How does the height a tennis ball is dropped from affect the percentage it rebounds back to?

Alex Nguyen
Tualatin High School

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Background information - .:. Top

The game of tennis was developed in the 1870s from the game of real tennis, a game that had been played for centuries already. The game consists of two or four players from different sides of a net hitting the ball back and forth, aiming to score the most points and beating the opposing side. The tennis ball has had multiple iterations, ranging from the original white rubber ball, which was solely made of rubber and consisted of pressurized gas, to the modern yellow ball that was introduced in 1986. Today, the iconic yellow tennis ball is used for the sport, and ranges from a mass of 56.0 to 59.4 grams, and a diameter from 6.54cm to 6.86 cm. Tennis balls are filled with air and are surrounded by a felt rubber.

Gravitational potential energy is defined as the energy an object has when it is in a gravitational field. This energy is stored when an object is lifted to certain heights. The gravitational potential energy of an object, or the ball in this case, is dependent on the mass of the object and the height at which it is raised. Objects that have more mass have greater gravitational potential energy when raised to the same height. There is also a relation between the potential and the height of an object as when the object is elevated higher, it has greater potential energy. These relationships can be expressed through the following equation:

$$PE_{grav} = mass * g * height.$$

The variable ‘g’ represents the gravitational field strength which is (9.81 N/kg on Earth) and it is also referred to as the acceleration of gravity. The ball can bounce/rebound due to the elastic potential energy it has. When the ball is lifted to a certain height, it has potential energy but when it is dropped, its potential energy is converted to kinetic energy as the force of gravity pulls it down. As it gets closer to the ground, the potential energy decreases but since it speeds up, its kinetic energy increases. The ball can rebound because it stores elastic potential energy, which is transformed into kinetic energy once it hits the surface. As the ball journeys back to where it began, the velocity and acceleration vectors point upward, but due to elasticity it pushes against the surface with a force greater than its weight and bounces upward. However, the ball can never rebound to its original height due to a limited capacity for storing elastic potential energy. Though energy cannot be lost based on the law of conservation of energy, it can change form. When the ball hits the floor, it loses kinetic energy as some of it is transferred into the ground, as well as the sound of the ball.

Statement of the problem :

The purpose of this investigation is to find out the relationship between the height at which a tennis ball is dropped, and the percentage of its initial height it rebounds.

Hypothesis:

If the ball is dropped at a higher height, the percentage that it rebounds back to the original height will only be slightly larger since while it will be able to store more gravitational potential energy, there is still a limited capacity with which the ball can store elastic potential energy. The variables include the original height at which the ball is dropped and will be measured in centimeters. I will then measure the height it rebounds to and calculate the percentage of its original height.

Materials

- Penn 2 Tennis Ball
- Measuring Tape
- Step-stool
- iPhone 11 digital camera
- Wooden floor

Variables

I. Independent variable: Drop height of tennis ball (cm)
II. Dependent variable: Rebound percentage of ball (cm)

III. Controlled variables :

A. Mass and Radius of Tennis Ball

i. Reason: Different tennis balls will have different masses and vary in compression. This would affect the rebound height.

ii. Method: The same Penn 2 tennis ball was used to perform the experiment

B. Type of floor

i. Reason: The ball has to be dropped onto the same floor to uphold consistency. Different floors depending on their compactness will affect the elastic energy.

ii. Method: The ball was dropped onto a sturdy wooden floor for every trial. This would minimize errors when collecting data.

Experimental Design .:. Top

This investigation aims to determine if a tennis ball's rebound percentage changes when dropped at differing heights. I will limit my study to the same tennis ball as well as the floor it will rebound upon. The **independent variable** is the drop height of the tennis ball in centimeters. The ball will be held up to the specified height and dropped by myself. Since some heights will not be able to be exact, there is an uncertainty of .05 centimeters,

The **dependent variable** is the rebound percentage of the tennis ball. Once dropped to the specified height, H, the ball will rebound one time after the first impact. The maximum height in between the first and second bounces will be measured as the rebound height, X. The percentage of rebound will then be calculated from the equation **X/H**, where X is the rebound height, and H is the initial drop height.

Methodology .:. Top

Experiment set-up

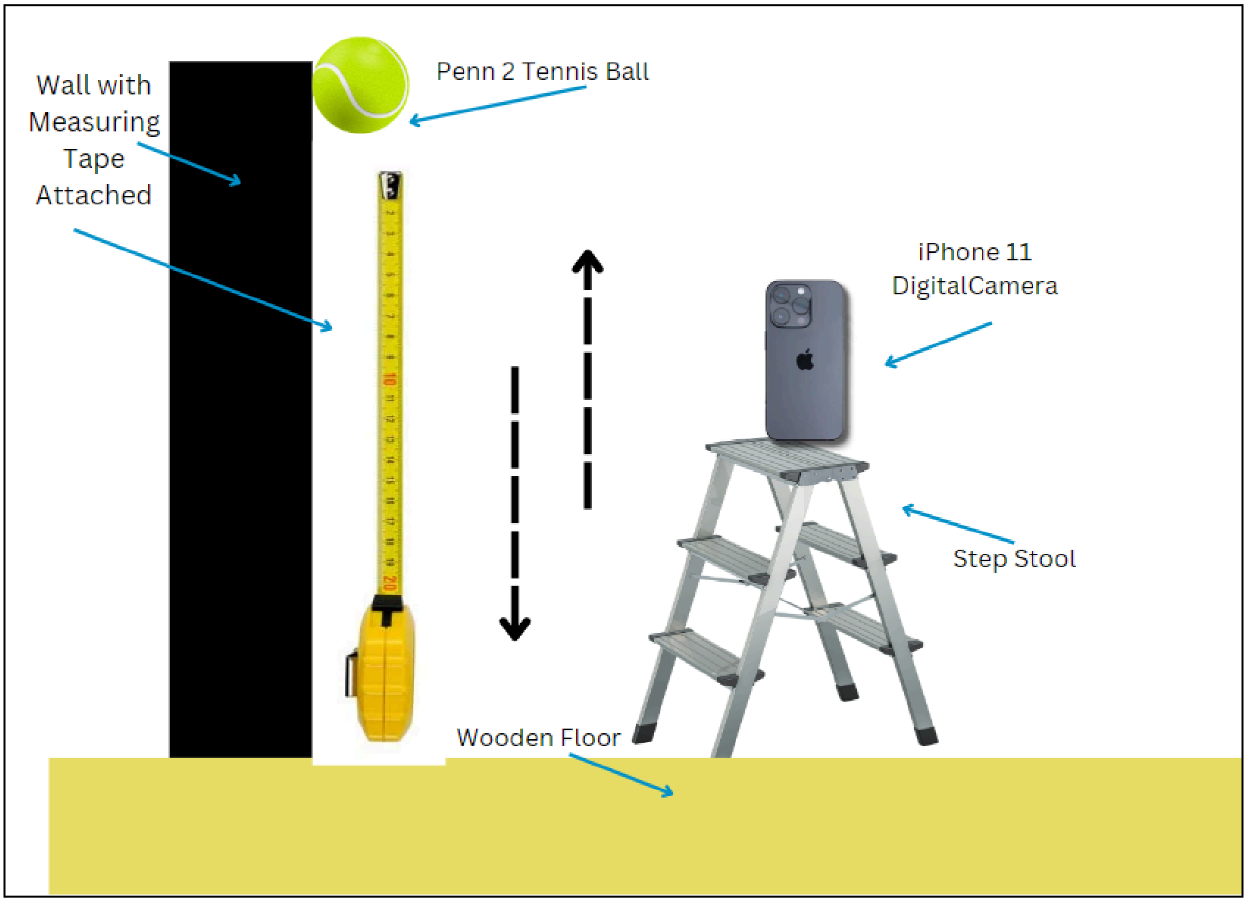

Figure 1: Diagram of Experimental Set-Up

Procedure .:. [Top]

The digital camera was placed 5 meters away from the drop area and raised to a height of 2 meters using a step stool to ensure a full view for analysis. This would also address any parallax errors. A strip of measuring tape was placed against a wooden wall and taped, which prevented any shift in the tape. 2.5 meters of the measuring tape labeled from 0 meters to 2.5 meters was against the wall. For each trial, the ball was held up to the specified height and then dropped onto a sturdy wooden floor while the camera was recording. The video would then be analyzed in slow motion and the maximum height after the first bounce was recorded using the measuring tape from the wall. For each specified height, three trials were recorded. There were ten drop heights that were recorded, starting from 100 centimeters to 200 centimeters in increments of 10 centimeters. Three trials were recorded in order to account for differences in drops. Though each drop was dropped the same way, it still could have bounced differently due to angles and wind resistance.

Risk Assessment

There is no risk involved in this experiment. No living beings were near the drop zone, preventing any harmful and physical contact from the ball to anyone else. There is also no harm done to the environment.

Data and Analysis .:. [Top]

Data Table 1: Raw data displaying 3 trials for 10 different height variations

Drop Height	Maximum Rebound Height in CM +/- .05 cm			
+/- .05cm				
x / cm	Trial 1	Trial 2	Trial 3	Average
100.0	52.00	51.80	51.90	51.90
110.0	54.00	52.50	52.70	53.07
120.0	61.00	60.00	60.20	60.40
130.0	72.00	71.00	69.90	70.97
140.0	72.00	73.00	63.00	69.33
150.0	77.00	77.10	77.20	77.10
160.0	83.00	82.40	83.80	83.07
170.0	90.50	89.10	90.30	89.97
180.0	96.00	94.10	92.00	94.03
190.0	98.20	101.50	97.00	98.90
200.0	108.20	99.10	104.00	103.77

Data Table 1 displays my raw data after 10 different drop heights with 3 trials each. Because the measuring tape used to measure the heights was in increments of .1 centimeters, an uncertainty of .05 was applied to the drop heights, as well as the rebound heights. This was calculated in the following equation:

$$.1/2 = .05cm$$

To calculate the averages for each height, I added up the quantities of the 3 trials and divided them by 3 to get my average. For example, my calculation for the height of 180.0 centimeters looked like this:

$$\frac{(96.00 + 94.10 + 92.00)}{3} = 94.03\ cm$$

Data Table 2: Converting the raw data into rebound percentages and calculating the uncertainty

Drop Height	Rebound Height Percentage (+/-0.05%)				
+/- .05cm				%	CM
x / cm	Trial 1	Trial 2	Trial 3	R_{avg}	Uncty
100.0	52.00	51.80	51.90	51.90	0.1
110.0	49.09	47.73	47.91	48.24	0.68
120.0	50.83	50.00	50.17	50.33	0.33
130.0	55.38	54.62	53.77	54.59	0.8
140.0	51.43	52.14	45.00	49.52	3.57
150.0	51.33	51.40	51.47	51.40	0.14
160.0	51.88	51.50	52.38	51.92	0.88
170.0	53.24	52.41	53.12	52.92	0.83
180.0	53.33	52.28	51.11	52.24	1.11
190.0	51.68	53.42	51.05	52.05	1.18
200.0	54.10	49.55	52.00	51.88	2.28

Data table 2 shows how I converted the raw data into rebound percentage from height, as well as the average and uncertainty. First, to convert from rebound height to rebound height percentage, I had to take each trial point from data table 1 and divide it by its initial height. For instance, at 110.0 drop height, I converted each trial into a percentage by doing this. This can be seen in the corresponding calculations:

$$\frac{54.00}{110.0} = 49.09\% \quad \frac{52.50}{110.0} = 47.73\% \quad \frac{52.70}{110.0} = 47.91\%$$

After calculating each rebound height into the percentage of the initial height bounced, I calculated the average percentage. To calculate this, I added the 3 trials and divided them by three. Using the same example for the drop height of 110.0, I calculated the average as 48.24%.

$$\frac{49.09 + 47.73 + 48.24}{3} = 48.24\%$$

Next, I calculated the uncertainties of each set of trials. To do this, I took the range of the 3 trials and divided that by 2. This can be seen in the following equation for x = 110.0 cm.

$$\Delta R = \frac{Rmax - Rmin}{2}$$

$$\Delta R = \frac{49.09 - 47.73}{2}$$

$$\Delta R = .68\ cm$$

This same method was used to calculate the other uncertainty values in Table 2. With all my averages and uncertainties calculated, I was able to compile my data into a linear graph as shown below.

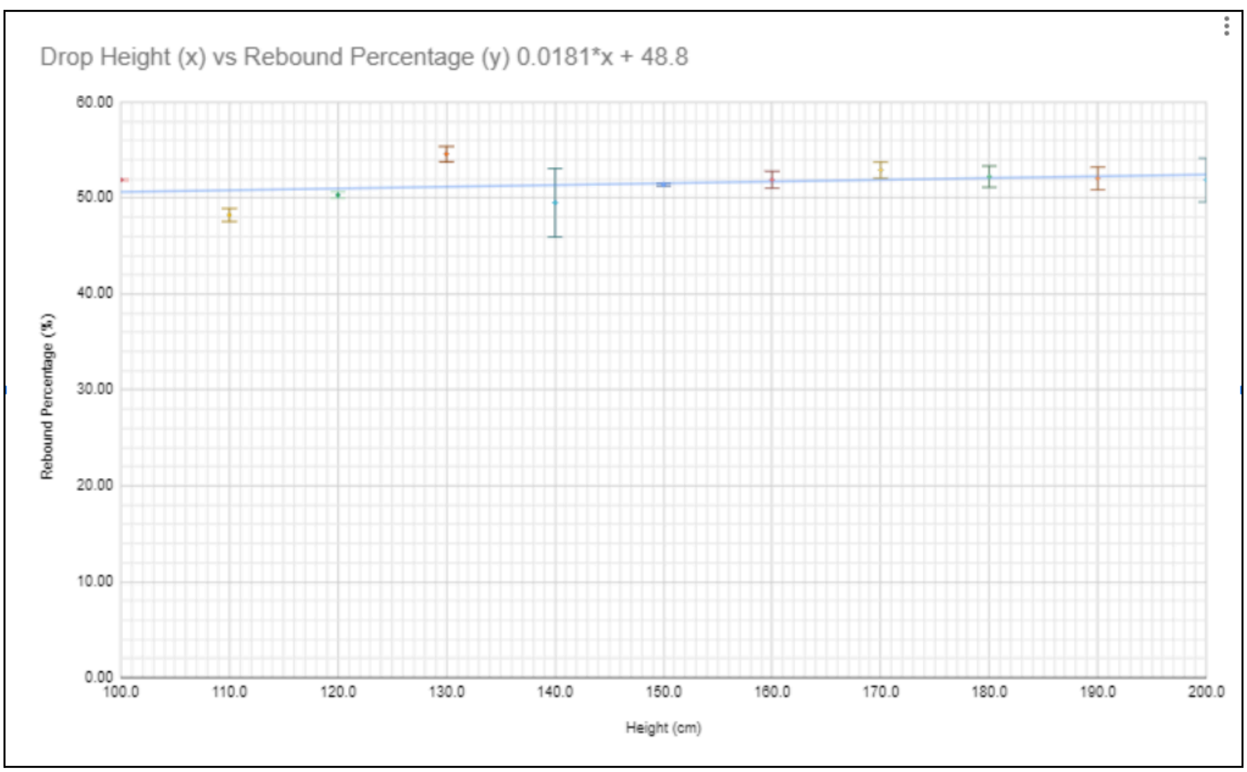

Figure 2: The relationship between initial drop height and the ball's percentage of rebound

The graph shows a slight positive linear relationship between the drop height and the percentage a tennis ball rebounds up to. The line of best fit predicts that the percentage of rebound height R is given by:

$$R = .0181x + 48.8$$

where *x* is the drop height of the tennis ball, in cm.

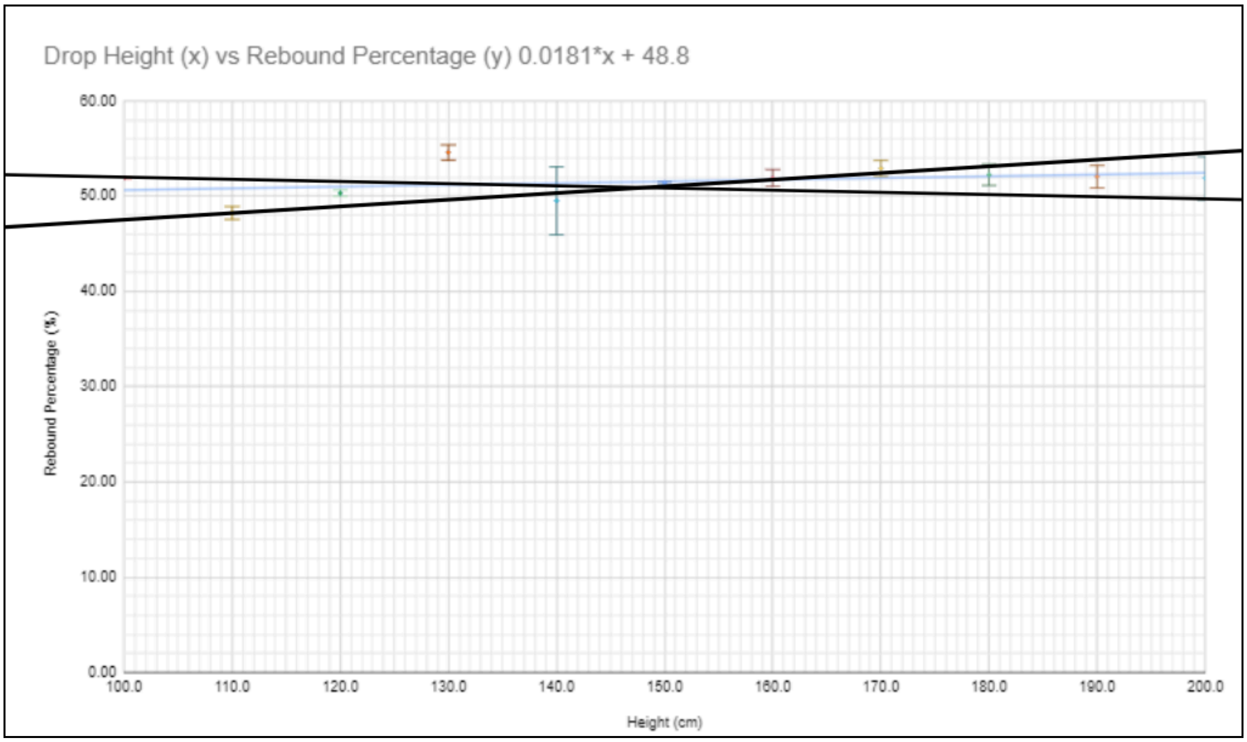

Figure 3: Graph with Maximum and Minimum Trendlines

Above is the same graph displaying the data but with maximum and minimum trendlines. When calculating the slope of the maximum line, it comes out to be .355. The minimum line slope is .335 cm^{-1}. To calculate the uncertainty of the slope, I took the difference between the maximum and minimum slope and divided it by 2 to get .01.

$$\frac{.355 - .335}{2} \approx .01$$

Thus, we can predict that the rebound percentage of a tennis ball will increase by .0181 $\pm$ .01% for every centimeter of height added to the drop height.

Conclusion - Data File .:. Top

The purpose of this investigation was to determine whether or not drop height would affect the percentage a tennis ball would bounce back. After analyzing the data, a slight relationship was found between the two variables. Though the trendline displays a positive relationship, the data points are relatively close to each other, suggesting that the initial drop height does not affect how much the percentage a tennis ball bounces back to. The ball always bounced back to around 50% of its original height. This does not reflect my original hypothesis, as I predicted there would be a more significant relationship between initial height and rebound percentage. Ideally, the ball would have conserved 100% of its energy based on the law of conservation of energy, which states that energy cannot be destroyed and must be conserved. If the ball had conserved all of its energy, the rebound percentage would have been 100%. However, since the ball's kinetic energy is transferred into outside sources on impact, it only bounces around 50%. The rebound percentage remains relatively constant throughout my trials likely because the energy released is proportional to the height. During the fall, the ball releases energy into the surrounding environment due to air friction and how the ground and ball are not elastic.

Due to the nature of the experiment, some sources of error likely occurred and affected the results I gathered. For instance, my measurements of the heights could have been more precise if I had used a mechanical method such as a video analysis program. Instead, I relied on measurements made with the eye on the slow-motion video. Since some errors could have occurred in the measurements, I could have missed a more accurate and established relationship between my two variables. Additionally, the method of dropping the ball could create errors. Sometimes, I found the ball dropping more to the side than directly straight down which was a human error. This was likely present in my fourth data point above, which would explain the large uncertainty in comparison to the other percentages. This could easily affect the motion of energy, as some of it could be used during the lateral movement. From this error, the calculations would have been affected and been made less accurate, lowering the chances of finding an established relationship.

Numerous improvements could be made to the experiment. One important improvement would have been to utilize more trials. Data tends to vary, so doing more than three trials would lessen any errors and overall create more reliable data. This would account for any sideway motions of the ball and establish more confidence. Since my data did produce a slightly positive relationship, using a larger range of heights could help establish a clearer relationship. My investigation used only heights from 100 cm to 200 cm, but increasing the maximum height would allow for more data and a more concise conclusion.

Additionally, if there was a more closed environment for the experiment, it would help with the vertical movement of the ball. This would allow the ball to fall without moving to the side and shifting its energy. A tube for instance would allow for this increased precision.

If I were to extend this research to a broader scope, I would vary how the ball is affected. For example, using tennis balls with different amounts of air would be interesting to see if that would affect the percentage of rebound. Also testing out different types of balls to see how they differ from tennis balls. Although I predicted a positive correlation between drop height and rebound percentage, I was able to find out that there is instead a constant relationship between the two, proving my experiment a success in terms of learning.

Related Links .:. Top

https://byjus.com/jee/gravitational-potential-energy/ - Site that gives general information on gravitational potential energy

https://www.eetimes.eu/the-laws-of-physics-in-tennis/ - This article talks about the physics behind tennis

https://pressbooks.howardcc.edu/jrip3/chapter/up-and-away-rebound-height-and-energy-changes-in-a-system-of-collisions/ - Paper that details how a ball rebounds, includes energy changes and more

www.physicsclassroom.com/class/energy/Lesson-1/Potential-Energy. - General information behind potential energy

https://www.teachengineering.org/activities/view/ball_bounce_experiment#:~:text=Working%20in%20pairs%2C%20they%20drop,and%20coefficients%20of%20elastici...&text=In%20this%20activity%2C%20students%20examine,when%20colliding%20with%20different%20surfaces. - Example experiment that tests different balls for rebound heights

Bibliography .:. Top

Admin. "Gravitational Potential Energy - Derivations, Formulas, Examples." *BYJUS*, BYJU'S, 6 June 2023, byjus.com/jee/gravitational-potential-energy/.

History of Tennis Balls - International Tennis Federation, www.itftennis.com/media/2280/balls-history-of-tennis-balls.pdf. Accessed 26 Jan. 2024.

"Potential Energy." *The Physics Classroom*, www.physicsclassroom.com/class/energy/Lesson-1/Potential-Energy. Accessed 25 Jan. 2024.