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# THE EFFICIENCY AND COEFFICIENT OF SPORTS BALLS RESTITUTION USING AN ACOUSTIC APPLICATION

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## ABSTRACT

Studying the efficiency of a sports ball and its coefficient of restitution is important for performance optimization, fairness, and consistency of play. This research paper is dedicated to studying the coefficient of restitution and bounce efficiency in sports ball. Ping Pong ball and tennis balls were used to show the relationship between the bounce height and drop height. This paper used standard laboratory equipment like meter ruler, retort stand, clamp and with the utilization of the acoustic program of the smartphone using PhyPhox. The result showed that the application was able to accurately measure the bounce height in relation to the drop height. This was showed in the straight-line graph plotted. There was a constant ball efficiency coefficient of restitution and have very small percent error from the standard. This experiment can boost the interest and confidence of students in the classroom. Being able to accurately measure the performance of different balls can help students understand the science and engineering principles behind how they work. This knowledge can benefit students by allowing them to make more informed decisions when purchasing sports equipment, as well as give them an opportunity to modify their playing methods and strategies.

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## Introduction

The world of sports is usually played with numerous bouncing ball. These include basketball, football, Ping Pong, tennis balls, to name a few. Each ball has its own particular way of bouncing and hence, bouncing efficiency. Bouncing efficiency can be calculated by measuring the drop height and its bounce height. The higher the drop height, the bigger is the efficiency (Preproom, 2023). The study of Morato, et al. (2018) showcased that balls that are bouncing higher and balls that moves faster can significantly increase the ability of a team to score.

When the ball is at the drop height, the ball has gravitational potential energy (gpe). There is a change in gpe from the highest position to lower position is which physically equivalent to mass times acceleration due to gravity (g) times change in height ($h_2$ – $h_1$). This change in energy is transformed to kinetic energy (ke) as the ball keeps falling down. When it impacts the ground, the energy is transformed to elastic potential energy (epe). After impact, the ball moves upward which meaning the ball is losing kinetic energy. This change in kinetic energy is due to the increase in elevation and this change in ke is increasing the gpe. All in all, the energy is transformed from gpe until all the energy is dissipates to the environment as heat and sound (Cross, 1999).

This research is concerned on the drop height and its bounced height of the ball. These two variables are needed in computing the efficiency and coefficient of restitution (cor). Measuring these quantities involved dropping the ball from a certain height and measuring the rebound or bounced height. The uncertainty that is involved in this kind of measurement is high like parallax error and may involved estimation on where was the rebound height. On the other hand, using the acoustic program of a mobile application can reduce these types of errors (Pacala, 2023). Schools with lacking science infrastructures would benefit from this experiment. This is the gap that this study wanted to address. Zhang, et al. (2018) argued that Apps can minimize random errors by accurately programming random allocations and regulating the distribution of experimental materials.

The objectives of this paper are: (1) to measure the efficiency of Ping Pong ball and tennis ball; (2) to determine the relationship between the drop height and bounce height and compare it to the literature; and (3) determine the value of coefficient of restitution of Ping Pong and tennis balls. Normally, this experiment is done by carefully looking into the drop height or by using a video to capture the moment of bounce. The error attributed to the manually estimating the bounced height is fairly high, like those of (Fei Ann, 2018). Video analysis of the bouncing ball is also one of the most common techniques in this field (Heck, Ellermeijer & Kędzierska, 2018; Haron & Ismael, 2012).

Smartphones can be used to measure the efficiency of sport ball throwing in the classroom by using a variety of apps. Some apps use accelerometers and other sensors to track the speed and trajectory of a thrown object, while others measure the force exerted on it through the use of pressure sensors. These measurements can then be graphed, tracked, and compared over time to determine how efficient a student's throw is in terms of power and accuracy. This data can also be used as an objective way to teach students about form mechanics and techniques so they can become more efficient throwers. This research tried to analyze the efficiency of the bouncing ball and compute the coefficient of restitution using the acoustic program of PhyPhox.

The use of smartphones to measure the efficiency of sports balls can have numerous positive effects for students. These include improved accuracy and consistency in tracking ball movements and parameters, giving students the confidence to make more informed decisions on how to further refine their skills and hone their technique (Fei En, 2018). Additionally, such tools will allow students to gain a better understanding of their performance as they are able to compare data points against previous results, enabling them to draw conclusions regarding areas that may need improvement so that they can become more proficient in their sport.

### *Theoretical Background*

Generally, when a ball is dropped, it will lose potential energy as it falls and gain kinetic energy as it accelerates downwards due to gravity. When the ball impacts with a surface and bounces back up, it will exchange kinetic energy for potential energy as its speed decreases then increases in the opposite direction. The bouncing ball has maximum gpe at its highest elevation which is the drop height in this experiment. This was compared to the gpe of the maximum bounced height. Meanwhile, efficiency is computed as



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$$\text{Efficiency } (\eta) = \frac{\text{total output energy}}{\text{total input energy}} \quad [1]$$

The input energy is coming from the maximum gpe while the output energy is the energy during the first bounced, also a gpe. Making the equation

$$\eta = \frac{\text{gpe at first bounced}}{\text{gpe maximum}} \quad [2]$$

The gravitational potential energy is equal to mass (m) times g times height (h). The height at the gpe of the first bounce is assigned to be $h_1$ while the height where the maximum gpe is $h_2$.

$$\eta = \frac{mgh_1}{mgh_2} \times 100\% \quad [3]$$

On [3] the m and g are the same, so the equation for η became

$$\eta = \frac{h_1}{h_2} \times 100\% \quad [4]$$

Notice that $h_1$ is the same as the bounced height and $h_2$ is equal to the drop height. Therefore, the final equation for the efficiency of the balls is

$$\eta = \frac{\text{bounced height}}{\text{drop height}} \times 100\% \quad [5]$$

The bounce efficiency of a ball is calculated by dividing the height to which the ball rebounds off a surface, usually by an initial height. The efficiency is therefore directly proportional to the bounced height based on equation 5. This means the higher is the bounced height, the more efficient the ball is. However, this efficiency is still less than 100% since the drop height is still larger than the bounced height. This is true because the collision between the ball and the bench is inelastic which means the kinetic energy is not conversed and dissipates as heat or sound during collision.

Moreover, the coefficient of restitution (cor) is a measure of how elastic the collision is. The coefficient of restitution is the ratio of the speeds of two objects after they collide with each other. Based on Newton's model, it is a ratio of final velocity (v) and initial velocity (u). When object is at maximum height, it has maximum gpe. Upon impact to the bench, the gpe is converted to ke.

$$\text{cor} = \frac{v}{u} \quad [6]$$

Using the energy transformation theory of gravitational potential energy (gpe) and kinetic energy (ke), the lost in gpe is equal to the gain in ke. Hence,

$$mgh = \tfrac{1}{2} mv^2 \quad [7]$$

Since the mass (m) is the same on equation 7, it will become $gh = \frac{1}{2} v^2$. Therefore, the velocity of a falling object is

$$v = \sqrt{2gh} \quad [8]$$

Substituting the velocity equation to equation 6 led to

$$\text{cor} = \frac{\sqrt{2gh_1}}{\sqrt{2gh_2}} \quad [9]$$

Due to the fact that all falling bodies have constant g, the final equation for the cor is

$$\text{cor} = \sqrt{\frac{h_1}{h_2}} \quad [10]$$

The coefficient of restitution has a numerical value from 0 to 1 used to measure the elasticity or bounciness of two objects after they collide. It is directly related to the energy lost in the collision and is used to determine how much kinetic energy remains in a system of colliding bodies after impact. A coefficient of restitution of 0 represents a perfectly inelastic collision where all the kinetic energy has been converted into heat, while a coefficient of restitution of 1 retains all the initial kinetic energy after contact.

## Research Methods

The materials were set-up as shown on the diagram below


**Figure 1**. The materials are readily available in a standard Physics Laboratory like retort stand, meter ruler, clamp, and with addition of smartphone's PhyPhox application.

Two metal bars were fixed together using a masking tape to form a one-meter retort stand. This was made sure straight using spirit level. The meter ruler was clamped on the retort stand to make sure it is steady. There was a total of six drop heights which are marked by a sticky paper. The smartphone is clamped on the retort stand. The position of the smartphone was at the near bottom so that it can hear easily the impact of the ball to the bench.

The tennis ball and the Ping Pong balls were standard balls by which the mass were 57 grams 2.7 grams respectively (Dimensions, 2023). The balls were weighed using a mass balance. They were bought from a local sports center. The brand of the ball does not matter as long as it is standard and its mass kept constant all throughout the experiments. The tennis ball and Ping Pong balls were dropped in succession. With the use of Phyphox application, the smartphone's acoustic



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program can determine the bounced height or rebound height of the balls. The application can actually record all the bounced height until the ball is at rest or no more rebounding energy as shown on the results section. However, this paper has used only the maximum bounced height for the calculation of the efficiency and cor. To reduce the systematic error over the device, there were five repetitions of bounced height that was recorded per drop height. The average was taken in these repetitions.

When all the data were gathered, the maximum bounce height in the y-axis and drop height on the x-axis was plotted using the a spreadsheet. If a straight-line graph is formed, then the relationship is true. Based on equation 5, the gradient of this line is the efficiency of the balls with the y-intercept as zero. Similarly, the square root of bounce height against square root of the drop height was plotted. The appearance of a straight line of best fit indicated that the relationship is true for a constant cor. The gradient of the graph of square root of bounce height against square root is the coefficient of restitution.

The independent variable of this study is the drop height and there were six drop heights. The drop height was measured using the meter ruler and the highest dropped height was two meters. The dependent variable was the rebound or the bounced height. If the drop height versus the bounce height is plotted, the gradient is the efficiency of the bounce which was calculated using equation 5. Additionally, the coefficient of restitution was measured using equation 10. When the square root of drop height versus square root of bounce height is plotted, the coeffect of restitution is found as the gradient of the line of best fit.

**Table 1.** The materials and their function

| Material/Equipment | Function |
|---|---|
| Retort Stand and clamps | To support the meter ruler. |
| Meter rule | To measure the variation of drop height. |
| Sports Balls (Ping Pong and Tennis balls) | These two balls are to de dropped from various heights and measure their bouncing efficiency. |
| Smartphone with PhyPhox | The acoustic program of this application measured the bounced height. This can also measure the energy from each bounce. |

Moreover, the control variables were mass and types of the balls, surface of the bench, type of phone used for the Phyphox, and environmental conditions like wind and heat. To reduce the random error caused by the environment, the windows of the laboratory were closed and the heating system is switched to standard room temperature of 25 degree Celsius. The experiments were conducted in the Presidential School of Qarshi City which is 386 meters in altitude above the sea level. The settings of the PhyPhox acoustics in the smartphone were also controlled. The threshold is 0.1 audio unit and the minimum time delay is 0.1 second.

## Result and Discussion

### *Bounce Efficiency of the Ping Pong and the Tennis Balls*

The bounce efficiency of a ball is a measure of the amount of energy that remains in the ball after each impact with a hard surface (Cross, 2002). The bounce efficiency of a ball is calculated by dividing the height of the return bounce by the height of the initial drop and multiplying it by 100 as stated in equation 5.

The plotted points for the two balls showed a linear graph with $R^2$ of 0.998 for the Ping Pong ball and 0.984 for the tennis ball. This graph means that the bounce efficiency is constant across all drop height which followed the theory based on equation 5. The bounce efficiency of the Ping Pong ball is 0.718 and 0.557 for the tennis ball. The experimental bounce efficiency of the Ping Pong ball is similar to the experiment reported by Shelby (2015) who stated

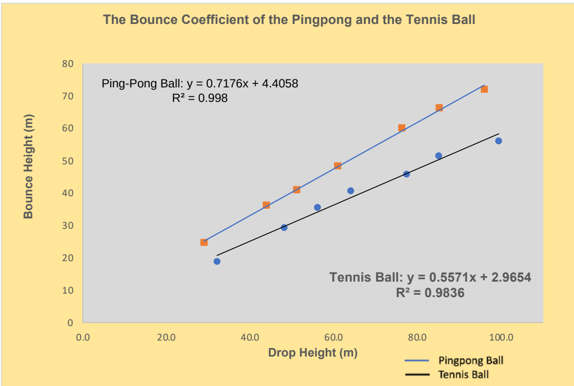


**Figure 2**. The bounce efficiency is the gradient of bounce height over the drop height. The gradient of the graph is 0.7176 for the Ping Pong ball and 0.557 for the tennis ball.



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that bounce efficiency is 0.66 and by Wilkins (2018 which reported bounce efficiency as 0.86. In addition, Shelby (2015) reported that the tennis ball's bounce efficient is only 0.46, though near to the experimental bounce efficiency equal to 0.557. However, the bounce efficiency reported by Heck, Ellermeijer and Kędzierska (2018) is 0.725 for the tennis ball which used a video capture analysis as a technique.

The literature reported various values of bounce efficiency of the Ping Pong and tennis balls. To get the theoretically correct bounce efficiency, an average was taken. So, the percent error was computed as the average theoretically correct value minus experimental value divided by the experimental value. Using this idea and formula, this report has a percent error of 5.56% for the Ping Pong ball and 5.3% for the tennis ball. This low percent error has showed that the experimental set up and procedure has measured the bounce efficiency accurately. This proved that the acoustic program of the smartphone, in the use of PhyPhox, has guaranteed success for the experiment.

*Coefficient of Restitution of the Ping Pong and the Tennis Balls*

The coefficient of restitution (cor) can be calculated by dividing the rebound height with the drop height.

The data of the square root of bounce height vs square root of drop height was plotted using a spreadsheet as shown in figure 3. The graph shown has a linear pattern which signified that the coefficient of restitution was almost constant all throughout the drop. This matched with the theory stated in the equation 10. The equation on the graph that was generated in a spreadsheet presented that the gradient for the Ping Pong ball is 0.809 and 0.736 for the tennis ball. Based on literatures, the coefficient of restitution for Ping Pong ball is 0.792 as described by Haron and Ismael (2012) and a coefficient of restitution of 0.783 was said by [9]. This experimental coefficient of restitution is almost the same with the literature. Moreover, the study of Cross (1999) reported that the cor of a tennis ball is 0.725 while Heck, Ellermeijer and Kędzierska (2018) stated a coefficient of restitution of 0.856. The data for the experimental coefficient of restitution is almost the same with the values from the literature.

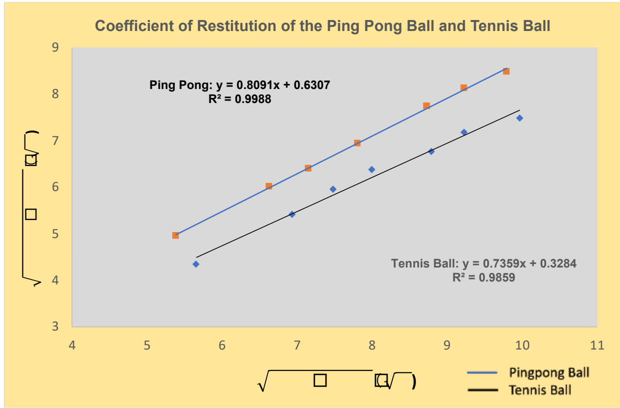


**Figure 3**. The coefficient of restitution is the gradient of the square root of bounce height over the square root of drop height. The gradient of the graph is 0.7091 for the Ping Pong ball and 0.7359 for the tennis ball.

The percent error was computed as well for this coefficient of restitution with similar procedure for the bounce efficient in section 5. From literature the computed theoretical correct average coefficient of restitution is 0.788 and 0.791 for the Ping Pong and tennis balls respectively. Therefore, this paper reported that the percent error of coefficient of restitution in the Ping Pong ball is 2.60% and for the tennis ball it is 7.47%. The accuracy of the experiment has been proven though this relatively low percent error. This means that the use of the acoustic program of the smartphone can accurately measure the cor.

Moreover, the $R^2$ value is 0.809 for the Ping Pong ball and 0.986 for the tennis ball. This means the values are precise with little uncertainty which is attributed to random error like air resistance and temperature. Higher R-squared values indicate better fit and more reliable results. In other words, the R-squared value of this paper, the data fit on the model.

*Uncertainty on the Bounce Efficiency and Coefficient of Restitution*

The uncertainty of the of the drop height is coming from the meter rule which according to De Anza College is equal to the smallest division (1mm or 0.1 cm) divided by the 2. So, in this paper the uncertainty of the drop height is 0.05 cm. Since the data is repeated on the bounce height, the uncertainty is computed as half of the range (largest data minus the smallest data) (SaveMyExams, 2022).

The uncertainty in the bounce efficiency



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($\Delta\eta$) was calculated using the error propagation formula for division

$$\Delta\eta = \left[\frac{\Delta \text{bounce}}{\text{ave bounce}} + \frac{\Delta \text{drop height}}{\text{drop height}}\right] x\ \eta \qquad [11]$$

The uncertainty in cor ($\Delta$cor) was computed using the error propagation formula for power

$$\Delta \text{cor} = \left[1/2\frac{\Delta \text{bounce}}{\text{ave bounce}} + 1/2\frac{\Delta \text{drop height}}{\text{drop height}}\right] \text{x cor} \qquad [12]$$

**Table 2. The uncertainty in bounce, bounce efficiency and coefficient of restitution of the Ping Pong Ball**

| Drop Height (cm) | Average Bounce (cm) | △Bounce (cm) | $\Delta\eta$ | △cor |
|---|---|---|---|---|
| 96.0 ± 0.05 | 52.2 | ± 0.3 | ± 0.004 | ± 0.003 |
| 85.2 ± 0.05 | 46.7 | ± 0.4 | ± 0.005 | ± 0.004 |
| 76.3 ± 0.05 | 42.0 | ± 0.3 | ± 0.004 | ± 0.003 |
| 61.0 ± 0.05 | 34.0 | ± 0.4 | ± 0.007 | ± 0.005 |
| 51.2 ± 0.05 | 28.8 | ± 0.3 | ± 0.008 | ± 0.005 |
| 43.9 ± 0.05 | 25.0 | ± 0.4 | ± 0.01 | ± 0.007 |
| 29.0 ± 0.05 | 17.0 | ± 0.1 | ± 0.007 | ± 0.004 |
| Average | 35.1 | ± 0.3 | ± 0.007 | ± 0.004 |

Therefore, the uncertainty on the bounce efficiency is ± 0.007 and for the coefficient of restitution is ± 0.004 for the Ping Pong ball as shown in table 2. For the tennis ball, the bounce efficiency's uncertainty is ± 0.007 and the uncertainty in the coefficient of restitution is ± 0.006. These values are pretty small uncertainty due to the $r^2$ in figure 1 and 2 which is almost 1. The R-squared value is a measure of how closely the data points fit a given regression line, or trend line.

The final value of the bounce efficiency of the Ping Pong ball is 0.718 ± 0.007 and its coefficient of restitution is 0.809 ± 0.004. Moreover, the tennis ball's bounce efficiency is 0.557 ± 0.007 and the coefficient of restitution is 0.736 ± 0.006.

**Table 3. The uncertainty in bounce, bounce efficiency and coefficient of restitution of the Tennis Ball**

| Drop Height (cm) | Average Bounce (cm) | △Bounce (cm) | $\Delta\eta$ | △cor |
|---|---|---|---|---|
| 99.4 ± 0.05 | 56.1 | ± 0.3 | ± 0.004 | ± 0.003 |
| 85.1 ± 0.05 | 51.6 | ± 0.3 | ± 0.003 | ± 0.003 |
| 77.3 ± 0.05 | 45.8 | ± 0.3 | ± 0.004 | ± 0.004 |
| 64.0 ± 0.05 | 40.7 | ± 0.6 | ± 0.01 | ± 0.008 |
| 56.0 ± 0.05 | 35.5 | ± 0.4 | ± 0.008 | ± 0.006 |
| 48.1 ± 0.05 | 29.4 | ± 0.3 | ± 0.007 | ± 0.006 |
| 32.0 ± 0.05 | 18.9 | ± 0.5 | ± 0.02 | ± 0.01 |
| Average | 39.7 | ± 0.4 | ± 0.007 | ± 0.006 |

*Classroom Implication*

The use of smartphones to measure the efficiency of sports balls and coefficient of restitution has had a profound effect on students' learning experiences in physical education classes. By using their own smartphones, students are able to access data quickly and accurately which helps them gain a greater understanding of the material. Smartphones allow students to observe how the sports ball behaves when it strikes the surface as well as track if its path deviates due to spin or other environmental factors, allowing them to analyze why it does so in a more detailed way. Astuti et al. (2018) argued that this encourages students to think more critically about their observations, rather than having a teacher explain the physics behind them.

In addition, smartphones provide students with immediate feedback on their results which can help improve performance in activities such as basketball, soccer, and volleyball. For instance, they can see how the trajectory of their shot was affected by changing the angle at which they directed it or varying the force applied. Knowing this information right away allows them to make necessary adjustments based on real-time data instead of relying solely on trial and error. Providing this kind of practical knowledge ensures that students are better equipped to excel during game-play as well as strengthen underlying skills such as hand-eye coordination.

Finally, smartphones create an opportunity for coaches or teachers in physical education classes to interact with their students in engaging ways without having to rely on traditional methods such as chalkboard lectures (Shim, Dekleva, Guo, & Mittleman, 2011). Through smartphone apps specifically designed for use in sport ball analysis, teachers are able to guide their pupils more effectively and answer any questions about topics like coefficient of restitution more quickly and efficiently. Furthermore, these applications can be used together with 3D visualizations that enhance students' understanding of abstract principles such as friction by showing how it affects sport balls within a two-dimensional environment or three-dimensional environment. González, González, Vegas, and Llamas (2017) argued that increased access to this type of technology also means that



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classes become less about memorizing formulas and more about experimentation leading to better comprehension overall.

## Conclusion

This research had conducted a simple experiment and demonstration concerning energy transformation, efficiency of a system, and the restitution. This paper was successful in verifying the concept and theory under the bounce efficiency and coefficient of restitution. It will be a fascinating experience for the students to know that their smartphone can help them in physics experiments than just mere texting, posting and photographing. There is so much delight for early physics learners in using this method. The integration of physics concept to sports was an avenue for interdisciplinary study and contextualization.

The PhyPhox application was successful in its program to compute the bounce height and at various drop height it showed that the efficiency was constant. Similarly, the coefficient of restitution was proven to be constant at different drop height. The PhyPhox application has greatly revolutionize on how physics experiment can be conducted. The use of smartphones to measure the efficiency of sport balls and coefficient of restitution can have several positive effects on students. For one, it can help to develop their math and scientific skills as they learn how to interpret the results of the analysis. Additionally, it can increase their interest in physics and sports, encouraging them to think more deeply about the science behind these two disciplines. Finally, using smartphones as a tool for data collection is an up-to-date approach that can help to engage younger students and encourage them to be more interested in experimentation. Therefore, it is recommendation to other teachers to try this fun way of classroom experiment.

As shown in the results and discussion the coefficient of restitution and bounce efficiency contain uncertainty. Though uncertainties are always present in an experiment, future undertakings can be improved by using a sensitive smartphone with background noise cancellation which can eliminate the systematic error coming of the device. Demonstrators and users of this experiment are advised to consider using higher drop height to see the effect coming from this perspective. From this higher drop height, an experimenter can check if the coefficient of restitution is increasing when the drop height is decreasing. This was observed by this paper although the difference is quite small and insignificant.

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