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ORIGINAL ARTICLE

Elite tennis player sensitivity to changes in string tension and the effect on resulting ball dynamics

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Abstract Eighteen elite male tennis players were tested to determine their ability to identify string tension differences between rackets strung from 210 N (47 lb) to 285 N (64 lb). Each player impacted four tennis balls projected from a ball machine before changing rackets and repeating the test. Eleven participants (61%) could not correctly detect a 75 N (17 lb) difference between rackets. Only two participants (11%) could correctly detect a 25 N (6 lb) difference. To establish whether varying string tensions affected ball rebound dynamics, the ball's rebound speed and landing position were analysed. The mean rebound ball speed was 117 km h^{-1}, with only the trials from the 210 N racket producing significantly lower ($P < 0.05$) rebound speeds than the 235 N and 260 N rackets. This is contrary to previous laboratory-based tests where higher rebound speeds are typically associated with low-string tensions. The anomaly may be attributable to lower swing speeds from participants as they were not familiar with such a low string tension. Ball placement did not appear related to string tension, with the exception of more long errors for the 235 N racket and fewer long errors for the 285 N racket. It was concluded that elite male tennis players display limited ability to detect changes in string tension, impact the ball approximately 6% faster than advanced recreational tennis players during a typical rallying stroke, and that ball placement is predominantly unrelated to string tension for elite performers.

Keywords Accuracy · Rebound speed · Sensitivity · String tension · Tennis racket

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1 Introduction

Recent research has identified the limited ability of advanced recreational tennis players to detect differences in string tension [1]. This is despite these players being very particular about the tension at which their racket is strung. Of the 41 players tested, only 18 (44%) could detect a 69 N (15 lb) difference or less. Fifteen players (37%) could not correctly identify a 98 N (22 lb) difference. These findings are significant in that they demonstrate how insensitive advanced recreational performers are to large variations in string tension. String tension can, however, influence the rebound speed of the tennis ball. It is well-documented that lower string tensions produce higher rebound velocity [3, 4, 6, 9–11], mainly due to the "trampoline" effect on the strings. When the ball impacts a tightly strung racket, more energy is lost to tennis ball deformation and the recovery of this is less efficient. For a loosely strung racket, the strings deform more and the tennis ball deforms less. This results in a slightly faster rebound since the strings return a greater fraction of their stored energy than the ball.

Laboratory tests have also shown that the path of the rebounding tennis ball can be altered by the chosen string tension [3]. For example, it is possible to increase the angle of rebound by up to 3° when decreasing the string tension from 270 N (61 lb) to 180 N (40 lb). This assumes a top-spin stroke where the relative angle between the racket and ball path is 45°. Forehands are typically hit with a relative angle of 47° [7] and backhands with an angle of 45° [8]. It is likely that the advanced recreational performers noticed the change in rebound angle, but on a whole were not able to relate this back to the string tension of the racket. Interestingly, the effect of string tension on the type of error is statistically measurable, and it is clear that more net errors occur with tightly strung rackets and more long errors occur with loosely strung rackets [2]. These results may be attributed to both the velocity and angle of rebound changes associated with variable string tensions as described earlier.

This investigation aims to determine whether elite performers are more sensitive than recreational players to variations in string tension. It will also examine whether the type of error is influenced by the string tension in each racket. It was hypothesized that the elite performers would be more successful at determining string tension differences, and that unlike advanced recreational tennis players, the type of error made would not be related to the racket's string tension. This second assumption is based on the greater ability of elite players to adjust to the variety of racket conditions tested. Elite players will be more familiar with adapting to varying on-court conditions such as temperature, court surface and speed, ball type and opponent style.

2 Methodology

2.1 Participants

Eighteen elite male tennis players agreed to take part in the study which was approved by the University's Human Research Ethics Committee. Each of these players was participating in a satellite tournament which took place at the location of testing. An elite tennis player was defined as holding either a national ranking for their country (predominantly Australian), or a world ranking in the top 1,500. These players were competing with the intention of establishing a career as a tennis professional and were considerably more skilled than the advanced recreational tennis players tested by [1]. Each participant completed a short questionnaire prior to testing that identified their preferred string tension, string type and whether they used a dampener. Their mean age was 20.0 ± 3.2 years and mean experience 11.0 ± 3.0 years.

2.2 Tennis rackets

Four TopSpin Pro tennis rackets were strung at 210, 235, 260 and 285 N (47, 53, 58 and 64 lb) with identical nylon string (1.3 mm, TopSpin Synthetic Gut). The 25 N (6 lb) tension difference between adjacent tennis rackets was confirmed by measuring the vibration frequency of the string plane as described by [5]. The rackets were all 355 g, which is slightly heavier than the average racket since professional tennis players generally prefer heavy, narrow body rackets. A circular rubber dampener (Jadee Sports) was placed on each racket so that sound from string vibration was attenuated. Without a dampener, tension differences are easier to detect by the sound. Apart from the string tension and a small code placed on each handle, all rackets were identical and rated medium in both head size and stiffness.

2.3 Testing protocol

Each test required the participant to compare two rackets in succession and state whether they noticed a difference in string tension and if so, which was tighter. The assessment was determined after using each racket to impact four tennis balls projected from a Tennis Tutor™ ball machine with an outgoing speed of 21.7 ± 0.6 m s^{-1} (78 ± 2 km h^{-1}). Following this, a second pair of rackets with the same tension differential was provided as a re-test. To succeed at a particular string tension differential, the participant had to correctly detect the tighter racket on both occasions. Guessing was specifically discouraged and all participants appeared to make an honest assessment. The first string tension differential examined their ability to detect a 50 N (11 lb) difference. If successful, they were provided with rackets varying in tension by 25 N (6 lb). If unsuccessful, rackets varying by 75 N (17 lb) were provided. This enabled an estimate of each participant's discrimination level to be determined. The order of testing and the decision process is shown in Fig. 1.

2.4 Ball rebound characteristics

All participants were requested to direct each stroke (forehand) cross-court and within the singles court. They were advised to hit the ball as they would during a rally in a game situation. A radar gun (Stalker Pro, Radar Sales Inc., Minneapolis, MN USA) measured the rebound velocity of the tennis ball. The success or failure of each stroke was recorded by an observer positioned laterally to the court. This included whether the ball landed in the court, in the net, long or wide. These data were gathered to determine whether there was any relationship between the string tension tested and the resulting speed or placement of the tennis ball.

To establish whether there was a relationship between the preferred string tension and the percentage of balls hit in for each tested string tension, all players were categorised into two groups based on their preferred string tension.

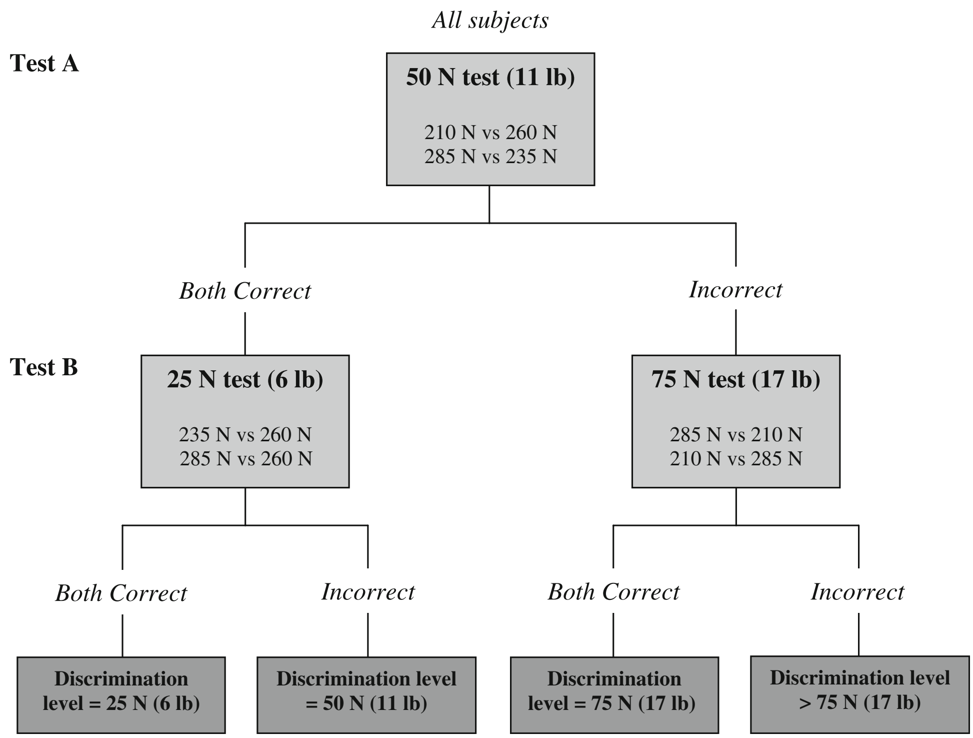

Fig. 1 Decision tree for testing

The lower preferred tensions were grouped from 245 to 270 N and the higher preferred tensions were grouped from 271 to 295 N. This resulted in nine participants being allocated to each group. The upper two string tensions analysed in this study were approximately at the mid point of these two groups (260 and 285 N). By establishing these two groups, it was possible to determine whether each group's string preference influenced the accuracy of their strokes. For example, the group preferring a higher string tension would be expected to be more accurate when utilising the rackets strung at 285 N and less accurate when utilising any of the lower string tensions. The opposite would also be expected for the group preferring a lower string tension. This assumption is based on their apparent familiarity with a certain string tension and an assumed difficulty in adapting to an alternate string tension. It also provides an objective means of measuring how important a player's preferred string tension really is to their performance.

2.5 Statistical analysis

A total of 864 forehands were analysed for this study. Mean rebound speed for each participant by each string tension was analysed using a repeated-measures ANOVA and the least significant difference (LSD) multiple comparison procedure. The assumptions of homogeneity of variance (Levene) and sphericity (Mauchly) were examined. Type of error (net, long and wide) was analysed using the Pearson's Chi-square to investigate whether this is influenced by string tension. Statistical significance was set at $P < 0.05$.

3 Results

3.1 Pre-test questionnaire

The pre-test questionnaire indicated that all participants in this study had a preferred string tension and chose to string their own racket at tensions ranging from 245 N (55 lb) to 294 N (66 lb). The mean tension was 272 N (61 lb) and eight (44%) of the participants typically use a string dampener. Seven (39%) use a nylon string, three (17%) use kevlar, two (11%) use gut and two (11%) use a polyester string. The remaining four participants (22%) did not have a string preference.

3.2 Level of discrimination

All 18 participants were tested at the 50 N (11 lb) level of discrimination and only five (28%) could correctly detect a difference in two successive trials (Fig. 1). This means that 13 (72%) of the participants could not identify which racket was tighter between say a 285 N (64 lb) and a 235 N (53 lb) string tension. For the five participants who passed the first test, two (11%) could correctly detect a 25 N (6 lb) difference. For the 13 participants who failed the first test, two (11%) could correctly detect a 75 N (17 lb) difference, and 11 (61%) were not successful. This indicates that over half of the elite participants tested could not discriminate correctly between a 210 N (47 lb) racket and a 285 N (64 lb) racket.

3.3 Ball rebound speeds

The mean rebound speed of the tennis ball was 117 ± 9 km h^{-1}. Maximum radar gun errors were calculated to be 0.61% or approximately 0.7 km h^{-1}. This was based on a maximum angular error between the path of the ball and the radar gun of 6.3°. Most strokes were well within this angle and would therefore have incurred a smaller error.

The assumptions of homogeneity of variance (Levene) and sphericity (Mauchly) were met for rebound speed by string tension. Repeated-measures ANOVA results produced significant differences ($F = 6.2$, $df = 3$, $P < 0.05$, Effect size = 0.27) in rebound speed by string tension. The LSD tests indicated that the 210 N tension produced significantly lower rebound speeds than both 235 and 260 N rackets. A summary of the rebound speeds can be found in Table 1.

3.4 Ball placement

Percentages of balls impacting various parts of the court are presented in Table 2. A Pearson's Chi-square value of 17.8 ($df = 9$, $P < 0.05$) was obtained confirming that string tension significantly effects the type of error made. It is clear from Fig. 2 that the 235 N tension produced the highest percentage of long errors, and the 285 N tension produced the lowest percentage of long errors. Error percentages for net and wide balls were lower than long balls and relatively consistent across all string tensions.

Table 1 Ball speeds for each string tension (speed ± standard deviation)

Tension (N)	*N*	Mean (km h^{-1})	Minimum (km h^{-1})	Maximum (km h^{-1})
210	18	114 ± 9.9	95	130
235	18	119 ± 8.3	104	132
260	18	119 ± 8.5	102	134
285	18	117 ± 9.2	103	133
Total	72	117 ± 9.0	95	134

Table 2 Ball placement by string tension

Tension (N)	Hit in net (%)	Hit long (%)	Hit wide (%)	Hit in (%)
210	9	13	5	73
235	7	22	5	67
260	5	16	5	74
285	8	9	6	77
Total	7	15	5	73

3.5 Preferred string tension versus tension used

Percentages for balls landing in for each string tension versus the grouped preferred string tensions are presented in Table 3. Overall, both groups hit approximately the same number of balls into court (75% for lower preferred string tension and 72% for higher preferred string tension). When participants utilised a racket that approximated their preferred string tension, there appeared to be no significant advantage in terms of the percentage of balls landing in.

4 Discussion

4.1 Discrimination level of elite players

The results of this study surprisingly reveal that elite tennis players are no better at detecting string tension differences than advanced recreational tennis players. The 28% of elite participants able to correctly discern a 50 N (11 lb) tension differential compares equally with the 27% for advanced recreational tennis players [1]. This is apparent despite the greater tennis ability of the elite players, the many more hours of practice and competition each week, the greater regularity at which elite players restring their racket, and the fact that all of the elite participants nominated a preferred string tension. For advanced recreational players, only 59% nominate a preferred string tension [1].

The limited ability to detect string tension differences seems contrary to the particular care elite tennis players take with their racket strings. Anecdotal evidence suggests

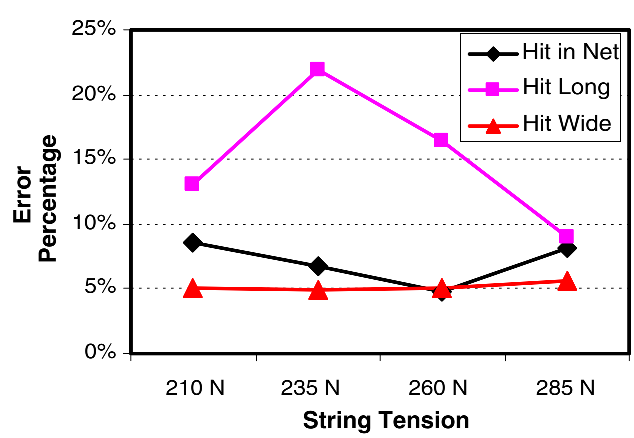

Fig. 2 String tension versus error (%) for each error type

Table 3 Balls landing in (%) by preferred string tension for each string tension tested

Preferred string tension	*N*	Balls landing in (%) for each string tension				
		210 N	235 N	260 N	285 N	All
Lower tension group (245 N–270 N)	9	74	64	77[a]	80	75
Higher tension group (271 N–295 N)	9	73	69	70	75[a]	72

[a] Utilising a racket approximating their preferred string tension

that many satellite tennis players restring their rackets prior to every match, presumably to minimise the effect of time on string tension loss. The physical benefit of this is questionable given the above results, but may benefit the performer through psychological means. It is not uncommon for an elite player to change their racket during a match, perhaps to a slightly higher or lower string tension. Interestingly, tennis players discern the tension by tapping the frame of one racket on the string membrane of the other racket in order to use sound cues. Given that these rackets are all likely to be strung the same or varying by only a few pounds, one must again question the practical benefit of such racket selection.

4.2 Ball rebound speed

Advanced male recreational players undertaking a similar experiment impact the ball at approximately 110 km h^{-1} [2]. Mean rebound speed for the current study of elite male performers was approximately 6% higher. This indicates a relatively small increase in rebound speed, suggesting that advanced recreational players are close to elite players in terms of rebound speed. Both studies, however, required the performer to stroke the ball projected from a ball machine whilst attempting to compare the string tension in each racket. This may have influenced their stroke mechanics and the speed difference is therefore only an estimate of what would occur during actual game play.

Previous laboratory tests indicate that string tension effects tennis ball rebound speed. Lower string tensions are known to produce higher rebound speeds and are typically measured using the coefficient of restitution or the apparent coefficient of restitution [3, 4, 6, 9–11]. The results of this study indicated that the 210 N racket produced a lower rebound speed than both the 235 and 260 N rackets. The obvious limitation with on-court testing is the inability for the participants to be consistent with their swing speed and timing of the tennis ball. The large number of trials for each racket, however, should partially overcome this.

One possible explanation for the lower rebound speed for the 210 N racket is that this tension was substantially below the nominated tensions of all participants. It may be possible that they were unfamiliar with the rebound characteristics of such a loosely strung racket, and consequently took a more cautious approach to each impact. Previous research has shown that during topspin strokes, loosely strung rackets project the ball at higher angles of rebound [3]. This, together with the greater rebound speed likely for the loosely strung racket, will create an impact that is more difficult to control. As a result, the players may have elected to control the ball by reducing their swing speed and therefore lowering the rebound speed of the ball.

4.3 Ball placement (accuracy)

When it comes to ball placement, long errors were twice as likely as net errors and three times more likely than wide errors (Table 2). The ratio of long errors to wide errors is comparable to previous research with advanced recreation players [2], but the ratio of long errors to net errors is far greater. The greater percentage of long errors compared to a net errors suggests that elite players are more likely to be pressing for deep strokes than strokes that just go in. This probably evolves from the need to keep the ball deep in order to prevent a skilful opponent from attacking a ball landing closer to the net. Elite players prefer to make a few more long errors if it means that their strokes are predominantly deeper during successful impacts.

With regards to string tension, more long errors were evident with the 235 N racket. This racket resulted in more than one in five balls landing past the baseline of the tennis court, and compares much less favourably than the 285 N racket where less than one in ten balls landed long. The high number of long errors was largely responsible for the 235 N racket having the lowest percentage of balls landing in. The other three string tensions resulted in approximately three-quarters of the strokes being successful, where as the 235 N racket enabled only about two-thirds.

It is difficult to conclusively identify the reasons for the above results. One possible explanation is that the 235 N racket was close to their range of preferred string tensions, but still below it. The participants therefore felt comfortable with the tension, but failed to consistently take into account the higher rebound speed and angle described earlier. The 210 N racket was significantly below the string tension elite players typically choose. They therefore may not have been comfortable with this racket and consequently took more care with each stroke. This produced a lower number of errors and explains the lower rebound speed evident for this string tension. The fewer long errors for the 285 N racket is more understandable, although this racket did not have a correspondingly greater proportion of net errors. Tighter rackets are known to project the ball at a lower angle of rebound when producing a topspin stroke [3]. Apart from these results, there appears to be no relationship between string tension and the type of error. This indicates that elite tennis players can adapt reasonably well to varying string tensions.

When considering the preferred string tension versus the string tension tested, the percentage of balls landing in was unaffected. Even if the player was utilising a racket with a tension the same or similar to their preferred tension, no differences were observed. This indicates that a player's preferred tension is not a factor in determining the percentage of successful strokes across the four string tensions tested under the conditions of this experiment. It also adds further credibility to the notion that elite tennis players can readily adapt to the string tension in a tennis racket during a typical rallying stroke.

5 Conclusion

It is clear from this study that elite tennis players exhibit limited ability to correctly detect changes in string tension. Only 28% of the participants could correctly detect a 50 N (11 lb) difference. Sixty-one percent of participants could not correctly identify a 75 N (17 lb) difference. These results are no better than advanced recreational tennis players from previous research, and indicate that the standard and amount of tennis played does not necessarily make one more familiar with string tension.

Elite male tennis players were able to project the ball approximately 6% faster than advanced male recreational players, but unlike laboratory results, the lowest string tension did not produce the highest rebound speed. This tension was substantially lower than a typical tension chosen by elite players and may have resulted in their swing speed reducing in order to aid the control of the ball.

Ball placement was predominantly unrelated to string tension, although the 235 N racket produced a greater percentage of long errors and the 285 N racket produced a lower percentage of long errors. This can partially be explained by previous research where it is known that lower string tension produces higher rebound angles and greater rebound velocity. The trend, however, did not continue for the lowest string tension (210 N) where the percentage of long errors was relatively small. This anomaly may be explained by a more careful approach taken by the participants for this excessively low string tension as evidenced by the lower rebound speed. Finally, the use of a racket strung near a player's preferred string tension does not produce a greater percentage of successful strokes. This suggests that elite tennis players are well-equipped to adapt to varying tennis racket string tensions during a typical rallying stroke.

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