HIGH SCHOOL EDITION
Journal of Student Research
Volume 14 Issue 1 (2025)

The Effect of Tennis Ball Pressure on Coefficient of Restitution and Force on Hand

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ABSTRACT

Wrist injury is prevalent among tennis players. While it is well known that switching the brands of tennis balls can greatly increase the risk of injury, this study hypothesized that changes in ball pressure, measured by the force on hand (FOH), could be another factor contributing to wrist injuries. The use of a vibration dampener was also investigated to determine if the device could provide any injury prevention benefits. A mechanics model of the racquet-hand system was utilized to derive the force on hand equation, and the relationship between the force on hand and the coefficient of restitution (COR) was established to facilitate data analysis. The study employed a camera system to capture ball-racquet collisions and developed a Python vision tracking program using OpenCV to determine balls' initial and final velocities and calculate the COR and FOH under four testing conditions. Results showed that, under the same constraint—whether with or without a vibration dampener—new balls exhibited a statistically significantly higher COR and FOH compared to dead balls when colliding with a racquet, which implies that the gradual decrease in ball pressure during a match could lead to notable changes in force on hand, potentially increasing the risk of wrist injury. Furthermore, statistical analysis confirmed that incorporating a vibration dampener not only decreased the force on hand irrespective of ball pressure but also reduced the variation resulting from the difference in FOH caused by varying ball pressure, thereby effectively mitigating the risk of wrist injury.

Introduction

Tennis is a widely played sport around the globe. It is a sport dependent not only on the player's physical and mental strength, but also on the equipment, including tennis balls and tennis racquets. The tennis racquet has a huge impact on a player's performance, influencing the power and spin imparted to the tennis ball. For that reason, professionals often carry multiple racquets of the same model and string tension in order to maintain consistency during matches. Likewise, the type of tennis balls plays a crucial role in how a player strikes the ball and predicts its movement (Baszczyński et al., 2016). Unfortunately, tennis balls are supplied by the tournament organizers (based on sponsorship deals), leaving players no choice over the type of balls used in competition. Different brands of tennis balls vary slightly in size, weight and material, yet perceptibly to professional tennis players, which can influence their bounce, speed, and overall feel during play. As a result, this can affect a player's timing, grip, and swing adjustments, potentially adding strain to the wrist, forearm, and elbow. Because players frequently compete in various tournaments with limited time breaks in between, they constantly need to adjust to playing with different types of tennis balls. Over time, these constant adjustments can lead to injuries like wrist tendinitis. As a result, professional players like Novak Djokovic and Daniil Medvedev have been openly advocating for a consistent brand of tennis balls across all tournaments (Ostlere, 2023).

Wrist injuries are among the most common injuries in tennis (Fu et al., 2018). For many professional tennis players, the repercussion of these injuries is long lasting. It is not uncommon for players to take breaks due to wrist injuries and even have to end their careers prematurely in severe cases, like Juan Martin Del Potro, an Argentinian player who won the US Open in 2009 (Rothenberg, 2014). As Rothenberg highlighted, the wrist is particularly vulnerable during play because the force generated from ball-racquet contact is transmitted directly through the wrist. According to (Chung & Lark, 2017), wrist injuries predominantly occur during forehand groundstrokes—the most frequently utilized strokes in tennis—due to the fact that increasing tennis ball velocity from medium to fast during a forehand stroke required 31% greater angular velocity of the wrist joint at impact. Playing speed significantly influences the intensity of vibrations and the force exerted on the wrist. Initially designed to reduce shock and alleviate strain on the player's arm to prevent injuries like tennis elbow, vibration dampeners have seen an increased use among tennis players across all skill levels. Although there is no consensus on the exact cause of tennis elbow, many believe that overloading the wrist extensors during the backhand stroke is a key contributor to the prevalence of this condition (Chung & Lark, 2017). Medically, tennis elbow and wrist injuries are interconnected, both stemming from repetitive hand and wrist motions that place strain on the tendons linking forearm muscles to the elbow. This strain can lead to pain and inflammation in both the wrist and elbow, reinforcing the potential role of vibration dampeners in mitigating wrist injuries. However, despite their popularity, the effectiveness of vibration dampeners remains a topic of debate and controversy within the tennis community and scientific field. A survey (RacquetInc, 2019) showed that while more than half of the world's top 100 professional tennis players found vibration dampeners beneficial and used them on a regular basis, some of the most successful players opted not to use them. In academia, studies, including using accelerometers with stationary and full movement swings on human subjects, have led to conflicting results (Stroede, 1999; Yeh et al., 2019).

Despite differences in size, weight and elasticity among various types of tennis balls, one thing that remains universal to all standard tennis balls is the gradual loss of air pressure over time, or depressurization. A new tennis ball, right out of its container (a pressurized can), should have an internal air pressure of around 26.7 psi, compared to external air pressure at about 14.7 psi (ITF, 2020). Due to the difference between the internal and external air pressures, tennis balls start losing their bounce once the can is opened. However, the rate of depressurization increases with the frequency and intensity of use. Repeatedly hitting a ball wears down its material, allowing more air to escape from the ball and reducing bounce over time. In order to alleviate this issue, it is required that the first set of six balls be replaced after seven games and every nine games thereafter, to prevent the balls from going flat or losing pressure (ATP, 2023; ITF, 2020). However, before these replacements occur, it is highly likely that the six balls have already depressurized, especially for professional tennis players, who, on average, hit the tennis ball at 75 mph and serve at 115 mph (ATP Stats, 2023). This constant depressurization requires players to adapt their strokes and movement to properly keep the ball in play.

Just like small variations in mass and material across different tennis ball brands can lead to potential wrist injuries due to the strain caused by constant adaptation, similar effects are expected from changes in a ball's internal air pressure. While these ideas are commonly accepted within the tennis community, no quantitative data currently exists to demonstrate how varying ball pressures may affect forces on the hand (FOH), highlighting a lack of scientific evidence that motivated this research project. Describing the force exerted on the hand during ball-racquet collision requires complex physics modeling. However, since this study is mainly focused on comparing the force generated by varying ball pressure—specifically the difference of FOH between normal and low-pressure balls—a simplified rigid beam model, treating the hand and the racquet as a single isolated system (Cross, 2010), suffices the purpose. An important and widely used concept in studying the air pressure of a tennis ball is the coefficient of restitution (COR), which is a measure of the elasticity of the collision between the ball and another object (such as the ground or a racquet). Prior studies have shown a logarithmic relationship between the COR and the internal air pressure of a rubber ball, where an increase in air pressure is associated with a higher COR and vice versa (Osman & Kim, 2009). Intuitively, higher ball pressure results in a greater velocity and a higher force on the hand. Consequently, it is anticipated that FOH and COR are also directly related. This study aims to investigate whether and how varying the air pressure in tennis balls influences the force exerted on a player's hand and also the coefficient of restitution via establishing the relationship between these two factors. In addition, the ongoing debate about the effectiveness of vibration dampeners in reducing the risk of injuries motivates this study to evaluate their impact by analyzing FOH and COR under conditions with and without a dampener.

Methodology

This study employed an experimental research design to examine how varying internal air pressure levels in tennis balls affect the coefficient of restitution and the force exerted on the wrist during ball-racquet collision. The experimental approach is chosen to allow for precise control of the independent variables—tennis ball air pressure and use of a vibration dampener—while observing the outcomes on the dependent variables—the COR and the FOH.

As the first step to achieve this goal, models were developed to determine COR and FOH, based on which the force on hand equation was derived, and the relationship between FOH and COR was established. Next, the experiment was set up to conduct the research. A single tennis racquet was secured in a fixed position across trials. A ball machine was used to shoot the tennis balls of various pressure levels toward the racquet, and a high-speed camera was employed to capture each ball's trajectory and contact point for subsequent calculations and analysis. The experiment included four testing groups based on pressure levels (high or low) and the utilization of a vibration dampener (with or without) on the racquet. Each group underwent thirty trials to ensure statistical reliability. For each trial, the ball machine and the camera were synchronized to record a clip of the ball hitting the racquet at a proper location. All trials took place in a controlled indoor setting to minimize the influence of wind, temperature, and humidity.

With the vast amount of video clips collected from the experiment, the method of extracting useful information to calculate the values of COR and FOH was crucial for drawing meaningful conclusions on the impact of ball air pressure on these two factors. The process of extracting data through video processing was established for this purpose.

The Coefficient of Restitution

The coefficient of restitution is a measure of how much kinetic energy is retained or lost when a ball collides with a rigid surface. It indicates how "bouncy" or elastic a collision is by comparing the ball's rebound speed to its initial speed. A COR of 1 implies a perfectly elastic collision without any energy loss, meaning the ball would bounce back with the same speed as the incoming speed, while a COR of 0 suggests a perfectly inelastic collection, where all kinetic energy is lost and the ball does not bounce at all. COR is calculated by finding the absolute value of the final velocity (v_f) over the initial velocity (v_i) as ("Ball COR", n.d.)

$$COR = \frac{v_f}{v_i}.$$

Force-on-Hand Model

To calculate the force of the collision on the racquet holder's hand, the study utilized a mechanics model, as shown in Figure 1.

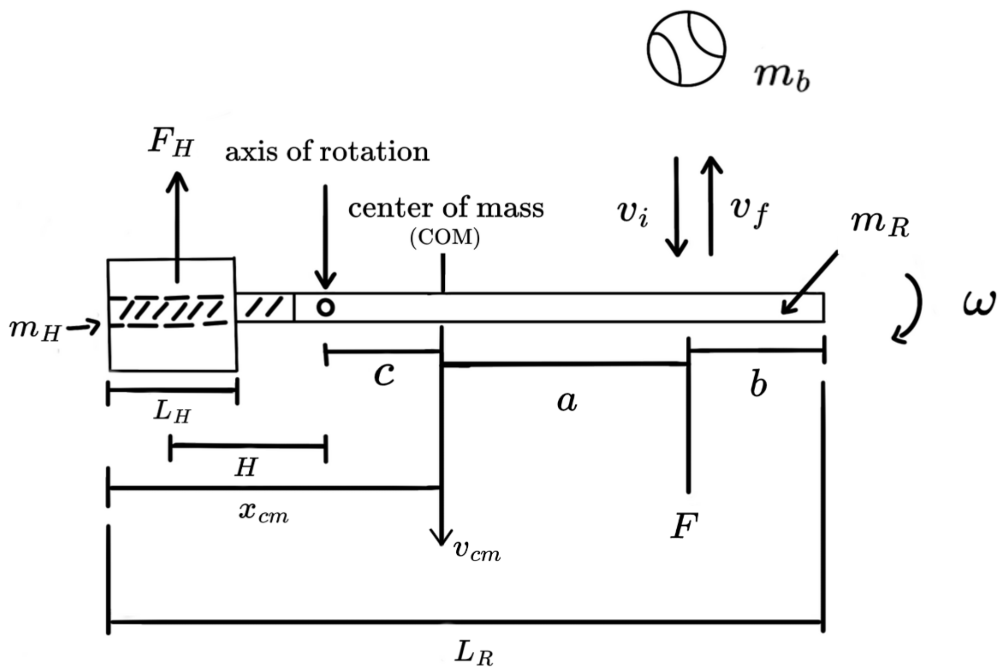

Figure 1. Mechanics rigid beam model of tennis racquet and hand.

This model is based upon a previous study (Cross, 2010), which treated the racquet and the hand as a single rigid beam and calculated the force on the hand as a function of the force of the ball colliding on the racquet head:

$$F_H = \frac{aHm_H}{I_{CM}} F ,$$

where a is the distance from the collision location to the center of mass, H is the distance from the center of the hand to the axis of rotation, m_H is the mass of the hand, I_{CM} is the moment of inertia of the racquet-hand object around its center of mass, F is the force of the ball striking on the racquet at the collision point, and F_H is the force on the hand.

F, the force of the ball on the racquet, can be determined (in terms of the initial and final velocity) using the change in momentum and the impact time. The magnitude of the change in momentum, in terms of the mass of the ball m_b, initial velocity v_i, and final velocity v_f, is found to be $m_b(v_i + v_f)$. Because the force is equal to the change in momentum over time t_d, it can be written as $F = \frac{m_b(v_i+v_f)}{t_d}$ (PhysLink, n.d.). Substituting this equation into F_H leads to

$$F_H = \frac{aHm_H(v_i+v_f)m_b}{I_{CM}\, t_d}.$$

The above equation indicates that the force on hand is directly proportional to the ball's initial velocity v_i and final velocity v_f: the higher the v_i and v_f, the larger the force experienced. Given that higher ball pressure results in a higher initial velocity, it can be inferred that increased ball pressure leads to a greater force on hand. In addition, as v_f is further related to v_i and COR through the COR equation, F_H can be rewritten as a function of COR by substituting $v_f = COR * v_i$ into the above force calculation:

$$F_H = \frac{aHm_H(v_i + COR * v_i)m_b}{I_{CM}\, t_d} = \frac{aHm_H m_b}{I_{CM}\, t_d}(1 + COR)\, v_i\,.$$

From this force equation, it is obvious that FOH and COR are indeed directly related—FOH is a linear function of COR. Therefore, evaluating the effect of varying ball pressure can be applied to both FOH and COR.

Ideally, for consistency in comparing forces under different conditions, it is necessary to keep the initial velocity of each collision constant. However, some inconsistency in launch speed of the ball machine was observed during the experiment. Considering the fact that the COR remains fairly stable across varying initial velocities, it can be assumed independent of minor fluctuations in launch speed (Roux & Dickerson, 2007). This assumption helps isolate the influence of ball pressure on the COR and the FOH measurements, allowing for fair comparisons across different pressure conditions without interference from inconsistent launch speeds. In this study, the initial velocity is assigned a value of $v_i = 10.0\ m/s$, which is the average speed across all trials.

The constants appearing in the force formula can be obtained from known average quantities and technical specifications of the racquet (*Wilson Pro Staff RF97*) used in the experiment. Specifically, the mass of the ball $m_b = 0.057\ kg$, the mass of the racquet $m_R = 0.355\ kg$, the mass of the hand $m_H = 0.460\ kg$, the impact time $t_d = 0.005\ s$, the distance from the tip of the racquet to the collision point $b = 0.165\ m$, the length of hand $L_H = 0.10\ m$, and the length of the racquet $L_R = 0.69\ m$ (Cross, 2010; ExRx, n.d.; Wilson, n.d.). Note that the location where the tennis balls contact the racquet strings has a big impact on the COR and experimental outcomes. For this study, the point of contact is set at the racquet's center of percussion (0.165 m from the tip of the head), which is generally referred to as the "sweet spot" of the racquet. While there is another spot on the tennis racquet, known as "the power point", that achieves the highest COR, it is not commonly used, because tennis players usually aim towards hitting closer to the center of the racquet strings rather than near the base of the racquet head (Bocchi, 2015).

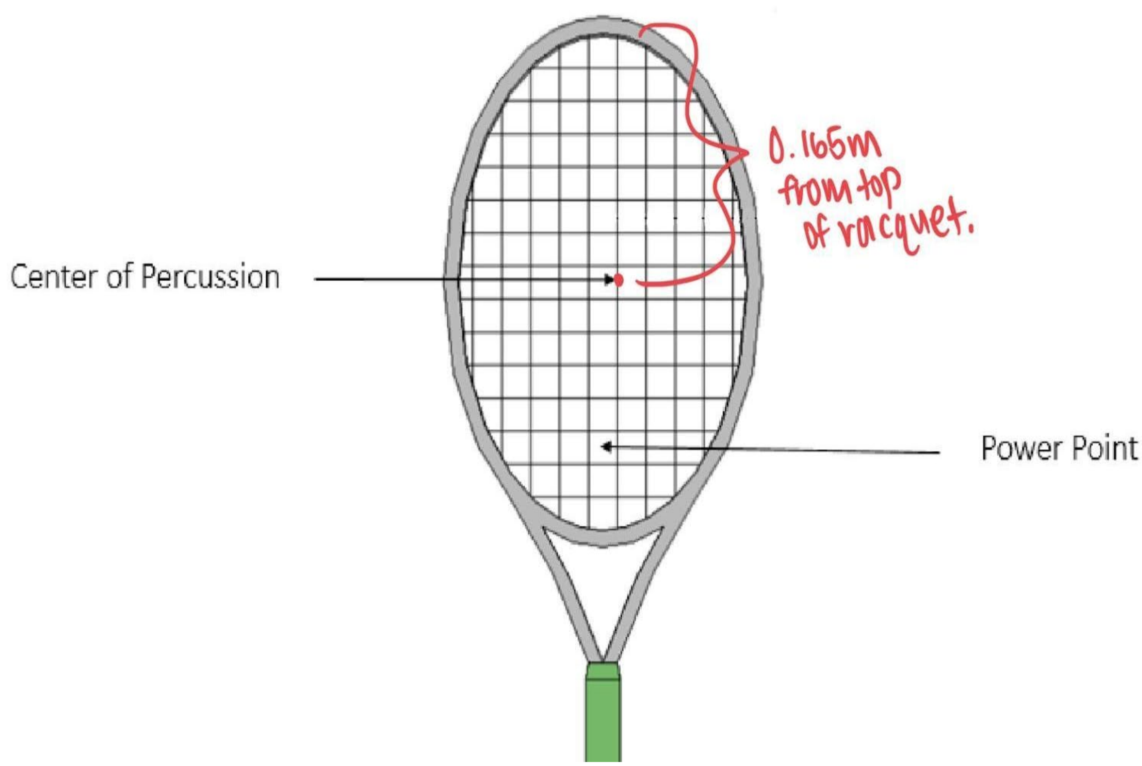

Figure 2. Illustration of tennis racquet's center of percussion and the power point

Based on these data, the values of a, H, and I_{CM} can be calculated accordingly. The distance from the center of mass to the handle end (of the racquet-hand single rigid beam) is

$$x_{CM} = \frac{\frac{L_H}{2}m_H + \frac{L_R}{2}m_R}{m_H + m_R} = 0.1785\ m.$$

Then, the moment of inertia at the center of mass of the racquet-hand object can be calculated (Baker & Haynes, n.d; Toppr, n.d.) as

$$I_{CM} = \frac{1}{12}m_R {L_R}^2 + m_R(\frac{L_R}{2} - x_{CM})^2 + \frac{1}{12}m_H {L_H}^2 + m_H(\frac{L_H}{2} - x_{CM})^2 = 0.0319\ kg \cdot m^2.$$

The distance from the collision location to the center of mass is

$$a = L_R - x_{CM} - b = 0.3465\ m.$$

And the distance from the center of mass to the axis of rotation is

$$c = \frac{I_{CM}}{a(m_R + m_H)} = 0.1130\ m.$$

Finally, the distance from the center of the hand to the axis of rotation can be obtained by

$$H = x_{CM} - c - \frac{L_H}{2} = 0.0155\ m.$$

Substituting these values into the final F_H equation leads to

$$F_H = 0.8838\ (1 + COR)v_i$$

measured in Newton (N). Thus, F_H can be calculated for each scenario using the COR and expressed in terms of v_i, a constant set for all conditions (i.e. 10.0 m/s).

Video Processing and Python Vision Tracking Program

The experiments conducted in this study generated a substantial amount of raw video data capturing balls' trajectory before and after colliding with the racquet. To ensure consistency and efficiency, each video file recorded the continuous sequence of the ball machine launching and the subsequent ball-racquet collision of each ball for a group of 10 balls. Therefore, the data processing began with cutting each video file into multiple smaller clips, with each clip containing a single ball's movement from leaving the ball machine to striking the racquet. These individual clips were then fed to a video processing program that tracks a ball's trajectory and measures its initial (v_i) and final (v_f) velocities. Finally, the coefficient of restitution and force on hand were computed using the COR and force equations with the collected velocities as inputs.

To perform the video processing, which involves object detection and tracking, this study utilized OpenCV (Open Source Computer Vision) Library, a powerful software tool designed to efficiently handle computer vision tasks. Specifically, an online OpenCV application was used to identify and track the ball's coordinates in each video frame (Rosebrock, 2015). The speed of the ball in pixels per second was calculated by dividing the distance travelled in each frame by the time span of the frame. To find the actual speed of the ball, the program used the ratio of the pixel radius of the ball (determined from object identification) to the actual radius (standard units in meters) to convert the ball's movement in pixels per second to meters per second (m/s). This application provided a robust foundation for accurate data extraction from the video clips.

A Python program was developed to automate the entire data processing workflow. This program took raw video files as input, processed the data to extract the ball's initial and final velocities, and calculated the COR and FOH as outputs.

Implementation

Tennis Ball Preparation

For this study, 60 Wilson Championship Extra-Duty tennis balls were used. These ITF (International Tennis Federation) regulated and USTA (United States Tennis Association) approved tennis balls were packaged in sealed plastic cans, with each can containing three tennis balls. The cans preserve the tennis balls' integrity and pressure until they are opened for use in the experiment. Extra duty felt is more durable than regular felt, which preserves the desired ball pressure for the trials.

To establish one of the independent variables, ball pressure, the tennis balls were sorted into two groups of 30 balls each: the new ball group (NBG) with the standard internal air pressure and the dead ball group (DBG) with reduced internal air pressure. No modifications were required for the NBG as the balls retained their factory-sealed pressure. For balls in DBG, consistent low air pressure was necessary to ensure reliable results in the experiment. In order to quickly relieve these balls of some air pressure, a small steel head pin was used to poke three holes into each ball. These balls were then left to sit in low air pressure containers and remained sealed for five days to further reduce their internal pressure. Afterward, the balls were taken out of the containers and placed back into their original cans for better organization and preservation of their altered conditions.

Ball Pressure Verification

To ensure air pressure consistency of the two ball groups (NBG and DBG), it was crucial to verify and, if necessary, adjust the air pressure of the balls to achieve uniform levels. A ball pressure gauge was initially considered. However, extensive research showed that no ball pressure gauges were readily available to accurately measure ball pressure without ruining the ball itself. As a result, an indirect, ITF authorized method was employed instead. This method involved dropping each tennis ball from the same height onto a concrete floor to ensure a constant initial velocity. Data on the ball's bounce height after collision with the ground were collected for analysis. Using the principle that given a fixed initial velocity, a ball's bounce height is directly proportional to its internal air pressure, this idea provided a systematic and non-invasive means of verifying the consistency of the ball pressures in both groups (Cross & Lindsey, 2007).

As mentioned earlier, a Python program utilizing the OpenCV library was developed to measure a ball's initial and final velocities and calculate the coefficient of restitution as the ratio of the ball's final velocity over its initial velocity. Since a higher internal air pressure results in a higher final velocity, and a higher final velocity leads to a higher COR given a fixed initial velocity, the COR serves as a reliable indicator of internal air pressure. Therefore, rather than directly measuring the bounce height, the outputs from the Python program can be readily used to check the internal pressure of the balls within each group.

The experiment was conducted in a spacious basement, a controlled environment free from external influences such as wind, temperature, and weather conditions, ensuring consistent testing parameters. An iPhone 12, mounted on a stable tripod, was utilized to capture the balls' movement with precision. Balls from both NBG and DBG groups were dropped from a stationary hand at a constant height to ensure uniform initial conditions. The camera was positioned slightly above the ground, facing a blank wall, to allow for clear visibility of the ball's trajectory when it made contact with the ground. The iPhone recorded the ball movement with 4K resolution at 60 frames per second (fps). The video recordings were fed into the Python program utilizing the OpenCV library, which extracted the balls' initial and final velocities and calculated COR accordingly. By comparing the COR values, necessary adjustments were made to ensure the balls in the dead ball group achieved a uniform and desired lower internal pressure.

Ball Machine Experiment

After the balls were tested and categorized into their respective groups, the primary experiment was conducted in the same basement mentioned earlier. This controlled setting ensured a consistent environment for reliable data collection, minimizing the influence of external factors. The experiment setup consisted of three main steps. First, a Wilson ProStaff RF97 racquet was securely bound horizontally to a heavy-duty fitness power cage. The handle of the racquet was tightly fastened, leaving the racquet head exposed to intercept balls shooting from the ball machine. Second, a tennis ball machine was placed 10 feet away from the racquet head. Its launching angle, the distance from the racquet, and the firing speed, once tested and adjusted, would remain constant throughout the experiment. Third, the same camera setup used in the ball pressure verification was deployed with slight adjustment. Positioned 2 feet away from the bound racquet and at an equal height, the camera was aligned to focus on the racquet's contact points to capture the ball-racquet collision. With all the equipment in place, the experiment was ready to commence. The ball machine, loaded with 10 tennis balls, launched them one by one at the mounted racquet while the camera recorded the entire process. After all 10 balls had been fired, the recording was stopped. As the purpose of this study was to evaluate how ball pressure influences the COR and FOH both in the absence and in the presence of a vibration dampener on the racquet, the ball machine experiment was designed to collect data for the following four scenarios: NBG without a dampener, NBG with a dampener, DBG without a dampener, and DBG with a dampener. Therefore, the above experimental procedure was repeated for each scenario until a sufficient amount of data (30 balls for each group) had been collected to ensure statistical reliability and consistency.

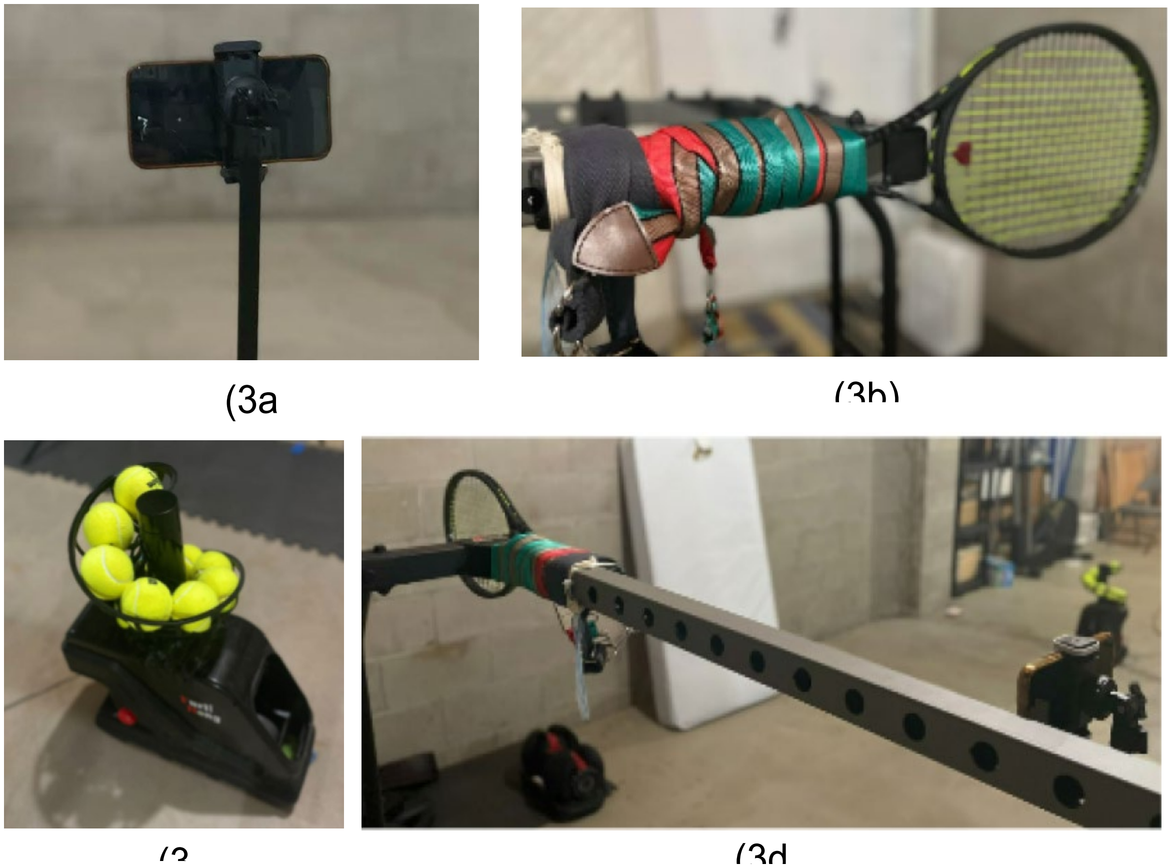

Figure 3. Ball machine experiment setup. (3a) Camera setup - an iPhone 12 is fastened on a tripod. (3b) The racquet is tightly bound to the iron bar. (3c) The tennis ball machine. (3d) Full view of the experiment setup.

Data Analysis

Data analysis techniques were employed to inspect, analyze and validate the experimental data obtained from the Python program. Key statistical measures, including the mean, standard deviation, and variance, were calculated for variables such as the ball's initial and final velocities, COR and FOH. These statistics were then compiled into summative data tables, presenting a clear view of the findings from the two ball-pressure-verification tests as well as the four ball-machine experiments. For hypothesis testing, this study utilized the one-tailed t-tests with unequal variances, as the focus was solely on the increase in COR and FOH. Additionally, due to the fact that the FOH was derived as a linear function of COR, statistical analysis produced identical results for these two dependent variables, meaning the p-values for COR and FOH were the same. An alpha level of 0.05 was used to determine statistical significance, with a p-value less than 0.05 indicating the rejection of the null hypothesis while a p-value greater than 0.05 indicating the acceptance of the null hypothesis.

Results

The results from both the ball pressure verification and ball machine experiment are summarized in the following tables and graphs. In each case, the Python program utilizing the OpenCV library took raw video data as input and calculated the balls' initial and final velocities. These velocities were then used to determine the coefficient of restitution and the force on hand. In addition, statistical analysis was performed to interpret and validate the collected data from all the experiments.

Drop Test Data (for Ball Pressure Verification)

The drop test was performed to confirm the balls in both the new ball group and the dead ball group had desired internal air pressure. Thus, only the COR values exported from the Python program were needed, as a higher COR indicated a higher final velocity, and consequently, a higher bounce and a higher air pressure. There were 30 trials conducted for each group. The results showed that the mean COR for DBG is 0.6502 while the mean COR for NBG is 0.6945.

Table 1. Summative Data Table for the Coefficient of Restitution (COR), Initial Velocity (m/s), and Final Velocity (m/s) of the Dead Balls When Colliding with the Ground After Dropping (30 trials).

	Coefficient of Restitution (COR)	Initial Velocity (m/s)	Final Velocity (m/s)
Mean	0.6502	8.2467	5.3616
Stand Dev	0.0124	0.2326	0.1746
Var	0.0002	0.0541	0.0305

Table 1 shows the mean, standard deviation, and variance for the coefficient of restitution, initial velocity, and final velocity, calculated over a sample size of 30 data points collected when each dead ball was dropped and collided with the ground.

Table 2. Summative Data Table for the Coefficient of Restitution (COR), Initial Velocity (m/s), and Final Velocity (m/s) of the New Balls When Colliding with the Ground After Dropping (30 trials).

	Coefficient of Restitution (COR)	Initial Velocity(m/s)	Final Velocity (m/s)
Mean	0.6945	8.2352	5.7186
Stand Dev	0.0152	0.1599	0.1369
Var	0.0002	0.0256	0.0187

Table 2 presents the mean, standard deviation, and variance for the coefficient of restitution, initial velocity, and final velocity, calculated over a sample size of 30 data points collected when each new ball was dropped and collided with the ground.

Table 3. Statistical Data Table for New Ball vs. Dead Ball Pre-Trial Drop Test.

	p-value	alpha = 0.05
COR	5.7917E-18	< 0.05

Table 3 displays the statistical analysis result of a one-tailed t-test with unequal variances on the COR data from the drop tests of new and dead balls. The p-value, significantly lower than the alpha threshold of 0.05, confirms a statistically significant difference (of internal air pressure) between the two sample groups.

Trial Data (from Ball Machine Experiment)

The ball machine experiment generated trial data under four conditions: (1) shooting dead balls at the racquet without a dampener, (2) shooting new balls at the racquet without a dampener, (3) shooting dead balls at the racquet with a dampener, and (4) shooting new balls at the racquet with a dampener. Each condition was tested over 30 trials to ensure robust statistical analysis. The Python program calculated the initial and final velocities, which were then used to compute the coefficient of restitution. In addition, the force on hand was also determined using the equation $F_H = 0.8838(v_i)(1 + COR)$, where $v_i = 10.0$ m/s representing the average initial velocity across all trials. This normalization ensured a fair comparison across all four conditions.

Table 4. Summative Data Table for the Coefficient of Restitution, Initial Velocity (m/s), Final Velocity (m/s), and the Force on Hand (N) of the Dead Balls When Colliding with a Racquet Without a Dampener (DB-D) (30 trials).

		Initial Velocity (m/s)	Final Velocity (m/s)	Force on Hand (N)
Mean	0.4772	10.1639	4.8544	13.0559
Stand Dev	0.0893	0.9384	1.0142	0.7888
Var	0.0080	0.8806	1.0285	0.6222

Table 4 shows the mean, standard deviation, and variance for the coefficient of restitution, initial velocity, final velocity, and force on hand when dead balls collide with a tennis racquet's strings without a vibration dampener.

Table 5. Summative Data Table for the Coefficient of Restitution, Initial Velocity (m/s), Final Velocity (m/s), and the Force on Hand (N) of the New Balls When Colliding with a Racquet Without a Dampener (NB-D) (30 trials).

	Coefficient of Restitution	Initial Velocity (m/s)	Final Velocity (m/s)	Force on Hand (N)
Mean	0.5648	10.2097	5.7726	13.8295
Stand Dev	0.0640	0.4995	0.7663	0.5656
Var	0.0041	0.2495	0.5872	0.3199

Table 5 shows the mean, standard deviation, and variance for the coefficient of restitution, initial velocity, final velocity, and force on hand when new balls collide with a tennis racquet's strings without a vibration dampener.

Table 6. Summative Data Table for the Coefficient of Restitution, Initial Velocity (m/s), Final Velocity (m/s), and the Force on Hand (N) of the Dead Balls When Colliding with a Racquet With a Dampener (DB+D) (30 trials).

		Initial Velocity (m/s)	Final Velocity (m/s)	Force on Hand (N)
Mean	0.4146	10.0746	4.1901	12.5026
Stand Dev	0.0847	0.9962	1.0112	0.7484
Var	0.0072	0.9924	1.0226	0.5601

Table 6 shows the mean, standard deviation and variance for the coefficient of restitution, initial velocity, final velocity and force on hand when dead balls collide with a tennis racquet's strings with a vibration dampener.

Table 7. Summative Data Table for the Coefficient of Restitution, Initial Velocity (m/s), Final Velocity (m/s), and the Force on Hand (N) of the New Balls When Colliding with a Racquet With a Dampener (NB+D) (30 trials).

		Initial Velocity (m/s)	**Final Velocity (m/s)**	**Force on Hand (N)**
Mean	0.4984	9.6743	4.8270	13.2428
Stand Dev	0.0767	0.2866	0.7926	0.6781
Var	0.0059	0.0821	0.6282	0.4599

Table 7 shows the mean, standard deviation, and variance for the coefficient of restitution, initial velocity, final velocity, and force on hand when new balls collide with a tennis racquet's strings with a vibration dampener.

Table 8. Statistical Data Table for New Ball Without a Dampener (NB-D) vs Dead Ball Without a Dampener (DB-D)

	p-value	**alpha = 0.05**
COR and FOH (N)	2.9848E-5	< 0.05

Table 8 presents the results of the statistical analysis using a one-tailed t-test with unequal variances on the COR and FOH between new ball and dead ball collisions with the tennis racquet without a dampener. Since FOH is directly proportional to COR, the t-test results are identical for both variables. The extremely small p-value, well below the alpha threshold, indicates statistical significance in the difference observed.

Table 9. Statistical Data Table for New Ball With a Dampener (NB+D) vs Dead Ball With a Dampener (DB+D).

	p-value	**alpha = 0.05**
COR and FOH (N)	8.7404E-5	< 0.05

Table 9 presents the results of the statistical analysis using a one-tailed t-test with unequal variances on the COR and FOH between new ball and dead ball collisions with the tennis racquet with a dampener. Since FOH is directly proportional to COR, the t-test results are identical for both variables. The extremely small p-value, well below the alpha threshold, indicates statistical significance in the difference observed.

Table 10. Statistical Data Table for New Ball Without a Dampener (NB-D) vs New Ball With a Dampener (NB+D).

	p-value	**alpha = 0.05**
COR and FOH (N)	2.9808E-4	< 0.05

Table 10 presents the results of the statistical analysis using a one-tailed t-test with unequal variances on the COR and FOH between new balls colliding with the tennis racquet with and without a dampener. As FOH is a linear function of COR, the t-test results are identical for both variables. The extremely small p-value, well below the alpha threshold, indicates statistical significance in the difference observed.

Table 11. Statistical Data Table for Dead Ball Without a Dampener (DB-D) vs Dead Ball With a Dampener (DB+D).

	p-value	**alpha = 0.05**
COR and FOH (N)	3.5912E-3	< 0.05

Table 11 presents the results of the statistical analysis using a one-tailed t-test with unequal variances on the COR and FOH between dead balls colliding with the tennis racquet with and without a dampener. As FOH is a linear function of COR, the t-test results are identical for both variables. The fact that the p-value is less than the alpha threshold indicates statistical significance in the difference observed.

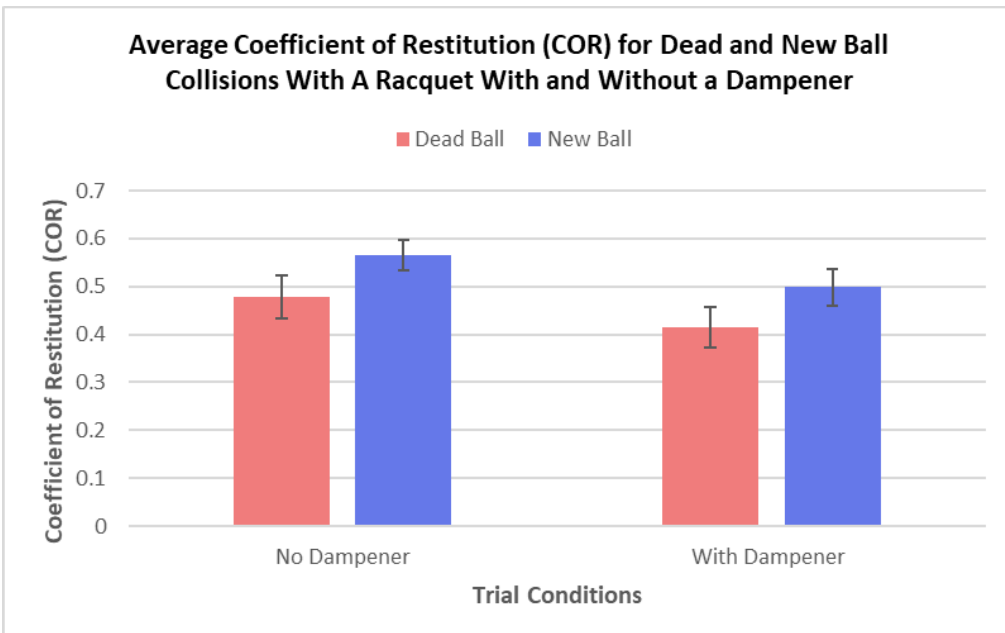

Figure 4. Average Coefficient of Restitution (COR) for Dead and New Ball Collisions With a Racquet With and Without a Dampener.

Figure 4 illustrates the mean COR values for the four testing conditions: DB-D (dead balls without a dampener), ND-D (new balls without a dampener), DB+D (dead balls with a dampener), and NB+D (new balls with a dampener). Each bar represents the mean COR for its respective condition, along with a one standard deviation error bar. Statistical analysis revealed a significant difference between DB-D and NB-D, with a p-value of 2.9848E-5, which is well below the 0.05 threshold. Similarly, a significant difference was observed between DB+D and NB+D, with a p-value of 8.7404E-5, also well below the 0.05 threshold.

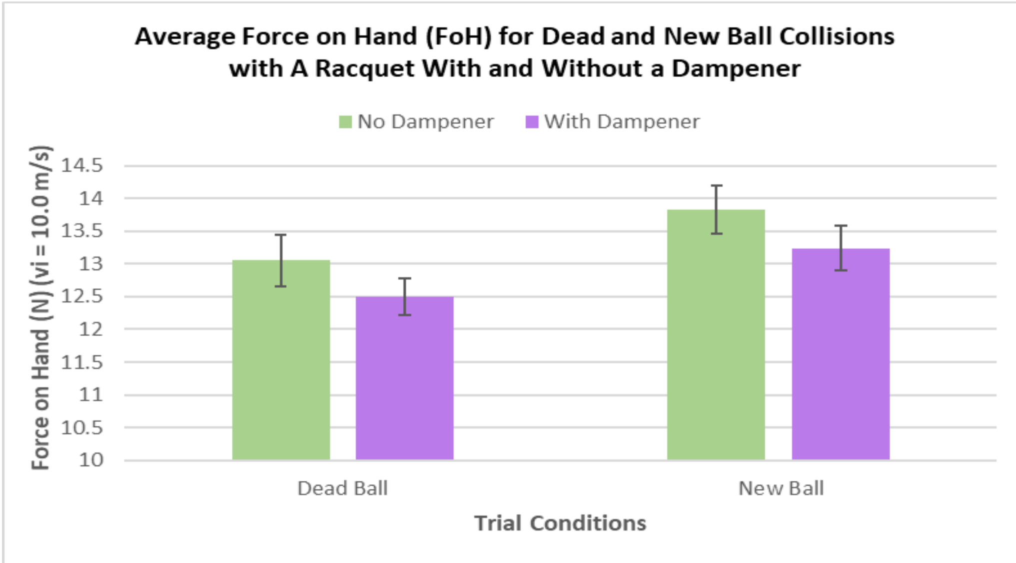

Figure 5. Average Force on Hand (FOH) for Dead and New Ball Collisions with a Racquet With and Without a Dampener (vi=10 m/s).

Figure 5 illustrates the mean FOH values (computed at vi=10 m/s) for the four testing conditions. Each bar represents the mean FOH for its respective condition, along with a one standard deviation error bar. Statistical analysis revealed a significant difference between DB-D and NB-D, with a p-value of 2.9848E-5, which is well below the 0.05 threshold. Similarly, a significant difference was observed between DB+D and NB+D, with a p-value of 8.7404E-5, also well below the 0.05 threshold.

Discussions and Conclusions

Summary of Results and Conclusions

The summative data tables for ball-to-ground collisions highlighted that dead balls exhibit a lower COR compared to new balls, with mean CORs of 0.6502 and 0.6945, respectively (Tables 1 and 2). Statistical analysis using a one-tailed t-test with unequal variances confirmed a significant difference between the CORs of dead balls and new balls, with a p-value approximate to 0, well below the alpha threshold of 0.05 (Table 3). This finding validates the hypothesis of a distinct difference between the CORs of the dead balls and the new balls. Furthermore, the minute standard deviations for the dead ball and new ball drop tests data, 0.0124 and 0.0152, respectively, emphasize the reliability of the experimental setup and the accuracy of the OpenCV-based program.

The primary purpose of this study was to test the two hypotheses: 1) varying ball pressure changes the force on hand; 2) a vibration dampener reduces the variation of force on hand when ball pressure changes. To this end, the ball machine experiment was designed to conduct under the following four testing conditions: 1) new balls colliding with a racquet without a dampener (NB-D), 2) dead balls colliding with a racquet without a dampener (DB-D), 3) new balls colliding with a racquet with a dampener (NB+D), and 4) dead balls collision with a racquet with a dampener (DB+D). The results thus obtained were consistent with the expectations and aligned with the two hypothesized predictions.

For the DB-D and NB-D testing cases, a noticeable difference between two FOH values was observed: 13.0559 N for DB-D and 13.8295 N for NB-D, supported by a very small p-value of 2.9848E-5, well below the alpha threshold (Tables 4, 5, 8). Additionally, the low standard deviations for DB-D (0.5656) and NB-D (0.7888) demonstrated consistency among trials (Tables 4 and 5). Therefore, null hypothesis 1 was rejected, supporting the alternative hypothesis that FOH was statistically significantly higher for new balls compared to dead balls when striking a racquet without a dampener.

When a vibration dampener was introduced, under the conditions of DB+D and NB+D, a noticeable significant difference between the two FOH values was also observed: 12.5026 N for DB+D and 13.2428 N for NB+D, supported by a very small p-value of 8.7404E-5, well below the alpha threshold (Table 6, 7, 9). Additionally, the low standard deviations for DB+D (0.7484) and NB+D (0.6781) demonstrated consistency among trials (Tables 6 and 7). This result, again, rejected the null hypothesis 1, confirming that FOH remained statistically significantly higher for new balls compared to dead balls in the presence of a dampener.

The two graphs (Figures 4 and 5) exhibited a noticeable decrease in COR and FOH when a vibration dampener was present, regardless of the ball pressure. Indeed, there was a statistically significant difference between the FOH/COR of new balls with (NB+D) and without a dampener (NB-D), with a p-value of 2.9808E-4, well below the alpha threshold (Table 10). The new balls' average COR decreased by 12% (from 0.5648 to 0.4984) when a dampener was plugged into the racquet, and its average FOH also decreased by 4% (from 13.8295 N to 13.2428 N) accordingly. Furthermore, the variation of FOH caused by ball pressure change was reduced by 4%: from 0.7736 N without a dampener to 0.7402 N with a dampener. Differences between DB-D and DB+D revealed a similar statistical trend, with a p-value of 3.5912E-3 for the COR and FOH, below the alpha threshold (Table 11). The dead balls' average COR decreased by 13% when a dampener was used, and its average FOH also decreased by 4% accordingly. Furthermore, the variation of FOH caused by ball pressure change was reduced by 4%. As a result, null hypothesis 2 was rejected, suggesting that the dampener is effective in cushioning the collision impact from balls with varying air pressure, decreasing the variation of FOH for both new and dead balls.

These results confirmed the effectiveness of dampeners both in reducing the force on hand regardless of the ball's internal air pressure and in mitigating the variation of the difference in force on hand caused by varying ball pressure. The former validation aligns with the observation that the dampener mutes vibrations on the tennis racquet, thereby lessening the shock transferred to the hand and wrist (Yeh et al., 2019). However, this finding is contrary to a prior study, which suggested that the dampener has been used more as an accessory than helping reduce vibration transmissions to the arm (Stroede, 1999). Considering the fact that Stroede's study was conducted in 1999, the conflict in results may be attributed to the limitations of less advanced technology and measurement techniques available at the time. While the existing results addressing the controversy of dampeners primarily focus on the former argument, the latter statement carries greater significance because it is the difference in FOH, albeit small, still perceptible to tennis players, that demands players' constant adaptation during competition and potentially leads to wrist injury overtime. By reducing the difference in FOH caused by changes in the internal air pressure of tennis balls from repeated impacts, a vibration dampener plays an important role in preventing injuries.

Overall, the consistent and statistically significant results support the following conclusions: 1) new balls produce a higher force on hand during racquet collisions compared to dead balls, and 2) vibration dampeners not only lower the FOH during ball-racquet collisions but also reduce the variation in FOH difference caused by changes in ball pressure. Therefore, new balls exert a greater force on the wrist compared to dead balls, and dampeners are able to reduce this force effectively. Similar to how small changes in ball material and weight increase the risk of injury, changes in the ball pressure—and consequently the COR and FOH—during a match also result in a higher likelihood of injury. The dampener mitigates this risk by reducing the variability of force resulting from differences in ball pressure.

Future Studies and Research Impact

Although the experimental conditions in this study were simplified, the resulting discovery is promising, which will motivate continued research at more realistic settings. One example is to study the effect of air pressure changes on COR and FOH for live/dynamic hittings, such as serving, volleying, and hitting groundstrokes (forehands and backhands). Examining different types of tennis strokes will allow for further exploration into how striking the ball at different locations on the racquet strings affects the force on the hand and upper arm as well. In addition, the simplified rigid beam model of treating the racquet and the hand as a single and isolated system can be replaced with some more realistic and sophisticated models, such as a flexible beam (Cross, 2010), or even a real force sensor if available. Pursuing this line of research further would provide valuable insights into understanding and preventing wrist injuries among tennis players.

This research contributes to both scientific understanding and practical applications for injury prevention in tennis. The demonstrated difference in the force on the wrist due to varying ball pressure could influence future tennis ball designs to reduce gradual pressure changes and inform future rule-making on ball replacement during matches to reduce injury risk. The validated effectiveness of dampeners in reducing the force on a player's hand can also inspire further design improvement. Additionally, this study showcases the success of using computer vision and programming for consistent and accurate measurement, motivating future researchers to adopt this methodology. Overall, this study successfully identifies factors that contribute to (and prevent) injury in tennis, assisting scientists and engineers in designing balls, racquets, and dampeners that are effective in reducing the likelihood of injury.

Acknowledgments

I would like to thank my family for their continuous support (providing all of the experimental materials and helping set up the experiment). I would also like to thank my teacher [redacted advisor name] for guiding me through the process and helping me improve my paper.

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