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Measurement of main strings movement and its effect on tennis ball spin

Yudai Washida[a], Nathan Elliott[a], Tom Allen[ab]*

[a]*Centre for Sports Engineering Research (CSER), Sheffield Hallam University, Collegiate Campus, Sheffield, S10 2BP, UK*
[b]*Department of Engineering and Maths, Sheffield Hallam University, City Campus, Sheffield, S1 1WB, UK*

Abstract

Ball spin plays an important role in the modern game of tennis. Previous work has shown that reducing the number of cross strings in a tennis racket can increase rebound ball spin. The aim of this study was to further our understanding of the effect of the number of cross strings on ball spin generation. Two rackets were tested, one with 16 main and 19 cross strings and the other with 16 main and 12 cross strings. The racket frame was fully-constrained and a ball was fired onto the strings at inbound angles of 24 and 38º. Inbound velocity was set at 30 m/s and inbound spin was varied from 0 to 500 rad/s. Ball velocity and spin, and lateral main string deflections during impact, were measured from high-speed video footage. Lateral string deflections were consistently larger for the racket with fewer cross strings. The racket with fewer cross strings produced slightly higher rebound spin and lower horizontal rebound velocity, which was attributed to the main strings returning during the restitution phase of the impact.

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Keywords: tennis; impact; high-speed video; spin; angle; string bed

1. Introduction

The introduction of composite materials in the 1970s led to considerable changes in tennis racket design, including increased stiffness and head size, alongside reduced mass (Haake et al., 2007). The faster swing speeds and larger head sizes, associated with the new racket designs, are believed to have enabled players to hit balls faster

* Corresponding author. Tel.: +44 (0)114 225 2255; fax: +44 (0)114 225 4356.
E-mail address: t.allen@shu.ac.uk

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and with more spin. Topspin generates a downwards force on a ball in flight called Magnus force, which enables players to hit their shots faster and still land within the court boundary. Both the International Tennis Federation (ITF) and equipment manufacturers are concerned with the mechanics of spin generation from a racket. The ITF aims to protect the nature of tennis, while manufacturers continually strive to make improvements to their products. Recent work has focussed on the effect of string bed properties on ball spin generation (Allen et al., 2010; Haake et al., 2012; Nicolaides et al., 2013).

Allen et al. (2010) used a computational model to show that reducing ball/string friction can increase rebound spin, although no experimental data was presented to validate the predictions. Haake et al. (2012) presented experimental data which showed rebound spin to be dependent on inter-string friction. Nicolaides et al. (2013) investigated the effect of string bed pattern on ball spin generation. They fired balls at a velocity of 24 m/s, an angle of 26º (relative to normal) and spin rate of 218 rad/s, onto 9 fully-constrained rackets with different string bed patterns. They found rebound angle to decrease with the number of cross strings, while rebound spin increased. Nicolaides and colleagues presented images, captured at high-speed, which indicated the lateral deflection of the main strings increased as the number of cross strings decreased, however, no measurements were taken.

The aim of this research was to further our understanding of the effect of the number of cross strings on spin generation, by measuring both ball rebound and lateral deflections of the main strings.

2. Method

Two prototype rackets with the same head size - 0.35 x 0.25 m inside dimensions - but a different number of cross strings were used in this research. Both rackets had 16 main strings, one had 19 cross strings (16 x 19) and the other had only 12 (16 x 12). These rackets were strung with Polyester string (Prince Beast XP 17, Prince) at a tension of 245 N 24 hr prior to testing. ITF approved tennis balls (HEAD Radical, HEAD) were opened 24 hrs prior to the testing to stabilise the pressure and were marked to enable measurement of spin.

The experimental setup followed closely Nicolaides et al. (2013). A ball pitching machine (BOLA, UK) with a bespoke barrel fired the ball onto the face of the racket (Figure 1b). The frame of the racket was fully-constrained to allow any lateral movements of the main strings to be observed in a mirror set at 45º beneath the string bed. The ball was fired at two inbound angles, 24º (S.D. 1.6º) and 38º (S.D. 1.3º). For each angle, the inbound velocity of the ball was set at 30 m/s (S.D. 1.5 m/s) and the inbound spin was varied from 0 to 500 rad/s. Inbound spin was defined as positive at backspin, while the outbound spin was positive at topspin (Figure 1b). The ball was targeted at the geometric centre of the string bed, which is typically where elite players aim to strike (Choppin, 2011). Each racket was impacted 24 times per inbound angle and the maximum number of impacts per ball was 15.

A monochrome high-speed camera (Phantom v4.3, Vision Research) – operating at 1,265 Hz at a resolution of 320 x 240 with exposure time of 30 μs – was placed perpendicular to the plane of motion to record the trajectory of the ball. The footage was automatically digitised with in-house software (SpinTrack3D), to obtain the spin and velocity of the ball. Manual digitization in Phantom Cine Viewer v2.0 was used to measure inbound spin for balls with minimal inbound spin, as SpinTrack3D is inaccurate at low spin rates (Kelley, 2011).

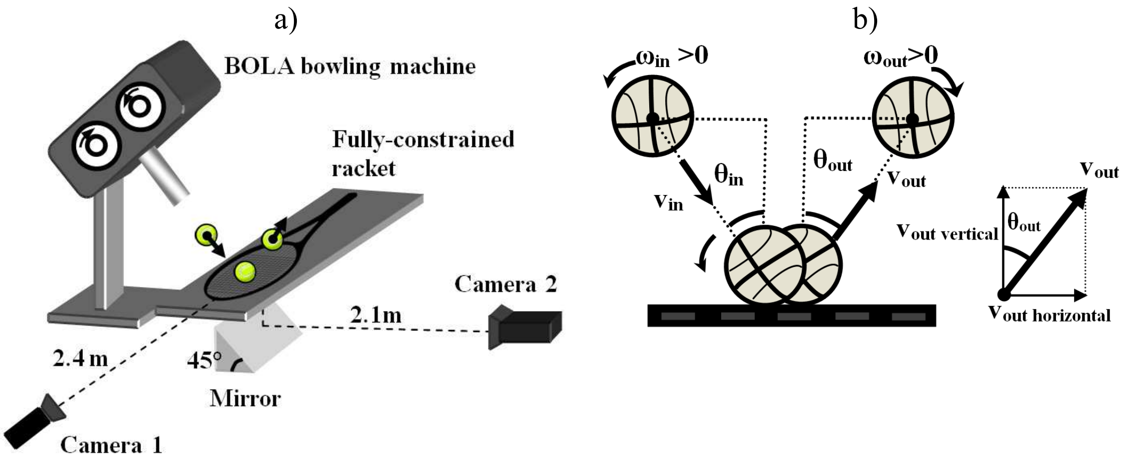

Figure 1a) Experimental set up, camera 1 is the Phantom v4.3 and camera 2 is the Phantom Miro and b) Inbound and rebound conditions

A colour high-speed camera (Phantom Miro, Vision Research) – operating at 3,502 Hz at a resolution of 320 x 240 and exposure time of 100 µs – filmed the string bed in the reflected view in the mirror. The camera was calibrated by placing a known sized checkerboard on the string bed (Figure 2a). The deflection of the main strings was measured manually. String deflection was defined as the distance between the initial position and the deflected position. For each impact 6 strings were analysed (Figure 2b) to find i) the string with the largest lateral deflection and ii) the image frame (FrameMax) which showed the string with the largest deflection at the time of maximum deflection. The deflections of the three most deflected strings in FrameMax were then recorded (Figure 2c). The mean of the three values for string deflection was taken as a measure for string deflection for the impact, defined as Mean Lateral String Deflection (MLSD). Since not all variables were distributed normally, according to a Shapiro-Wilk test, a non-parametric Wilcoxon Rank-Sum Test was conducted on each variable (horizontal and vertical rebound velocity, rebound spin and MLSD), with the racket type as a between factor.

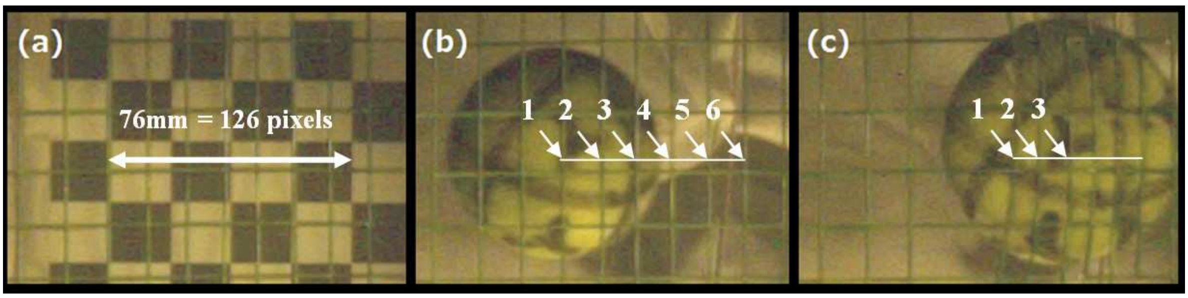

Figure 2 a) Calibration of camera 2, b) six strings selected for analysis, before the impact and c) three most deflected strings in FrameMax which were used to calculate the Mean Lateral String Deflection

3. Results

Figure 3 shows the results for vertical rebound velocity. Vertical rebound velocity remained fairly constant with increasing inbound spin, at both inbound angles. There was a fairly large amount of scatter in the data and no clear differences can be observed between the two rackets, at either inbound angle. There is also a clear outlier for the racket with fewer cross strings at the inbound angle of 24º and inbound spin rate of ~200 rad/s. The Wilcoxon Rank-Sum test indicated vertical rebound velocity between the two rackets was significantly different at the inbound angle of 24º (W = 398, p = 0.002).

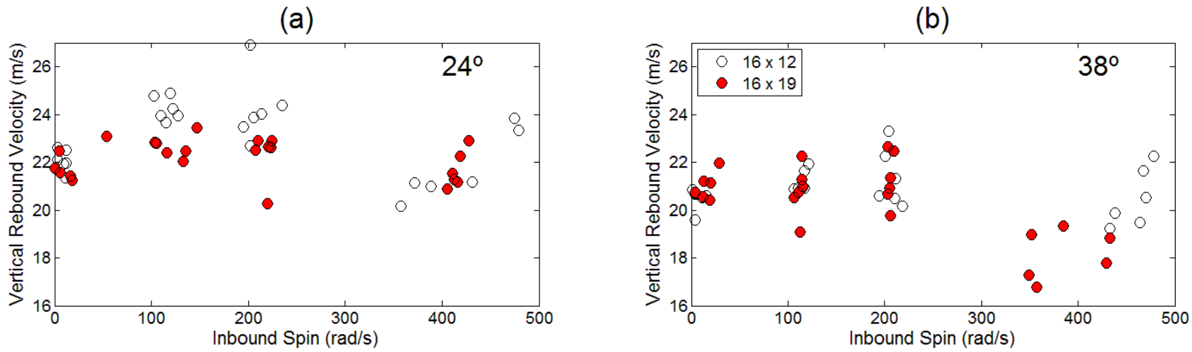

Figure 3 Results for vertical rebound velocity, a) inbound angle of 24º and b) inbound angle of 38º.

Figure 4 shows the results for horizontal rebound velocity. Horizontal rebound velocity decreased with increasing inbound spin, at both inbound angles. As with vertical rebound velocity, scatter in the data was fairly high. In general, lower horizontal rebound velocities can be observed for the racket with the reduced number of cross strings. The Wilcoxon Rank-Sum test indicated significant differences in horizontal rebound velocity between the two rackets at inbound angles of 24º (W = 117, p < 0.001) and 38º (W = 100, p < 0.001).

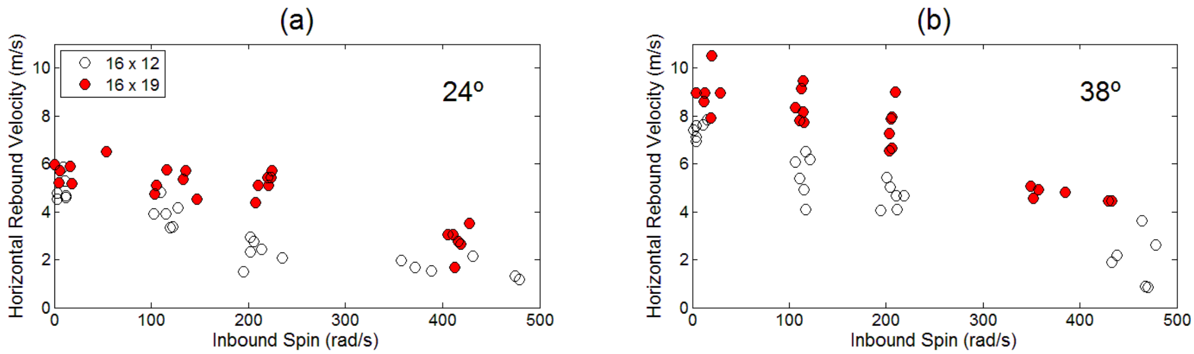

Figure 4 Results for horizontal rebound velocity, a) inbound angle of 24º and b) inbound angle of 38º.

Figure 5 shows the results for rebound spin. At the inbound angle of 38º rebound spin decreased with increasing inbound spin, for both rackets. Rebound spin also decreased with increasing inbound spin for the racket with more cross strings at the inbound angle of 24º. For the racket with fewer cross strings at the inbound angle of 24º, rebound spin increased with inbound spin from 0 to 100 rad/s, and then decreased as inbound spin increased from 100 to 500 rad/s. As with the results for rebound velocity there was a relatively large amount of scatter in the data. In general, slightly higher rebound spin rates can be observed for the racket with fewer cross strings for inbound spin rates above 100 rad/s, at both inbound angles. For inbound spin greater than 100 rad/s, the mean rebound spin was 25 rad/s higher at the inbound angle of 24º and 16 rad/s higher at the inbound angle of 38º. The Wilcoxon Rank-Sum test indicated significant differences in rebound spin between the two rackets at inbound angles of 24º (W = 436, p = 0.002) and 38º (W = 388, p = 0.040).

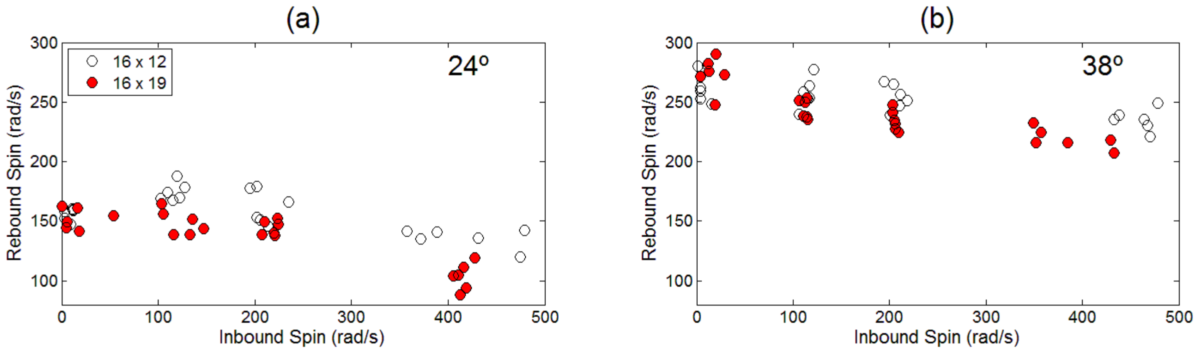

Figure 5 Results for rebound spin, a) inbound angle of 24º and b) inbound angle of 38º.

Figure 6 shows the results for MLSD. The results indicate that the MLSD increased with inbound spin, and larger deflections can clearly be observed for the racket with fewer cross strings. The Wilcoxon Rank-Sum Test indicated significant differences in MLSD between the two rackets, at inbound angles of 24º ($W = 576$, $p < 0.001$) and 38º ($W = 576$, $p < 0.001$).

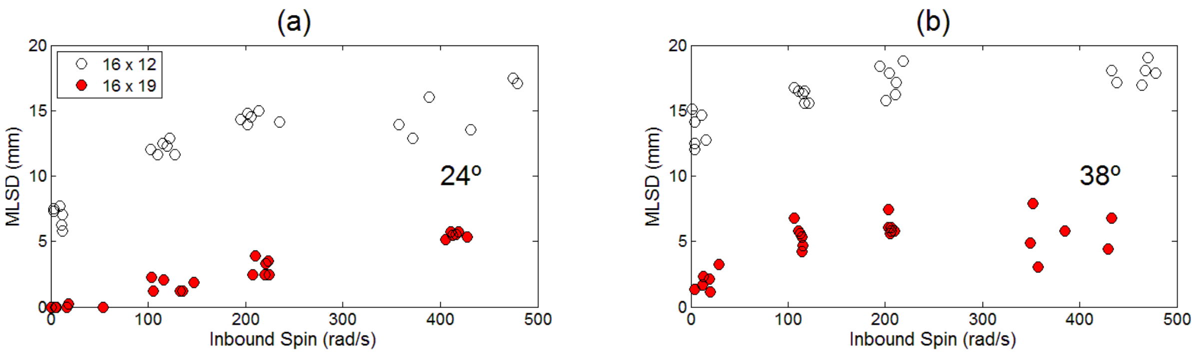

Figure 6 Results for mean lateral string deflection (MLSD), a) inbound angle of 24º and b) inbound angle of 38º.

4. Discussion

Decreasing the number of cross strings in a tennis racket with a fully-constrained frame, from 19 to 12, increased the maximum lateral deflection of the main strings during impact. In general, the results showed lower horizontal rebound velocities and higher rebound spin rates for the racket with fewer cross strings, in agreement with Nicolaides et al (2013). It is likely that the returning movements of the main strings, in the restitution phase of the impact, acted to decrease the horizontal velocity of the ball, while increasing its topspin. Vertical rebound velocity was slightly higher for the racket with fewer cross strings at the inbound angle of 24º. Decreasing the total number of strings is likely to have reduced the stiffness of the string bed in the vertical direction, resulting in lower energy losses in the ball.

The results indicate that the effect of string bed pattern on ball rebound was dependent on both inbound angle and spin. Marginal differences in rebound spin and horizontal velocity, between the two rackets, were observed for impacts with little or no inbound spin. For both inbound angles, larger differences in rebound spin were observed between the two rackets when inbound spin was greater than 100 rad/s. As the relationship between inbound conditions and ball rebound is complex, further work is required before the effect of string bed pattern on ball spin generation is fully understood. Further work is required to further our understanding of the effect of string bed patterns on actual tennis strokes. The effect of string bed pattern on ball rebound angle, in addition to spin, on actual tennis strokes would be of particular interest.

There was a fairly large amount of scatter in the experimental results. Further work could aim to refine the methodology and collect a larger data set. Temporal measurements of main string movements throughout impact could contribute to furthering our understanding of the mechanics of ball spin generation and the influence of string bed parameters. The results presented here are limited to a string type (material and diameter) and tension, a racket head size and shape and one inbound velocity. Increasing the length of the main strings, by increasing the length of the racket head, may allow them to displace laterally, store elastic energy and return more easily, which could result in greater increases in rebound spin. Further research could expand the foundation work present here to include a range of string types and tensions, racket head geometries and inbound velocities.

5. Conclusion

Lateral main string deflections were found to be larger during impact for a fully-constrained racket with 12 cross strings in comparison to 19. In general, rebound spin was higher for the racket with fewer cross strings and horizontal velocity was lower. Further work could aim to determine the effect of string bed pattern on actual tennis strokes.

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