer ball. The three different symbols represent different surfaces. ****Vertical error bars are too small to be visible****

Size 3 Soccer Ball

Stone	Pressure (+/- 0.5lbs.)				
Height rebounded	10.0	8.0	6.0	4.0	2.0
Trial 1(+/- 0.1cm)	92.0	72.7	34.3	13.8	2.1
Trial 2(+/- 0.1cm)	92.8	72.1	41.0	25.2	1.8
Trial 3(+/- 0.1cm)	92.1	73.0	33.8	17.1	3.2
Average (+/- 0.01cm)	92.3	72.6	36.4	18.7	2.4
Coefficient of Restitution (+/-$3.6x10^{-3}$)	0.8	0.7	0.5	0.4	0.1

Dirt	Pressure (+/- 0.5lbs.)				
Height rebounded	10.0	8.0	6.0	4.0	2.0
Trial 1(+/- 0.1cm)	0.0	3.0	4.0	9.0	0.0
Trial 2(+/- 0.1cm)	0.0	2.0	6.0	8.0	3.0
Trial 3(+/- 0.1cm)	0.0	0.0	5.0	11.0	0.0
Average (+/- 0.01cm)	0.0	1.7	5.0	9.3	1.0
Coefficient of Restitution (+/- 0.0)	0.0	0.1	0.2	0.2	0.1

Grass	Pressure (+/- 0.5lbs.)				
Height rebounded	10.0	8.0	6.0	4.0	2.0
Trial 1(+/- 0.1cm)	72.0	71.0	25.0	11.0	4.0
Trial 2(+/- 0.1cm)	76.0	67.0	22.0	13.0	6.0
Trial 3(+/- 0.1cm)	74.0	68.0	1.0	8.0	4.0
Average (+/- 0.01cm)	74.0	68.7	16.0	10.7	4.7
Coefficient of Restitution (+/-$3.3x10^{-3}$)	0.7	0.7	0.3	0.3	0.2



Graph 2: Coefficient of Restitution for size 3 soccer ball. The three different symbols represent different surfaces. ****Vertical error bars are too small to be visible****

Size 5 Soccer Ball

Stone	Pressure (+/- 0.5lbs.)				
Height rebounded	12.0	9.0	7.0	4.0	2.0
Trial 1(+/- 0.1cm)	87.8	73.1	41.3	17.2	6.1
Trial 2(+/- 0.1cm)	92.9	67.0	39.6	21.5	5.8
Trial 3(+/- 0.1cm)	89.3	74.7	43.2	18.2	4.2
Average (+/- 0.01cm)	90.0	71.6	41.4	19.0	5.4
Coefficient of Restitution (+/- 3.5×10^{-3})	0.8	0.7	0.5	0.4	0.2

Dirt	Pressure (+/- 0.5lbs.)				
Height rebounded	12.0	9.0	7.0	4.0	2.0
Trial 1(+/- 0.1cm)	0.0	3.0	6.0	9.0	0.0
Trial 2(+/- 0.1cm)	0.0	0.0	4.0	11.0	0.0
Trial 3(+/- 0.1cm)	0.0	0.0	5.0	13.0	0.0
Average (+/- 0.01cm)	0.0	1.0	5.0	11.0	0.0
Coefficient of Restitution (+/- 0.0)	0.0	0.1	0.2	0.3	0.0

Grass	Pressure (+/- 0.5lbs.)				
Height rebounded	12.0	9.0	7.0	4.0	2.0
Trial 1(+/- 0.1cm)	79.0	62.4	38.1	16.0	5.7
Trial 2(+/- 0.1cm)	80.8	63.1	37.8	15.4	4.3
Trial 3(+/- 0.1cm)	76.8	67.9	40.3	13.2	6.0
Average (+/- 0.01cm)	78.9	64.5	38.7	14.9	5.3
Coefficient of Restitution (+/- 3.2×10^{-3})	0.7	0.7	0.5	0.3	0.2

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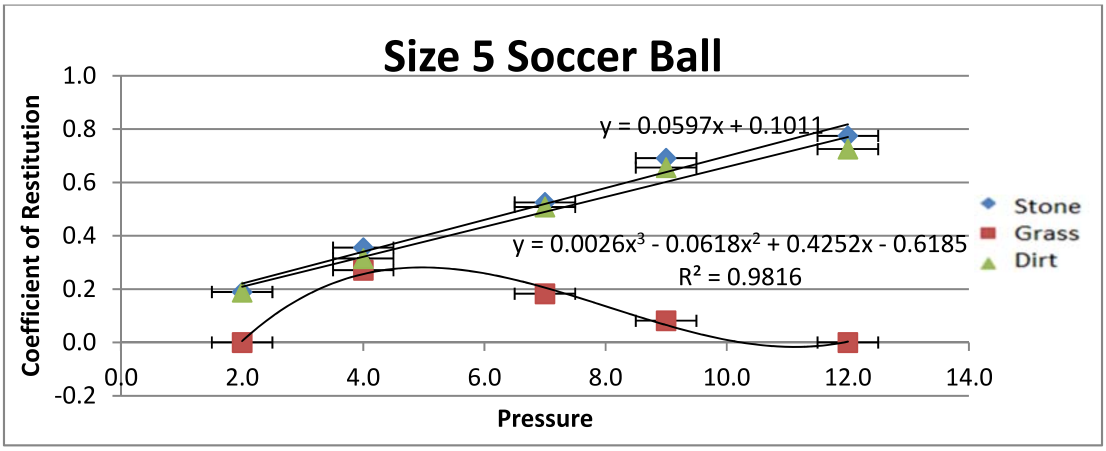
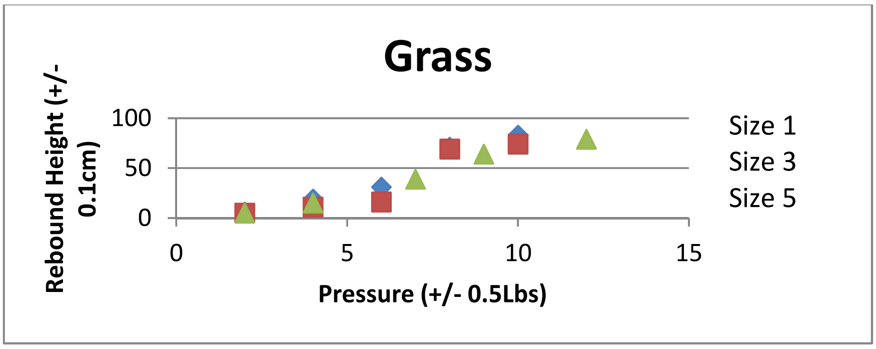
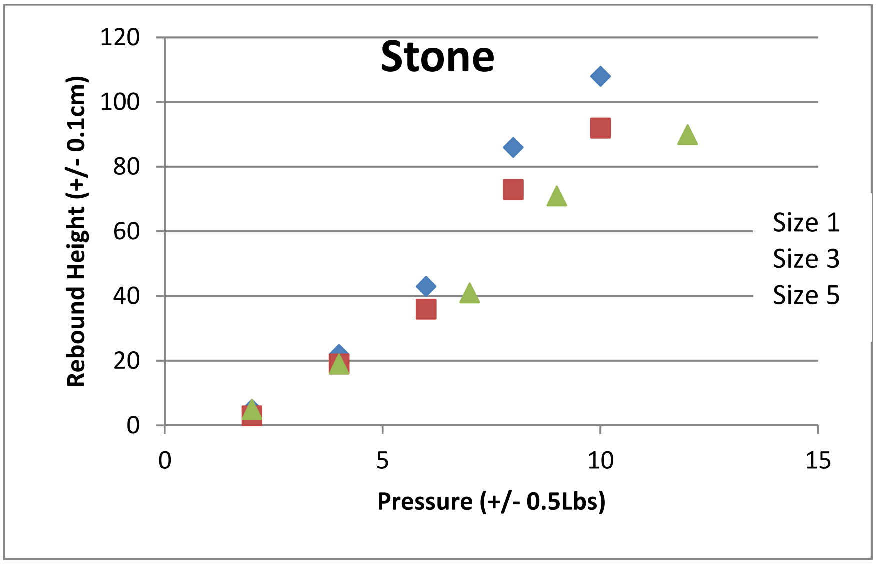


Graph 3: Coefficient of Restitution for size 5 soccer ball. The three different symbols represent different surfaces. ****Vertical error bars are too small to be visible****



Graph 4: The above graph shows the rebound height of the three balls when they are dropped on grass.



Graph 5: This graph shows the rebound height of the three balls when they are dropped on stone.

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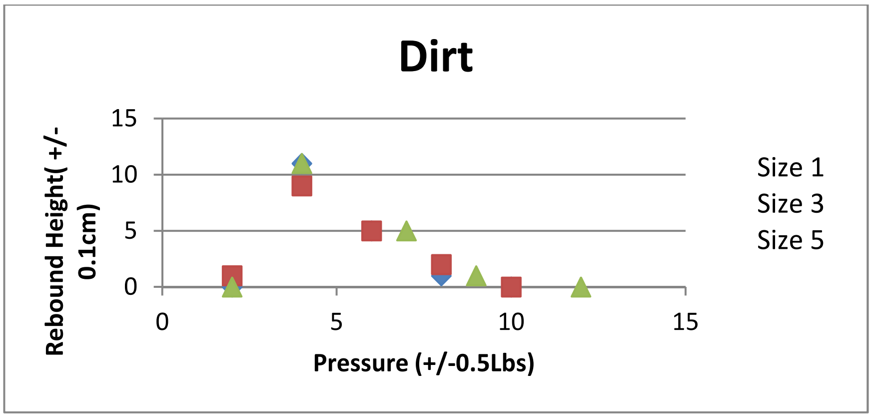

Graph 6: This graph shows the rebound height of the three balls when they are dropped on dirt.

Conclusion and Evaluation

This experiment confirms the relationship between the pressure of a soccer ball and the rebound height of the ball. I also investigated if the surface which the ball bounced on affects the rebound height. The data I have collected shows the same relationship for all three sizes of soccer balls. For grass and stone, the rebound height increased as the pressure increase. A linear trendline was used to fit the data. When the ball bounced on dirt, all three sizes responded the same way to a change in pressure. At the highest and lowest pressure, the rebound height was 0 except the size three ball rebounded 1cm when the pressure was 2 lbs. As the pressure increased by 2 lbs. the rebound high increased approximately 12cm. This was the maximum height reached by the ball when it bounced on dirt. As the pressure increased from 4 lbs. to 10 lbs. the rebound height decreased linearly.

When the soccer balls were dropped with the same pressure on the three different surfaces, the rebound height was the highest with the stone, followed by the grass and then the dirt. The rebound height was higher with the stone than the grass because there is some grass between the ball and the grass. Although the ball was not rolling on the grass, there is friction as the ball falls vertically through the blades of grass. As the ball falls on the grass the blades bend out to the side from the weight of the ball. This is evident when you look at the grass after the ball hit the ground; you can see an indent in the grass. The friction between the stone and the soccer ball is negligible in comparison with the friction presented by the grass. The ball's higher rebound height on the stone is also due to the compactness of the different materials. The stone is a much denser than the grass which means the ball deforms more as it hits the stone causing it to lose less energy when it rebounds. The grass is cushioning the ball as it hits the ground which causes the rebound height to be reduced.

When the ball bounced on dirt at low pressure our results were expected, the ball reached a very low rebound height. As the pressure increased the ball started to bounce higher, again this is what I expected. The results then veered away from my hypothesis as I continued to increase the pressure. When the pressure reached about 6 lbs. the rebound high started to decrease again. This can be seen in graph 6. I think that this trend was observed because as the pressure increased, the ball became firmer. When the ball became firmer it hit the ground with a greater power. This caused a bigger indent in the dirt (since it was soft) which cushioned the ball.

If energy is never created or destroyed, why do some balls bounce higher than others if they are dropped from the same height? Since they are dropped from the same height, they have the same amount of energy. My conclusion is that when an under inflated ball hits the ground, the ball is more deformed than when an over inflated ball hits the ground. When the ball is deformed to a large magnitude, a larger portion of the surface hits the ground. This means that more energy is transferred into the ground. Also since there are fewer gas molecules in the ball, it is harder for the ball to regain its original shape. When the ball deforms the area inside the ball is essentially smaller. This means that the air molecules are colliding with the side of the ball more frequently causing the ball to regain its shape. When the ball is regaining its shape and the area increases, the number of collisions with the surface of the ball decreases. This means that there are weaker forces to 'push' the ball off the ground. With a high pressure the number of molecules inside the ball is greater. This means that as the ball deforms the collisions between the molecules and the soccer ball are more powerful and at a greater frequency. This causes the ball to rebound faster and with a greater magnitude.

The dirt was not very hard packed so it 'cushioned' the balls as they fell. This was a source of energy loss. Due to the 'cushion' effect of the dirt, the rebound height was significantly lower than stone and grass. This can be seen in graph 1, graph 2 and graph 3.

Besides energy loss to sound, heat and friction as the ball hit the surface, there was energy loss due to air resistance. When the ball fell from its initial height I assumed that all the energy was transferred to kinetic but in fact some energy is transferred to the air. Therefore it is not possible to reach the initial height when it rebounds back up, even if no energy was transferred to sound, heat or friction on the ground.

The unevenness of the surfaces also caused some problems with the data collection. The ball did not always bounce in a perfectly vertical manner. It would rebound on an angle causing the motion detection to record incorrect values. Since the ball was traveling at an angle, the vertical component of it was smaller than it would have been if it bounced straight up.

When processing my data I was only concerned with the first rebound height, not the successive bounces. The data for the first rebound height seemed to follow a general trend and the trials seemed to be precise but I don't think the actually values for the rebound height are accurate. Some trials show that the second rebound is higher than the first rebound. From

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qualitative observations I know that this did not occur. This confirms that the motion sensor was not always collecting the maximum height of the rebound. This will be discussed in further detail when I explain improvements to the lab.

To improve this investigation I could ensure all the balls were made from the same brand and made from the same material. The material of the soccer balls used in this experiment were all different. The different materials have different properties that could have made them react differently on the three surfaces. The material of the size 3 soccer ball seemed worn in comparison to the size 1 and size 5 soccer balls.

Next time I would have used a dirt surface that was harder packed. Since the dirt was lightly packed every trial made the dirt harder packed for the next trial. This means that the later trials would essentially be bouncing on a different surface because the dirt would become less ‘absorbent’ as the ground compresses.

To improve my investigation I would set LabPro to collect data from the motion sensor every 0.01 seconds instead of every 0.05 seconds. Since the ball bounces so quickly, it could have reached hit the ground and start bouncing back up before data is collected for its maximum displacement. If the data was taken every 0.01 seconds our data would be more precise to the real displacement of the ball.

To further investigate the optimal conditions for a soccer ball I could explore the relationship between the design in the leather and rebound height. Different balls have different aerodynamics due to the different design of the ball. Some are made out of hexagons and pentagons (the traditional way) while others are made with irregular shapes. The aerodynamics of the ball affects the velocity that the ball has when it hits the ground. I would expect that at different velocities the rebound height would change.