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THE IMPACT OF RACKET STRING TENSION ON TENNIS RACKET PERFORMANCE

Mingshun JIA, Xiaobin LAN, Tao ZHUANG, Bo SUN*

School of Physical Education, Liaocheng University, Liaocheng, China
*corresponding author, *sunbo@lcu.edu.cn*

This paper investigates the impact of tennis racket string tension, within the same material, on the effectiveness of ball striking. The images were recorded by a high-speed camera, and 8 kinds of string pounds were used in the experiment to fix the frame of the tennis racket, and a homemade ball dispenser was used to launch tennis balls with different incidence velocities and angles to the geometric center of the racket head. Within the tested range, the 40-pound string tension demonstrated the highest coefficient of restitution (COR), while the 70-pound tension showed a comparatively lower value.

Keywords: string pounds; coefficient of restitution; angle of rebound; contact time.

1. Introduction

In the sport of tennis, racket string tension is one of the key factors affecting racket performance. It not only determines the elasticity and energy transfer efficiency of the racket but also directly influences the player's control over the ball and the ball's striking speed (Ghaednia *et al.*, 2015). Research on speed aspects is commonly evaluated using the coefficient of restitution (COR), which represents the ratio of the ball's rebound speed to its pre-impact speed (Cross, 1999). Variations in the COR reflect the elastic characteristics of the interaction between the ball and the racket strings, which are influenced by the string tension (Cross & Bower, 2001). Lower string tensions can produce faster rebound speeds, primarily because the string bed deforms more during impact, the ball deforms less, and the strings can store more energy to return to the tennis ball as kinetic energy, causing the ball to rebound at a faster speed (Cross, 2000; Haake *et al.*, 2003; Kotze *et al.*, 2000). Existing studies have indicated that the selection of string tension should not be too low, nylon strings at around 50 pounds of tension can rebound at faster speeds (Baker & Wilson, 1978; Bower & Cross, 2008; Goodwill & Haake, 2004; Hatch *et al.*, 2006).

String tension and incident speed are key factors affecting the rebound angle (Bower & Cross, 2005; Bower & Sinclair, 1999), and for the same angle of incidence, the smaller the rebound angle, the easier it is for the racket to control the ball, and the better the stability of the racket. The rebound angle of a tennis ball is an important indicator for testing the stability of a racket's control over the ball. Goodwill and Haake (2004) conducted simulated ball-striking experiments with rackets at 40 pounds and 70 pounds of string tension and found that the rebound angle of the tennis ball was influenced by the string tension, with the racket at 40 pounds showing a lower rebound angle than the 70-pound racket. Bower and Sinclair (1999) used rackets with string tensions of 40 pounds, 51 pounds, and 62 pounds for their experiments and found that when the tennis ball struck the 40-pound racket, the rebound angle was closer to the normal of the racket face, while the 62-pound racket produced a rebound angle further away from the normal of the racket face.

In the sport of tennis, the interaction between the ball and the racket has a decisive impact on the outcome of matches (Cross *et al.*, 2000). Particularly, the string tension of the racket and the contact time between the ball and the string are key parameters affecting racket performance and player performance (Bao *et al.*, 2003). The tension of the strings not only affects the rotation and controllability of the ball but is also directly related to the player's feel and comfort (Bendtsen *et al.*, 2015; Bower & Cross, 2003; Hennig, 2007; Kawazoe *et al.*, 2012). In actual competition, the contact time between the ball and the strings is extremely short, usually at the millisecond level (Miller, 2005). This brief contact time significantly influences the ball's speed, spin, and trajectory (Bao *et al.*, 2003; Cross, 2003). Goodwill and Haake (2004) found that the contact time for a 40-pound string is higher than that for a 70-pound racket, suggesting a negative correlation between string tension and contact time. Baktiar *et al.* (2020) conducted impact force tests on two rackets with different tensions and the results indicated that the higher the string tension, the shorter the duration of the collision.

For most recreational players, opting for lower string tension (e.g., 48 lbs) can enhance the racket's elasticity, making it easier to hit the ball and improving both the striking success rate and speed. Medium string tension (e.g., 54 lbs) offers better striking effect and control, while reducing the impact on the forearm (Zhao *et al.*, 2025). Excessively high tension may lead to poor ball placement control and increased errors, whereas overly low tension, though boosting ball speed, can compromise accuracy (Baszczyński *et al.*, 2016). Professional players choose string tension based on match specifics and their technical strengths. For instance, they may select higher tension for more spin and control on certain courts and lower tension for greater speed and coverage on others. When choosing string tension, professionals prioritize the ball's rebound characteristics and the racket's control across various strokes (Allen *et al.*, 2016; Chadefaux *et al.*, 2016).

The current research has the following limitations. First, previous studies have mainly focused on nylon strings, and their findings may not directly apply to other common materials like polyester fiber strings, which have different properties affecting the ball-hitting effect. Second, prior research has a relatively narrow scope regarding racket string tension, impact speed, and incident angle. To better understand the complex interaction between tennis balls and racket strings, these variables need wider-ranging research. Third, while some studies have explored the impact of racket string tension on specific parameters (e.g., coefficient of restitution or rebound angle), they lack comprehensive analysis integrating multiple factors, thus failing to fully understand how string tension affects racket performance. This study selects commonly-used polyester strings, experiments with various tensions, three impact speeds, and five incident angles, and compares the results with previous studies. By studying the effect of different racket string tensions on the rebound speed and angle of tennis balls after impact, it can be found that the same incident speed but different string tensions leads to different rebound speeds. A faster rebound speed indicates a better striking effect, enabling athletes to generate higher ball speeds. A smaller rebound angle means less striking deviation and better ball control, making it easier for athletes to direct the ball to the desired position. Conversely, a larger rebound angle results in poorer ball control, increasing the risk of the ball going out of bounds or having a larger landing point deviation.

2. Materials and methods

2.1. Experimental materials

Wilson Tennis Racket (Wilson Pro Staff v10): The unstrung racket weighs 315 g and is strung with 16 main strings and 19 cross strings. The strung racket weighs 340 g, has a head size of 626 cm^2 (97 square inches), and the racket length is 68.58 cm (27 inches). Luxilon tennis strings (35, 40, 45, 50, 55, 60, 65, 70 pounds): Made of polyester material, with a string diameter of 1.25 mm. Slazenger Tennis Balls: The balls weigh 58 g each. Two light sources, a reflector, a tripod, and a suitably sized wooden board are used to secure the racket; the central part of the board corresponding to the racket head is hollowed out to prevent the string bed from contacting the board upon impact at the racket head.

2.2. Experimental equipment

Before the experiment, a vise and an angle meter were used to adjust the desired angle. A high-speed camera (NX3-S3) produced by IDT Corporation in the United States, with a shooting frequency of 1500 frames per second and a lens focal length of 16 mm, was employed. The scale bar is 0.23 m in the horizontal direction and 0.5 m in the vertical direction. Finally, SIMI-motion software from Germany was used for image analysis.

2.3. Experimental scheme

Before the experiment, a marker was used to label the tennis ball for better determination of the geometric center of the racket face, and the reflective tape was applied for marking. The main optical axis of the high-speed camera was aligned at the same height as the center of the racket head, with the camera position fixed. The tennis ball was placed at the geometric center of the racket, and manual aperture adjustment was made for focusing, with the ability to accurately recognize the markings on the tennis ball as a reference. A plane mirror was positioned at a 45-degree angle in front of the side of the racket to ascertain whether the tennis ball struck the geometric center of the racket face. The ball-feeding machine was adjusted and placed approximately 1.5 m away from the racket, with the prepared scale bar placed at the geometric center of the racket for filming (Fig. 1). In this study, eight racket string tensions were tested. For the 35 lbs tension, impacts at 0°, 30°, 40°, 45°, and 50° incident angles were performed at 20 m/s, 25 m/s, and 30 m/s using a homemade launcher aimed at the racket's geometric center. After the 35 lbs tests, the strings were cut, and a stringing machine was used to restring the racket for the 40 lbs tests, and so on for subsequent tensions.

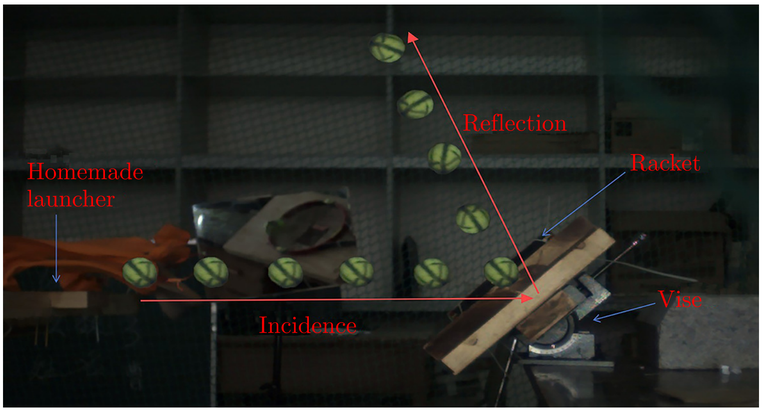

Fig. 1. Superimposition of multiple images of actual tennis incidence and rebound.

2.4. Data processing

The data were statistically processed using a Microsoft Excel spreadsheet for each beat-string poundage, plotted using origin2021 software to plot the selected parameters as a scatterplot, and fitted to the data based on the scatterplot trend. If close to linear, a linear fit was used. In this experiment, the angle between the incident line and the normal is called the angle of incidence α, and the angle between the reflected line and the normal is called the angle of reflection β. The partial velocity perpendicular to the y-axis direction of the racket surface is denoted by

$$v_{yi} = v_i \cdot \cos\alpha. \tag{2.1}$$

The partial velocity of the tennis ball after rebound is expressed as

$$\upsilon_{yr} = \upsilon_r \cdot \cos\beta. \tag{2.2}$$

Calculation of the COR is expressed as

$$e = \frac{\upsilon_{yr}}{\upsilon_{yi}}. \tag{2.3}$$

The ratio of the angle of rebound to the angle of incidence is expressed as

$$\delta = \frac{\beta}{\alpha}. \tag{2.4}$$

Select two fixed points at the top and bottom of the racket head to establish a straight line connecting these two points. Identify the frame immediately preceding the moment of ball impact as the incidence moment, and use the center of the ball in this frame as a fixed point. Connect the centers of the ball from all frames before the impact with this fixed point to obtain multiple straight lines representing the ball's trajectory before impact. For the frame in which the ball leaves the racket after impact, consider it as the bounce moment, and use the center of the ball in this frame as a fixed point. Connect the centers of the ball from all frames following the impact with this fixed point to obtain multiple straight lines representing the ball's trajectory after impact. By connecting the obtained straight lines before the ball impacts with the straight line through the top and bottom points of the racket head, the angles of incidence before the ball strikes the racket can be determined. Calculate the angles of incidence θ by subtracting the complementary angles from 90°. Select the average of the angles of incidence from the 5 consecutive frames with the closest values within the last 10 frames before impact as the incidence angle. Similarly, the rebound angle can be obtained (Fig. 2).

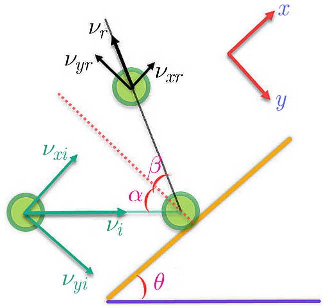

Fig. 2. Schematic diagram of tennis ball incidence and rebound.

3. Results

3.1. Correlation between racket string tension and coefficient of restitution and rebound speed

A fitting equation was established between racket string tension and the COR. At various incidence angles and different ball speeds, there is a correlation between string tension and the COR. The COR tends to decrease with an increase in string tension (Fig. 3). At an incidence angle of 50°, the COR for strings is greater than that at 45°, followed by 40°, then 30°, and the coefficient is the smallest at 0° incidence angle. Moreover, the COR increases with the increase in incidence angle. At 0° incidence angle, the COR decreases with the increase in incidence speed. At an incidence speed of 20 m/s, the coefficients of restitution for 40-pound and 35-pound strings are close and greater than those of other tensions, while the coefficient for 70-pound strings is smaller (Fig. 3a). At incidence speeds of 25 m/s and 30 m/s, the COR for

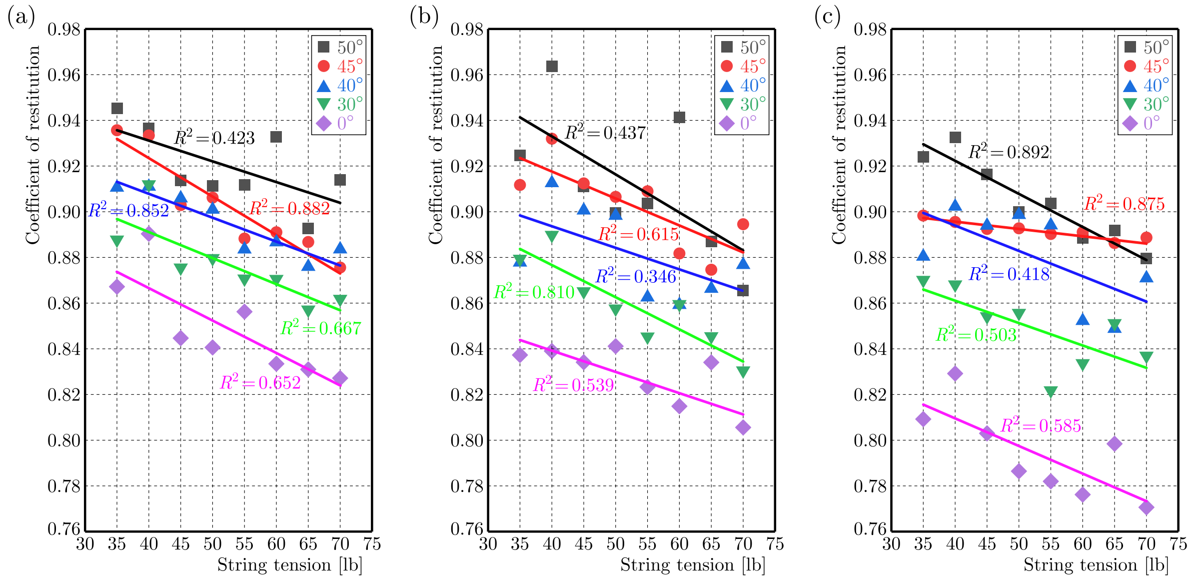

Fig. 3. Linear fitting plots of racket string tension versus coefficient of restitution at various incidence angles and ball speeds: (a) incident speed of 20 m/s; (b) incident speed of 25 m/s; (c) incident speed of 30 m/s.

40-pound strings is greater than that for other tensions, and the coefficient for 70-pound strings is smaller (Fig. 3b and 3c). Additionally, it can be observed from the figures that the COR decreases as the string tension is reduced from 40 pounds to 35 pounds.

By establishing a fitting equation between string tension and rebound speed, it is found that under various incidence angles and ball speeds, the rebound speed decreases as the string tension increases. Specifically, the rebound speeds at 40 and 35 pounds of string tension are greater than those at other tensions (Fig. 4).

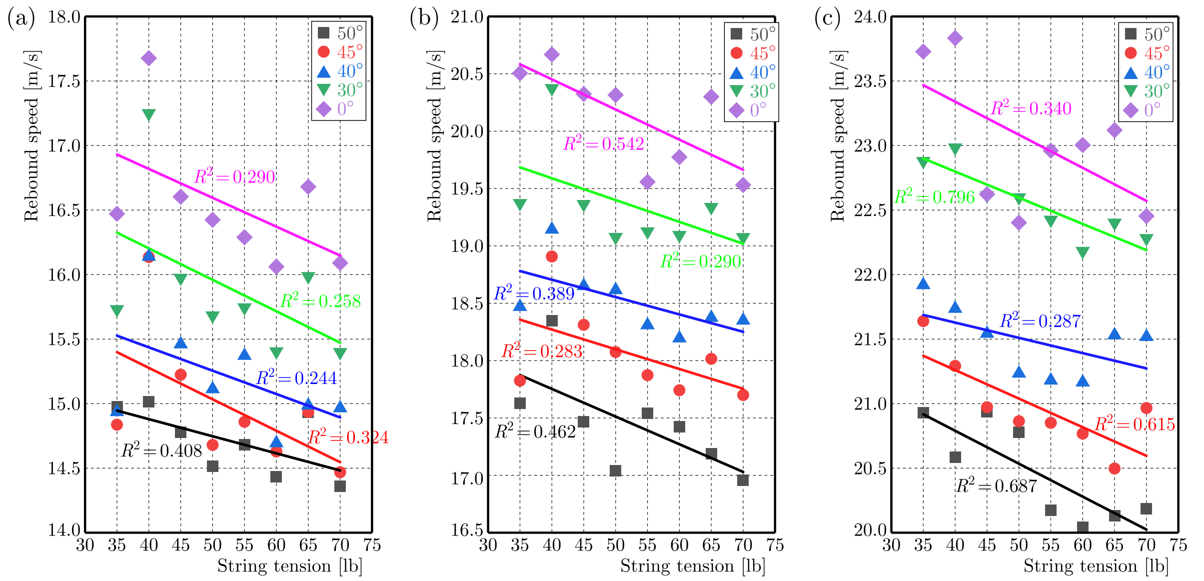

Fig. 4. Linear fitting plots of racket string tension versus rebound speed at various incidence angles and ball speeds: (a) incident speed of 20 m/s; (b) incident speed of 25 m/s; (c) incident speed of 30 m/s.

3.2. Correlation between racket string tension and angle ratio

By establishing a linear fitting equation between racket string tension and the angle ratio, the study results indicate a linear correlation between string tension and the angle ratio. As the string tension increases, the angle ratio tends to increase (Fig. 5). Furthermore, with the increase in incidence velocity, the angle ratio exhibits an overall decreasing trend. At various incidence angles (excluding 0°), the angle ratio for 35-pound string tension is significantly lower than that for 70-pound string tension. Additionally, at the same string tension, the angle ratio increases with the increase in incidence angle. The angle ratio for strings at an incidence angle of 50° is greater than that at 45°, followed by 40°, with the angle ratio at an incidence angle of 30° being the smallest.

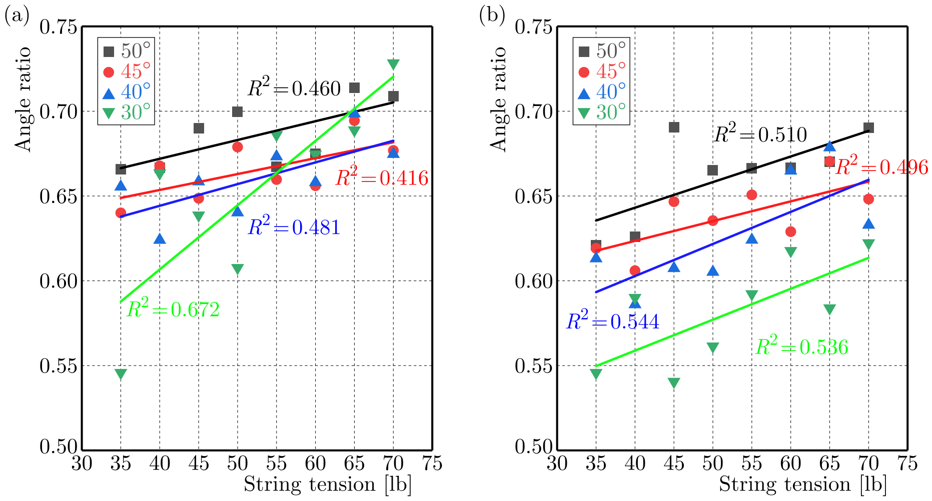

Fig. 5. Linear fitting plots of racket string tension versus angle ratio at various incidence angles and ball speeds: (a) incident speed of 25 m/s; (b) incident speed of 30 m/s.

3.3. Correlation between racket string tension and contact time

By establishing a linear fitting equation between racket string tension and contact time, the study results indicate a linear correlation between the two variables. As the string tension increases, the contact time exhibits a decreasing trend (Fig. 6). Across various incidence angles, the

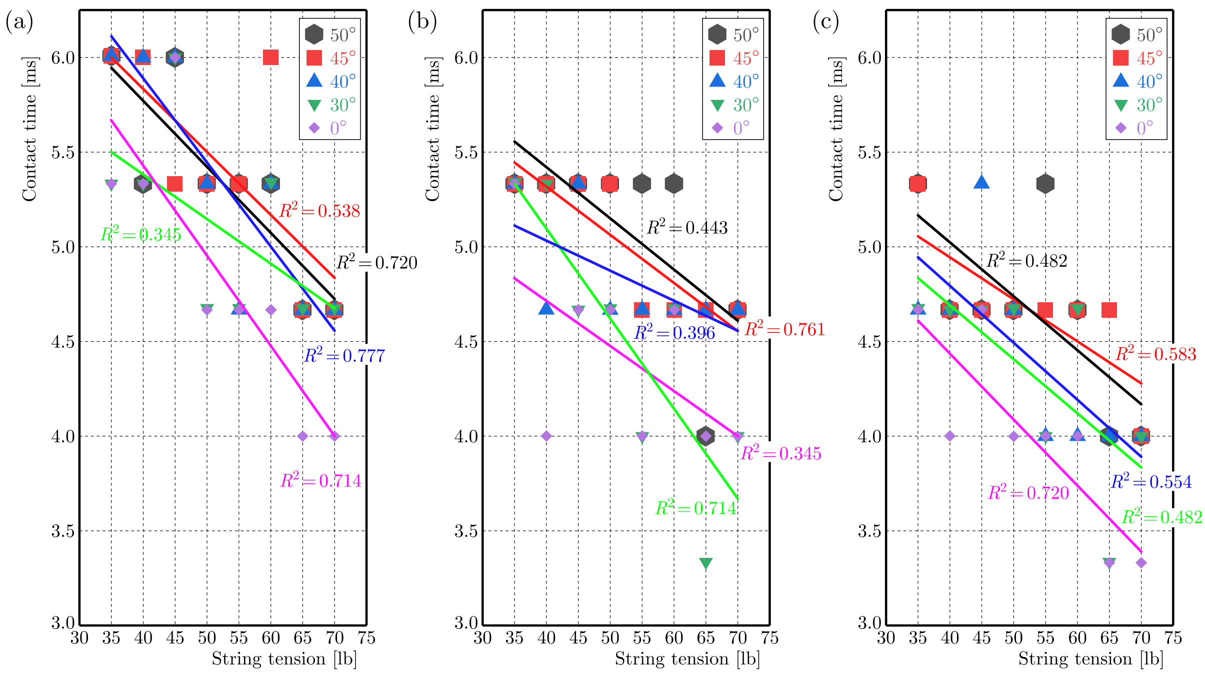

Fig. 6. Linear fitting plots of racket string tension versus contact time at various incidence angles and ball speeds: (a) incident speed of 20 m/s; (b) incident speed of 25 m/s; (c) incident speed of 30 m/s.

contact time for 35-pound tension is longer compared to other tensions, with 70-pound tension having the shortest contact time. At incidence angles of 0° and 30°, the contact time between the tennis ball and the racket strings is shorter than at 40°, 45°, and 50°, suggesting a slight increase in contact time with the amplification of the incidence angle. Across different incidence angles, the contact times in Fig. 6a are overall longer than those in Figs. 6b and 6c, where the contact times are the shortest, demonstrating that with the increase in incidence velocity, the contact time shows a decreasing trend.

4. Discussion

The aforementioned research results indicate that with the increase in incidence velocity, the COR exhibits a decreasing trend (Fig. 3). The possible reason for this is that in the range tested, most of the kinetic energy is dissipated due to the movement inside the racket frame or due to the greater deformation of the tennis ball with the string, resulting in more energy dissipation (Bao *et al.*, 2003). The study found that with the increase in the angle of incidence, the COR tends to increase, which is consistent with the research findings of (Cross, 1999). Additionally, the study discovered that within the tested range, the COR decreases with the increase in racket string tension; the 40-pound string tension exhibits the highest COR, enabling a faster rebound speed for the tennis ball, while the 70-pound string tension shows the lowest COR, resulting in the slowest rebound speed (Fig. 4). The reason may be that at lower string tensions, the string bed can undergo greater deformation, absorbing more energy, which leads to less energy loss for the tennis ball. Consequently, the overall energy loss in the system of the racket and the tennis ball is reduced. Therefore, when the tennis ball leaves the string bed, the strings can transfer a larger portion of energy back to the tennis ball, enabling it to have a faster speed and thus increasing the COR (Baktiar *et al.*, 2020). When the string tension is high, the degree of deformation of the strings is minimal, the whole system energy loss between the string and the tennis ball increases, and the string can only provide a small portion of the energy to the tennis ball as it leaves the string, resulting in a slower tennis ball after rebound, leading to increased energy loss in the system comprising the strings and the tennis ball. Consequently, lower tension strings can enable a faster rebound speed (Bower & Cross, 2005; Cross, 2000; Haake *et al.*, 2003). Within the tested range, a decreasing trend in the COR was observed when the tension was reduced from 40 pounds to 35 pounds. The reason might be that when the tennis ball impacts strings with excessively low tension, the greater degree of string deformation leads to increased energy loss due to excessive movement, resulting in a decrease in the speed of the ball and a decrease in the COR after rebound (Baker & Wilson, 1978).

At various incidence angles (except for 0°), the study indicates that the angle ratio increases with the increase in racket string tension (Fig. 5), and lower tension rackets result in smaller rebound angles, which is consistent with the findings of (Bower & Cross, 2005; Goodwill & Haake, 2004). This suggests that a tennis ball striking a high-tension string (70 pounds) rebounds on a trajectory further away from the racket's normal, which is less favorable for ball control. Conversely, a tennis ball striking a low-tension string (35 pounds) rebounds on a trajectory closer to the racket's normal, offering better control and exhibiting superior stability performance. However, these findings diverge from those of (Brannigan & Adali, 1981), who did not measure the ball's rebound angle but relied on simulation results without experimental validation.

Within the tested range, the study indicates that as the racket string tension increases, the contact time between the tennis ball and the strings shows a decreasing trend (Fig. 6), with the 35-pound tension exhibiting longer contact times compared to other tensions, and the 70-pound tension having the shortest contact time. This is consistent with the research of scholars (Baktiar *et al.*, 2020) and colleagues. It may be because when the tennis ball impacts lower tension strings, the deformation of the strings is greater, leading to an extended contact time. Longer contact times result in reduced impact vibrations transmitted to the racket and the player's hand (Kawazoe *et al.*, 2012), and increasing the contact time between the tennis ball and the strings can enhance a player's control over the ball. Therefore, to improve hitting comfort and control effectiveness, lower tension strings are a good choice (Cross, 2000). Additionally, within the tested range, the study also found that as the incidence angle increases, the contact time between the tennis ball and the strings increases slightly. The reason may be that with an increase in the incidence angle, the tennis ball slides or rolls a longer distance on the contact surface (Goodwill & Haake, 2004). With an increase in incidence velocity, the contact time shows a decreasing trend. The possible reason is that the greater deformation of the strings results in shorter contact times (Baktiar *et al.*, 2020).

In this study, three impact velocities (20 m/s, 25 m/s, 30 m/s) were used, whereas prior studies mostly employed a single one (Baker & Wilson, 1978; Baszczyński *et al.*, 2016). The eight-string tensions selected here differ significantly from the 1–3 used in previous research (Bower & Cross, 2005; Kawazoe *et al.*, 2012; Zhao *et al.*, 2025). Also, the five impact angles were chosen to contrast with the single or fewer angles used before (Bower & Sinclair, 1999; Cross, 1999). This approach helps comprehensively understand the overall trends in the relationship between string tension and coefficients of restitution, angle ratios, and contact times. It also highlights the substantial influence of string tension on tennis racket performance. Lower tensions (e.g., 40 lbs) yield higher coefficients of restitution, smaller rebound angles, and longer contact times, boosting ball speed and control precision (Allen *et al.*, 2016; Chadefaux *et al.*, 2016; Zhao *et al.*, 2025). Selecting optimal tension requires a comprehensive consideration of speed, control, comfort, and performance (Baszczyński *et al.*, 2016). Beginners and intermediate players are advised to choose medium tensions (40 lbs–50 lbs). Advanced players can select based on personal preference and technique, with lower tensions for power-oriented players and higher tensions for control-focused ones.

This study established three levels of incident speed. Within the same level, each launch speed was nearly identical but not exactly equal. The main factors affecting the launch speed were the stretching time and length of the launcher's elastic band, as well as the ball's position inside the launcher. These factors caused slight differences between the set speed and the actual launch speed. During data analysis, the launch speed obtained from the tennis image analysis was used for calculations, which did not affect the results. The relatively low R-squared value observed in this study may be attributed to the uneven stress distribution at the seams resulting from the internal structural composition of tennis balls during impact events. However, this localized phenomenon does not substantially influence the overall trend of the data.

5. Conclusion

Lower string tensions result in a higher COR and rebound speed. Lower string tensions also lead to smaller reflection angles for the same incidence angle, contributing to more stable ball striking. Additionally, lower string tensions correspond to longer contact times between the tennis ball and the racket strings.

Authors' contributions

All authors contributed equally to this work.

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