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# String tension effects on tennis ball rebound speed and accuracy during playing conditions

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**Abstract**

The primary aim of this study was to determine whether variations in rebound speed and accuracy of a tennis ball could be detected during game-simulated conditions when using three rackets strung with three string tensions. Tennis balls were projected from a ball machine towards participants who attempted to stroke the ball cross-court into the opposing singles court. The rebound speed of each impact was measured using a radar gun located behind the baseline of the court. An observer also recorded the number of balls landing in, long, wide and in the net. It was found that rebound speeds for males ($110.1 \pm 10.2$ km · h$^{-1}$; mean ± *s*) were slightly higher than those of females ($103.6 \pm 8.6$ km · h$^{-1}$; $P < 0.05$) and that low string tensions (180 N) produced greater rebound speeds ($108.1 \pm 9.9$ km · h$^{-1}$) than high string tensions (280 N, $105.3 \pm 9.6$ km · h$^{-1}$; $P < 0.05$). This finding is in line with laboratory results and theoretical predictions of other researchers. With respect to accuracy, the type of error made was significantly influenced by the string tension ($P < 0.05$). This was particularly evident when considering whether the ball travelled long or landed in the net. High string tension was more likely to result in a net error, whereas low string tension was more likely to result in the ball travelling long. It was concluded that both gender and the string tension influence the speed and accuracy of the tennis ball.

**Keywords:** *accuracy, errors, gender, rebound speed, string tension, tennis*

## Introduction

The game of tennis requires a combination of strength, speed, balance and control to successfully keep the tennis ball within the boundaries imposed by the court. This, however, does not necessarily ensure success, as the player must also conquer the opponent's attempts to gain the ascendancy in each rally. The success or failure of any one stroke may only be a matter of a few centimetres. To win a match the number of errors must be minimized, as the player with the least number of unforced errors is usually successful. In this study, we examine the interrelationship between the performer and equipment. Specifically, we look at how string tension affects the rebound speed and accuracy of the ball under simulated playing conditions for both males and females.

Previous studies on tennis rackets have primarily been performed under laboratory conditions (Bower & Sinclair, 1999; Brody & Knudson, 2000; Cross, 1999, 2000; Cross & Bower, 2001; Cross, Lindsey, & Andruczyk, 2000; Hatze, 1993; Stroede, Noble, & Walker, 1999). A common topic of interest is the tension at which a racket is strung. Presumably, this is because string tension is one of the few controllable factors available once the tennis racket has been manufactured. It is generally accepted that within the range of commonly used string tensions, low tension provides greater rebound velocity (Baker & Wilson, 1978; Brannigan & Adali, 1980; Bower & Sinclair, 1999; Brody, 1979; Elliott, 1982) and high tensions aid control (Groppel, Shin, Thomas, & Welk, 1987).

Control is the ability to place the ball with the desired speed and spin to a particular area of the opponent's court. To perform this task successfully, players must be familiar with the rebound characteristics of their racket and its particular set-up. In laboratory tests, a clamped racket strung loosely, for example, can project the ball up to 3° closer to the normal to the racket face than a racket strung tightly (Bower & Sinclair, 1999; Goodwill & Haake, 2004; Knudson, 1997). This produces a ball path that is

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approximately 2° higher when a topspin stroke is generated with a moving racket (Figure 1). For a ball struck at 20 $\mathrm{m \cdot s^{-1}}$ with an angle of inclination of 14°, a 2° increase would result in a 2.5-m increase in the range of the ball and a 0.36-m increase in the maximum height of its flight path. These variables must be accounted for if the performer is to maintain the ball within the projectile limits of the court.

In Figure 1, the ball is projected at an angle further from the normal to the racket face at the lower string tension. This initially appears to be inconsistent with the laboratory results. The two sets of results involve different reference frames, however, and are not inconsistent (Figure 2).

Consider the situation shown in Figure 2a, where a ball is incident horizontally at speed $v_{\text{in}}$ on a racket moving at speed $v_R$ at an angle to the horizontal. The same impact can be viewed in a racket reference frame where the racket is at rest, by subtracting the $v_R$ vector as shown in Figure 2b. If the ball is incident at speed $v_1$ in the racket frame, it will rebound at speed $v_2$ as shown in Figure 2c. The ball rebounds closer to the normal to the racket face at low string tension than it does at high string tension. To observe the outcome in the court frame, one has to add the vector $v_R$ to the result in Figure 2c, obtaining the result shown in Figure 2d. At low tension, the ball rebounds at a higher angle in the court frame.

Advanced recreational players appear to be unable to relate such variations in rebound speed and direction to the actual string tension of the racket (Bower & Cross, 2003). This inability is somewhat understandable as they typically play with the same tennis racket and string tension tends to vary only gradually over time. As a result, the performer has time to make the necessary technique adjustments to account for any changes in flight path and ball speed. The question each performer must address is which racket type and string tension is most suited to his or her natural game. The interaction between the physical parameters of a tennis racket and the complex nature of the human performer is one that requires detailed analysis.

The purpose of this study was to examine the effects of string tension on rebound speed and accuracy during performance for both male and female tennis players. It was hypothesized that moderate changes in string tension would have a significant effect on the type of error made, particularly with respect to the height and depth of the impending ball path. This hypothesis was formulated on the basis that the participants would not have time to become accustomed to the various string tensions they tested. It was also hypothesized that the previous laboratory findings relating to changes in ball rebound speed with varying string tensions would not be discernible with the methodology used in this study, since the variability in racket head speed for any given participant would be greater than the small change in ball speed resulting from a change in string tension. Finally, it was hypothesized that males would impact the ball at a greater speed than females and consequently produce more "long" errors.

## Methods

### *Tennis rackets*

Three Volkl Pro Comp graphite tennis rackets were strung at 180 N, 230 N and 280 N (40 lb, 51 lb and 62 lb) using a standard nylon string. These tensions were considered to be loose, medium and tight for this type of racket. All three rackets were otherwise identical and rated medium in both size and stiffness. A small code was placed on each racket so that it was only identifiable to the researcher.

### *Participants*

Forty-one advanced competition players (26 males, 15 females) volunteered for the study. All players

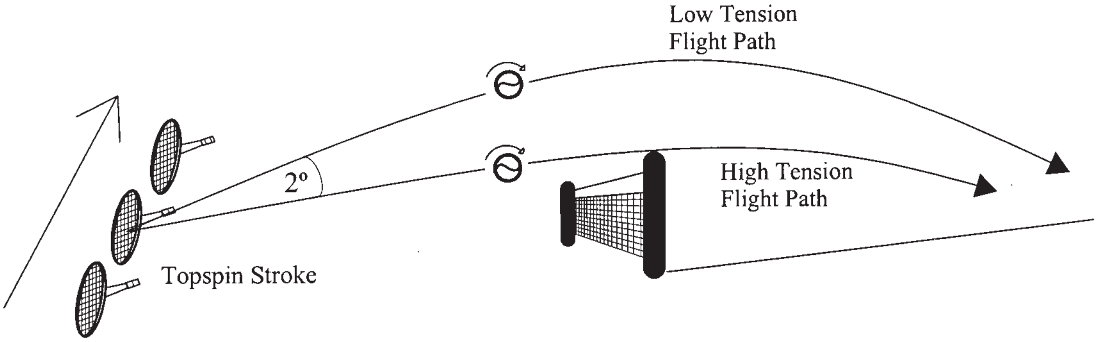
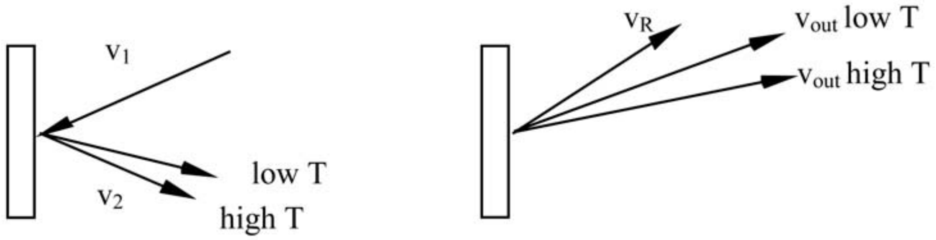


Figure 1. Typical flight paths for a topspin ball impacted with loose and tight strings. The high-tension strings produce a rebound that is approximately 2° closer to the normal to the racket face.

(a) Court frame (b) Racket frame



(c) Racket frame (d) Court frame

Figure 2. Rebound angle of a tennis ball where (a) the ball is incident horizontally at speed $v_{\text{in}}$ on a racket moving at speed $v_{\text{R}}$ (b) as previously but in the racket frame of reference, (c) for low and high tension strings, (d) as previously but in the court frame of reference.

provided informed consent to participate. Formal ethical approval was deemed not necessary for this research since the participants were involved in activities completely integrated into their normal training and competition. These participants were tested following a competition set which provided an adequate warm-up. Participants were competing in an "A grade" local competition and could all hit the ball consistently well. As an indication of their playing ability, males were able to serve at an average speed of 44.7 $\text{m} \cdot \text{s}^{-1}$ (161 $\text{km} \cdot \text{h}^{-1}$) and females at 36.1 $\text{m} \cdot \text{s}^{-1}$ (130 $\text{km} \cdot \text{h}^{-1}$). The mean age of the participants was 27.1 years and the mean number of years playing experience was 16.3 years.

Each participant was required to stroke four forehands with each racket as part of another study testing player sensitivity to string tension (Bower & Cross, 2003). The rackets were rotated several times so that each player impacted at least 8 balls with each racket, but no more than 16 balls. These impacts were performed in groups of four strokes with a maximum of 48 forehands performed by any one player. This included impacts with two additional rackets not described in the present study. The test procedure took between 15 and 20 min per participant and was not considered to be arduous. The order of testing varied randomly between participants in accordance with Table I.

### *Ball machine and radar gun*

A ball machine (Little Prince, Prince Manufacturing Inc., NJ, USA) was positioned centrally on the baseline of the court and projected new Slazenger tennis balls towards the centre of the opposing baseline. Alongside the ball machine was a radar gun (Stalker Pro, Radar Sales Inc., Minneapolis, MN, USA) that measured ball rebound speed. The radar gun was positioned between two markers located 4 m apart and identified the target area for each participant to aim at. The purpose of the radar gun was to ascertain whether measurable differences in rebound speed could be gauged during simulated game conditions. The radar gun was also used to monitor the speed of each ball launched by the ball machine. The launched ball speed remained steady at 75 ± 3 $\text{km} \cdot \text{h}^{-1}$ and was not a significant variable in this experiment.

### *Observer protocol*

Accuracy for each stroke was determined by an observer (one of the researchers and an experienced tennis player) who recorded its success or failure. This was completed by categorizing each forehand as "in", "long", "wide" or "net". An "in" ball was recorded if the ball landed anywhere within the singles lines on the deuce side of the court. Where a ball landed both long and wide, the more blatant of

Table I. Order of testing.

| | Order of testing | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| Test protocol | Tension (N) | | | | | | | |
| A | 180 | 230 | 280 | 230 | 180 | 280 | 230 | 230 |
| B | 280 | 230 | 180 | 230 | 280 | 180 | 180 | 280 |
| C | 180 | 230 | 280 | 230 | 280 | 180 | 280 | 180 |
| D | 230 | 180 | 230 | 280 | 180 | 280 | 230 | 230 |

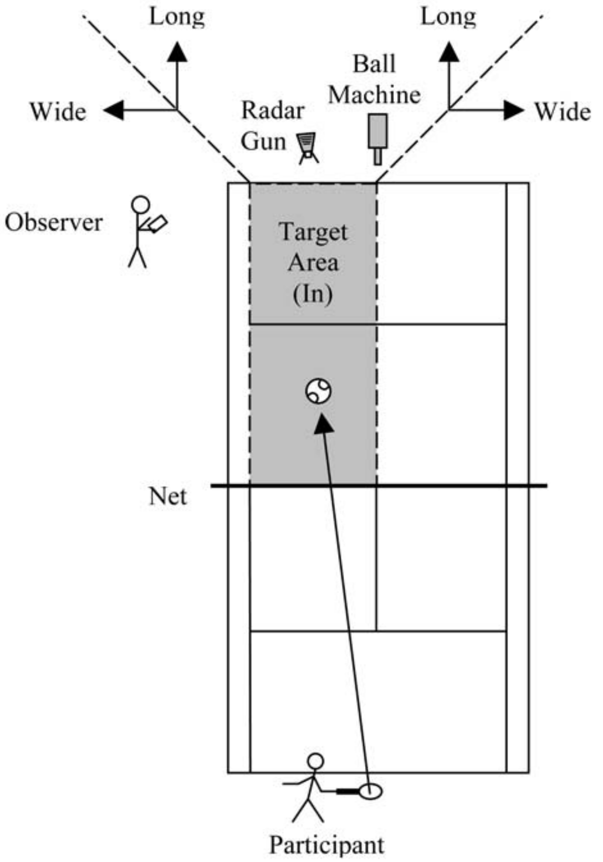


Figure 3. Experimental set-up showing position of participant, observer, ball machine, radar gun and target area. Dotted lines beyond the baseline represent demarcation between long and wide errors.

the two errors was recorded. This type of error was determined by assessing whether the ball landed more lengthwise from the baseline or more laterally from the singles line. Figure 3 indicates the location of the demarcation lines that determined whether a ball was long or wide. The observer reported having no difficulty in assessing the result of each stroke.

### Participant behaviour

As part of the test procedure for the original study on player sensitivity to string tension (Bower & Cross, 2003), participants were asked to concentrate on detecting differences in string tension while attempting to hit the ball cross-court into the singles court. Participants were advised that the radar gun was used to monitor the ball speed from the ball launcher but they were not informed that the gun was also used to monitor the ball rebound speed. Furthermore, participants were not informed about the role of the observer recording errors. This provided an ideal opportunity to measure these variables without prior knowledge of the test procedure influencing participant behaviour. Thus, any significant results could be more confidently attributed to racket mechanics during play, as opposed to participants either consciously or subconsciously trying to influence the results themselves.

### Statistical analysis

In total, 1312 trials (32 forehands each struck by 41 participants) were analysed in this study. Mean rebound velocities for each participant by gender were analysed using a factorial analysis of variance (ANOVA). For string tension, mean rebound velocities for each participant were analysed using a repeated- measures ANOVA and the least significant difference (LSD) multiple comparison procedure. The assumptions of sphericity (Mauchly) and homogeneity of variance (Levene) were also explored. A Pearson's chi-square analysis was conducted to establish whether the type of error (net or long) was influenced by the racket's string tension. All tests were conducted with a statistical significance of $P < 0.05$.

## Results

Before on-court testing, 24 (59%) of the 41 participants indicated a preferred string tension. Males were more likely to nominate a preferred string tension than females (73% vs. 33%). Of those that did nominate a preferred tension, the mean was 260 N, which was towards the upper end of the range of string tensions tested.

Mean rebound speeds were 6% higher ($F = 4.30$, d.f. = 39, $P < 0.05$) for male participants (Table II). Although statistically significant, the effect size was too small to be of practical importance, suggesting that gender did not substantially influence rebound velocity. A repeated-measures ANOVA revealed significant differences (F = 20.7, d.f. = 39, $P < 0.05$) in rebound velocity for varying string tensions. The effect size was large (0.35), indicating that string tension is an important factor in determining rebound velocity. There was no interaction between string tension and gender. The LSD tests reveal that the 280 N racket produced significantly lower rebound velocities than both the 180 N racket and the 230 N racket. There was no significant difference between the medium and low string tensions.

Table II. Rebound speed by gender and string tension (mean ± *s*).

| String tension (N) | Speed ($\mathrm{km \cdot h^{-1}}$) Males | Females | Total |
|---|---|---|---|
| 180 | 111.2 ± 10.2 | 104.9 ± 8.3 | 108.1 ± 9.9 |
| 230 | 111.1 ± 10.7 | 103.5 ± 9.6 | 107.3 ± 10.8 |
| 280 | 108.2 ± 9.8 | 102.4 ± 8.2 | 105.3 ± 9.6 |
| Total | 110.1 ± 10.2 | 103.6 ± 8.6 | 106.9 ± 10.1 |

When considering the placement of the ball (Table III), rackets strung at 230 N produced the greatest number of "in" balls for males (80%) and overall (74%). Females seemed to be more successful with the 280 N racket, mainly due to the low percentage of "long" errors at this tension (3%). The main source of error for males was hitting the ball long with the 180 N racket (23%). This was by far the largest error count recorded by these tests and may be attributed to the difficulty in controlling the greater rebound speed and angle at low string tensions and the greater rebound speed associated with males.

A strong correlation was seen between the tension at which the racket was strung and the type of error produced (Figure 4). Figure 4 shows that high string tensions result in an increase in the number of net errors and a decrease in the number of balls hit long. The Pearson's chi-square value of 12.71 was significant (d.f. = 2, $P < 0.05$), confirming that string tension affects the type of error made.

## Discussion

These results indicate that on-court test procedures produce surprisingly similar results to laboratory tests where the racket is usually clamped. Furthermore, the variation in rebound speed between low

Table III. Ball placement by string tension and gender.

| | Hit in net (%) | | | Hit long (%) | | | Hit wide (%) | | | Hit in (%) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Tension (N) | M | F | M&F | M | F | M&F | M | F | M&F | M | F | M&F |
| 180 | 9 | 15 | 11 | 23 | 10 | 17 | 5 | 6 | 6 | 63 | 69 | 66 |
| 230 | 13 | 14 | 13 | 5 | 16 | 10 | 3 | 2 | 3 | 80 | 68 | 74 |
| 280 | 17 | 19 | 18 | 10 | 3 | 7 | 2 | 5 | 4 | 70 | 73 | 71 |
| All | 13 | 16 | 15 | 14 | 9 | 11 | 4 | 5 | 5 | 69 | 70 | 69 |

*Note*: M = male, F = female.

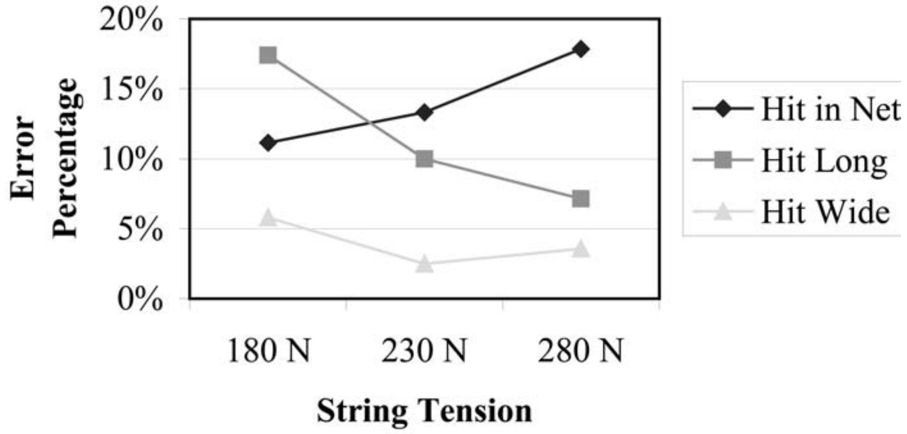


Figure 4. String tension versus error (%) for each error type.

and high tension for all participants was approximately 3%, a value that is consistent with theoretical estimates. The ball speed off the strings ($v$) is given by

$$v = e_A \times v_{in} + (1 + e_A)V_r$$

where $v_{in}$ is the speed of the incoming ball, $V_r$ is the speed of the racket head at the impact point and $e_A$ is the apparent coefficient of restitution (Hatze, 1993). At a string tension of 280 N, the apparent coefficient of restitution is typically about 0.4 for an impact in the middle of the strings. If the string tension is reduced by 20% to 224 N, the apparent coefficient of restitution increases by about 7% to 0.43 (Brody, Cross, & Lindsey, 2002). For realistic racket and ball speeds, the result is an increase in ball speed of about 2 or 3% for a groundstroke and less than 1% for a serve (where $v_{in} = 0$).

The agreement between the theoretical estimate and our experimental data is perhaps surprising given the likely variability in racket head speed at which participants swing a racket. However, the large number of trials yielded a result that was statistically significant. Furthermore, the test procedure involved an equally large number of trials with players using the same racquet several times on separate occasions to hit four balls, in which case no statistically significant difference in ball speed was found for rackets strung at the same tension.

The increase in long balls for lower tensions may be attributed to the ball's angle of rebound. Low-tension rackets produce higher rebound angles (Bower & Sinclair, 1999; Goodwill & Haake, 2004), which adds to the complexity of maintaining the ball within the boundaries imposed by the court. Conversely, the lower rebound angle associated with tightly strung rackets may contribute to the greater number of net errors. It is interesting to note that despite the contrast in the type of error for each string tension, participants were still poor in ascertaining which of the rackets was more tightly strung (Bower & Cross, 2003).

## Conclusion

It is evident from these results that string tension affects both ball rebound speed and accuracy, and that these changes are measurable outside of laboratory conditions. This result is somewhat surprising when considering the likely variation in rebound speed during on-court testing and the small changes in rebound speed associated with changes in string tension. Males on average impacted the ball faster than females and were more likely to stroke the ball long. Females tended to produce slightly more net errors. The large and significant change in the type of error made with varying string tensions has implications for the performer. When increasing the string tension, the ball's rebound is lower and slower. When decreasing the string tension, the ball's rebound is higher and faster. The performer may become accustomed and adjust to these parameters during performance.

The implications of the preceding results vary depending on the type of player. In general terms, the 230 N racket produced the least number of errors overall, with nearly three-quarters of all balls impacted landing successfully in the court. Conversely, the 180 N racket produced the greatest number of errors, with only two-thirds of the balls impacted being successful, and the greatest percentage of long errors (17%). Results for the 280 N racket were between the low and medium string tension rackets but incurred a substantially lower number of long errors (7%) and higher number of net errors (18%). Therefore, a player who naturally incurs a larger number of net errors could consider a more loosely strung racket, as the increased ball speed and angle of projection will provide a greater clearance over the net. Conversely, a performer who typically hits the ball long should consider a more tightly strung racket. In this case, the tighter strings will slow the ball down and lower the angle of projection. It should be noted, however, that these results do not take into account the adjustments that players may make over time as they become accustomed to the same racket type and string tension.

This study was limited to one type of racket, one string type and three string tensions. Furthermore, the ball machine used would not simulate exact game conditions. The hand-held racket and on-court environment, however, have enabled these results to relate as closely as possible to what would occur under match conditions. This is particularly significant when considering that the vast majority of previous studies investigating string tension have been performed indoors with a statically fixed racket.

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