Investigating the Effect of the Internal Pressure of a Basketball on its Initial Bounce Height

Introduction:

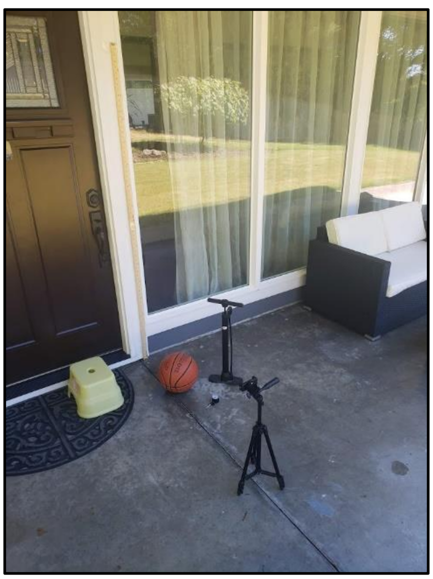
Throughout the 2020-2021 school year, I struggled to fully apply the concepts of kinematics and forces, although ironically, I was able to perform well on the projectile motion and energy units. Furthermore, given that I play tennis daily, I hit numerous amounts of balls and noticed that the more hits a ball sustains, the lower its bounciness which results in many missed shots. As such, the physics IA seemed like the perfect opportunity to explore the relationship between the internal pressure of a ball and its subsequent first bounce height.

Hypothesis: The relationship between pressure and rebound height will be linear because I researched that $P = \frac{F}{A}$, so pressure should be proportional to force meaning that rebound height should be linear.

Background Information:

As a general term, pressure in physics represents the perpendicular force that is exerted on an object per unit area, within a constricted fluid (Britannica, 2019). Remembering Newton's third law, we can see that for higher pressures the reaction when hitting the ground is larger, leading to a higher bounce height. However, different types of pressure can be derived from the general definition. As such, it is important to distinguish which type of pressure is being observed in this experiment. Atmospheric pressure, also known as barometric pressure, is formed by the weight of all the particles in the atmosphere above the object of measurement, typically used to determine wind and storm patterns (Britannica, 2021). Absolute pressure is the pressure measured relative to a perfect vacuum, with the lowest reading possible at 0 (Britannica 2019). Gauge pressure is the measure of pressure relative to atmospheric pressure (Britannica 2019). For all purposes of this investigation, the pressure measurements of the basketballs will represent **gauge pressure**, the difference in pressure between the ball and the atmospheric pressure around the gauge in **psi** (pounds per square inch), a common unit of measurements for sports balls. Gauge pressure was chosen over absolute pressure because it ensures that in environments with different atmospheric pressures, if the gauge pressure remains the same, the ball will bounce at similar heights.

Procedure:



The lab setup utilized in this procedure is as depicted in the image above. A level was used beforehand to ensure that the wall that the yardsticks rest on was near vertical while stepping stool was used to provide me with additional height, to ensure that I was releasing the ball at the correct height to prevent inaccuracies in drop height.

A bike pump and an analog ball pressure gauge were used to increase the gauge pressure of the ball and measure it accordingly. A tripod was placed an appropriate distance away from the yardsticks, holding a Samsung S9 mobile phone, to clearly and accurate measure the initial rebound height of the basketball.

As for gathering data points, the procedure goes as follows: Take an initial video of a single basketball drop and rebound. To do so, the ball should be held in front of your arms, perpendicular to the yardstick. Sequentially, if the video recording shows that the height of the tripod was too low to record the rebound height of the basketball precisely (due to the parallax effect), delete the video and adjust the height of the tripod accordingly and repeat until the recording is even with the peak rebound height of the ball, minimizing perspective warp. Then repeat dropping the ball and recording its rebound height until you have six trials for one manipulation of pressure. Pressurize the ball by pumping it with a bike pump fitted with a ball pump needle, checking the pressure with the ball pressure gauge after each pumping cycle. If the pressure is too high, release the right amount of pressure using the ball pressure gauge's built-in mechanism. If the gauge reads too low, pump the ball with more air, and repeat until the pressure is satisfactory. Once six trials for each pressure manipulation are achieved, the video data from the recording device should be transferred to a personal computer. On the computer, look through each video, slowing the footage and scrubbing the footage to look for the peak height of the basketball's rebound. Since the yardsticks are in the background of the footage, compare the basketball peak rebound height measured accordingly on the yardstick to get the height. Repeat this process with all videos to gather all rebound height data points.

Variables:

The independent variable in this investigation will be the internal pressure of the basketball. It will be changed via a bike pump with ball pump needle, increasing and decreasing the internal pressure as needed. The pressure will be measured using a ball pressure gauge. The dependent variable in this investigation will be the rebound height of the basketball, measured by a yardstick attached to a flat wall, utilizing a camera.

There are several control variables to this experiment. Firstly, the basketball used will remain constant throughout different trials, to reduce deviation in mass, material, and other factors that could significantly influence the rebound height. The drop height remained constant at six feet, the top of the measuring apparatus to allow for reasonable measurements of rebound height for trials with lower internal pressures. To ensure that the ball was dropped from the same point every trial, the ball was aligned with the flat wall, inspected visually to make sure that the ball was level with the top of the yardsticks, before being dropped vertically without horizontal movement. The position of the camera is also a significant factor in collecting data. Shifting positions could introduce varying degrees of perspective distortion and more uncertainty into the experiment. As such, the camera remained at one position on the floor using a tripod which held the camera in place, apart from changing the height to record rebound heights of balls with higher pressures. Doing so also ensured that the ball would hit nearly the same spot on the floor each trial. As the floor is not perfectly flat, this reduced uncertainty in rebound height.

The range of internal pressure of the basketball will range from 0 psi to 9 psi. 9 psi was taken as the upper bound because any higher pressure could cause the basketball to dangerously burst. Basketballs within the range of 0 psi to 9 psi are considered “ordinary balls,” commonly seen in households.

Raw Data:

The raw data gathered in this experiment is as depicted in the table below.

	First bounce height (inches) ± 1					
Pressure of basketball (psi) ± 0.1	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Trial 6
0.0	23	24	24	24	23	24
3.0	35	33	35	34	35	35
5.0	39	38	39	41	41	40
7.0	42	44	44	43	43	43
9.0	47	47	47	46	47	46

As shown above, the pressure of the basketball is associated with a $\pm$ 0.1 psi uncertainty. Given that the smallest increment of the pressure gauge was 0.2 psi and the measuring tool in question is an analog gauge, the uncertainty should be half of the smallest division. As such, the uncertainty in internal pressure of the basketball is $\pm$ 0.1 psi.

As for the first bounce height, there was a wide range of variables that could introduce uncertainty. Given that the smallest increment of the yard sticks is an eighth of an inch, the base uncertainty is 0.125 inches. However, when dropping the ball, the height of the ball relative to the top of the yardstick (representing the constant drop height) can shift by 0.875 inches. Additionally, parallax effect from the camera not being positioned perfectly could introduce a further 0.125 inches of uncertainty. Lastly, there could be another 0.125 inches of uncertainty from the yardsticks not being perfectly vertical which results in an uncertainty subtotal of 1.25 inches. Rounded to one significant figure, the total uncertainty for height measurement is 1 inch.

Processed Data:

Pressure of basketball (psi)	Average first bounce height (inches)	± Uncertainty in pressure of basketball (psi)	± Uncertainty in first bounce height (inches)
0.0	24	0.1	1
3.0	34	0.1	2
5.0	40	0.1	2
7.0	43	0.1	1
9.0	46	0.1	1

The pressure of the basketball remains constant and does not have to averaged. The same can be said for the uncertainty for the pressure of the basketball. However, there are multiple data points for first bounce heights, so they must be averaged.

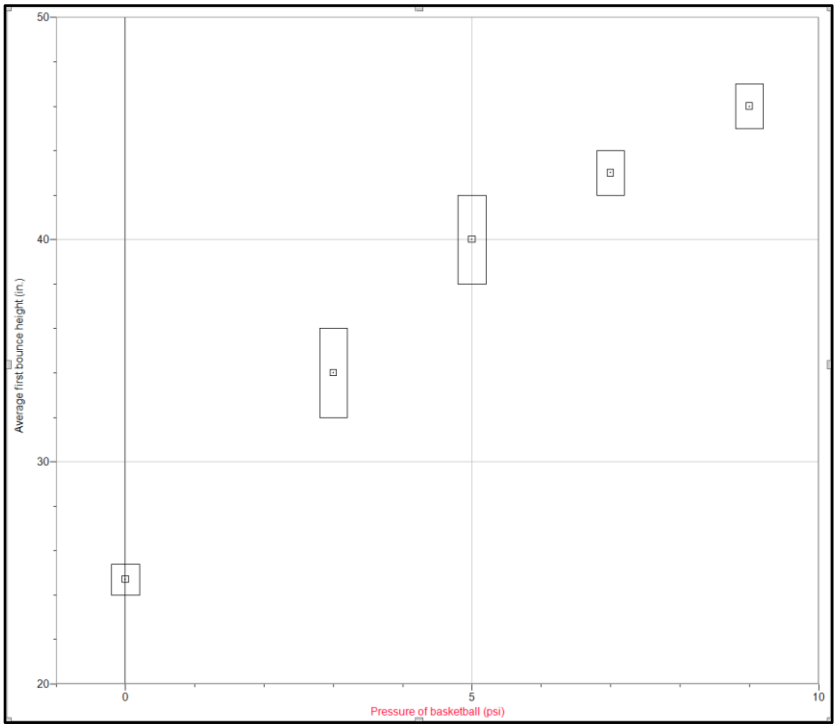
The average first bounce height was calculated with the lowest pressure using the formula below.

$$h_{avg} = \frac{h_1 + h_2 + \cdots + h_n}{n} \qquad h_{avg} = \frac{23+24+24+24+23+24}{6} = \boxed{24\ in.}$$

The average uncertainty for the first bounce height for the lowest pressure data values is calculated with the formula below.

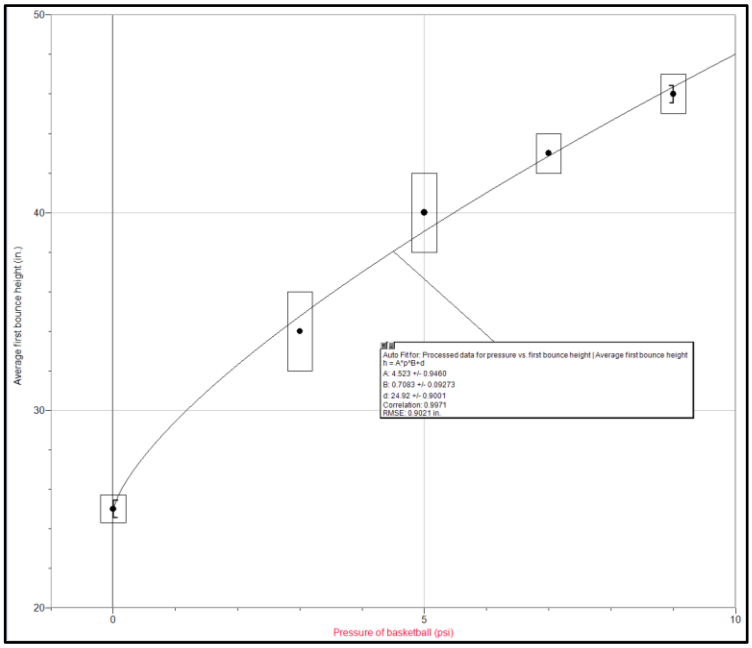
$$\Delta h = |h_{avg} - h_{farthest\ from\ h_{avg}}| \qquad \Delta h = \left|23\frac{2}{3} - 23\right| = \boxed{0.7\ in.}$$

Raw Graph:



Depicted above is a plot of the raw data gathered in this experiment. Looking at the shape of the graph, the function could be represented using a linear function, a logarithmic function, an nth root function, or a piecewise function. Seeing that the function has a steep initial rise with a slow falloff near the end, it is uncharacteristic of a single linear function. This behavior could be represented by either a logarithmic function or an nth root function. However, a logarithmic function cannot have a y-intercept without horizontal translation to the left. I do not expect pressure to be negative. Furthermore, I expect that even at 0 psi the ball should bounce at a positive or zero value, meaning that the graph should have a y-intercept. As such, it would be better to use an nth-root function with a vertical shift to holistically represent this data set. Moreover, according to Occam's razor, the nth-root function would be simpler. To truly confirm the relationship, the data must be linearized first.

Processed data:



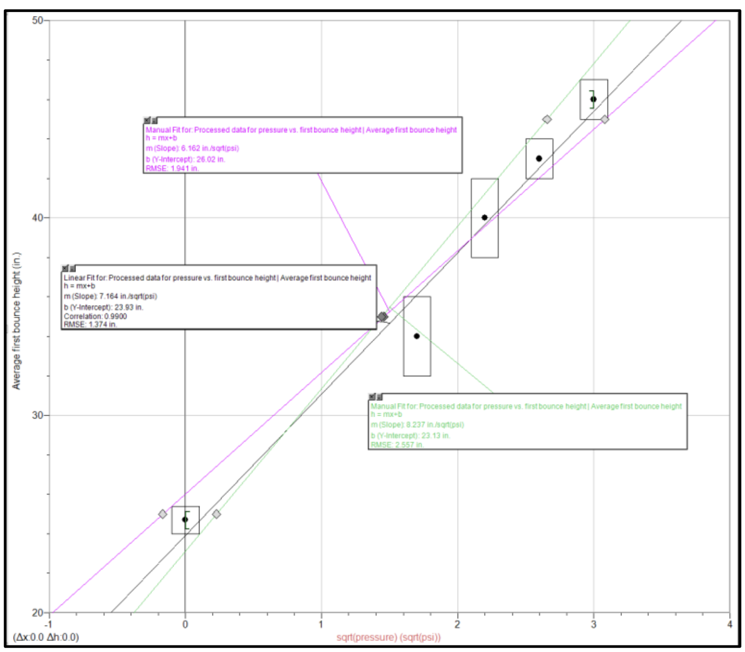
sqrt(pressure) (sqrt(psi))	Average first bounce height (inches)	± sqrt(uncertainty in pressure of basketball) (sqrt(psi))	± Uncertainty in first bounce height (inches)
0.0	24	0.1	1
1.7	35	0.1	2
2.2	40	0.1	2
2.6	43	0.1	1
3.0	46	0.1	1

Looking at the graph with an nth-root fit, the curve nearly goes through the centers of all the points, confirming that the relationship is most likely nth-root. The simplest relationship would be the function $h = k\sqrt{p}$ where $h \; \alpha \sqrt{p}$. As the raw data represents $h \; \alpha \sqrt{p}$, pressure needs to undergo a square operation to fulfill a proportional relationship. Since the accuracy of the linearization relies on the uncertainty, the uncertainty must be calculated first. The uncertainty for the data point being linearized is completed with the highest psi, using the equations below.

$$\sqrt[n]{A + \Delta A} = \sqrt[n]{A} \pm \frac{\Delta A\%}{n}$$, the uncertainty is scaled by a factor of $\frac{1}{n}$

$\sqrt{9.0 + 0.1} = \sqrt{9.0} \pm \frac{1}{2}\left(\frac{0.1}{9.0} \cdot 100\%\right) = 3.0 \pm \frac{1\%}{2}$. Converting the percentage back to absolute uncertainty, $\frac{\Delta A}{A} \cdot 100 = \Delta A\% \therefore \frac{\Delta A\%}{100} \cdot A = \Delta A$. Substituting the same sample point as the calculation above, $\Delta A = 9.0 \cdot \frac{1.11}{100} = 0.09\, psi$. Here we have to round the uncertainty up, since the precision of the uncertainty should not be greater or lesser than the precision of the measurement itself, so the final equation is $3.0 \pm \frac{0.1}{2} = 3.0 \pm 0.05$, which again is rounded up to $3.0 \pm 0.1\, psi$.

Linearized graph:



As seen in the graph above, the linearized graph illustrating the height of the first rebound versus the square root of pressure is now linear. I know that it is linear because most of the linear best fit lines shown in the graph above pass through the error boxes of each data point. The graph has a positive y-intercept. This makes sense, since the ball itself is elastic and should bounce on the ground even with zero internal pressure (if it retains its ball shape before it is dropped, which it did). Moreover, the slope is positive, which is expected; as internal pressure increases, the ball should rebound higher. Additionally, the end behavior of the nth-root function makes sense. The function is restricted to the first quadrant as neither pressure nor height should be negative. As the pressure increases, the height of the ball should gradually approach a certain value, since the ball can only hold up to a certain pressure before exploding. These behaviors establish the nth-root curve as the best fit, since it can be vertically shifted (for a y-intercept), and gradually tapers as x increases, features which the similar-shape logarithmic graph does not have. The fact that the best fit line goes through all the data points further supports that the curve is a good fit. Therefore, the function $h(p) = 7.164\sqrt{p} + 23.93$ represents the position versus height relationship of a basketball. However, one may notice that the linearized graph isn't a perfect fit, especially for outer and central data points, which are influenced by sources of uncertainty and error. As I did the experiment outside, environmental factors such as wind could affect the recorded rebound height by shifting the position of the ball. In addition, the experiment extended from the afternoon into evening, two times at which temperatures greatly differ. As pressure gauges are adversely affected by temperature changes, this could potentially significantly impact the experiment. Furthermore, several aspects of the experiment could be improved to limit uncertainty. For example, using a right angle to drop the ball more accurately from the same height each trial.

Conclusion:

In conclusion, the relationship between discovered in this investigation regarding the gauge pressure of a basketball and its first rebound height can be represented by the function $h(p) = 7.164\sqrt{p} + 23.93$, an nth-root function. Although this is not to say that there were no challenges within this investigation; using 0 as a data point proved as a challenge to calculate uncertainties and introduced possible fallacies within calculation. Furthermore, I couldn’t use a tennis ball like I had intended in the beginning because pressure measurements and manipulations were too difficult to control, which led to its substitution with a basketball. Some possible applications of the knowledge acquired from this experiment could be calculating the ideal amount of pressure needed to get the ideal bounce height from a basketball and possibly for other variants of bouncy balls.

References

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