The Tennis Strike Simulation Machine Identified and Confirmed Power Spot Location on Tennis Racket during Flat First Serve

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ABSTRACT

Pavilas C, Suwanthada S, Chaiwatcharaporn C. The Tennis Strike Simulation Machine Identified and Confirmed Power Spot Location on Tennis Racket during Flat First Serve. JEPonline 2015;18(3):14-26. The aim of this study was to determine the location of the power spot on tennis racket during flat first serve by studying the maximum ball outbound velocities and their behavior at five typical different impact locations on the string-bed of a tennis racket using a tennis strike simulating machine. Data were collected from striking tennis balls by a tennis racket that was clamped to a rotating swing arm driven at 450 rev-min\(^{-1}\) in the tennis strike simulating machine equipped with a high speed, high precision 3D motion capture and analysis system. This study focused on ball-racket interaction of flat serve from the instance of pre-inbound to post-outbound kinematics at five different impact locations and their respective smash ratios of an RR-model tennis racket. P1 was designated as impact location one tennis ball above Geometric String-bed Center, GSC of the racket, P2 was half a ball above GSC, P3 was at GSC, P4 was half a ball below GSC, and P5 was half a ball to the right of GSC. One way ANOVA was used to analyze the data. The results showed that resultant pre-impact ball velocities (ball\(_{\text{pre}}\)) at these positions (P1-P5) differed statistically, except at P5 which was offset to the right of P3, with mean square error of 0.026 (LSD). Post-impact ball velocities (ball\(_{\text{post}}\)) at P1 to P5 were 43.482 ± 0.245, 44.436 ± 0.226, 43.701 ± 0.194, 43.668 ± 0.161, and 43.578 ± 0.178 m·s\(^{-1}\) respectively, which confirmed the power spot with highest outbound velocity was P2 (an impact location that is half a tennis ball above GSC). Pre-impact racket speed (racket\(_{\text{pre}}\)) at P1 to P5 were ~30.823 ± 0.305 m·s\(^{-1}\), thus resulting from the initial
setting of swing speed at 49.99 rad·s⁻¹. Therefore, the smash ratio (ball_{post}/racket_{pre}) at P1 to P5 were 1.406 ± 0.015, 1.444 ± 0.012, 1.415 ± 0.008, 1.414 ± 0.018, and 1.412 ± 0.016, respectively, which reconfirmed that power spot P2 had the highest smash ratio. Maximum ball outbound velocity and smash ratio at power spot were higher than those of GSC by 1.681% and 2.049%, respectively. This implies that concept of power spot could be used to customize a tennis player's first serve style.

Key Words: Ball Outbound Velocity, Power Impact Spot, Tennis Flat Serve, Tennis Racket

INTRODUCTION

Tennis racket materials have changed over the years from wood to aluminum alloy to fiber composites. These developments have changed the way the game is played. Advances in tennis racket technology, especially developments in materials, have allowed players to hit shots faster with greater accuracy [2,13]. The new rackets have also increased the speed of the game. Modern composite rackets are generally stiffer with lower mass and moment of inertia compared with traditional wooden rackets [1,16]. The reduction in mass and the increase in structural stiffness of tennis rackets, dating from 1870s to 2007, have increased serve speed by ~17.5%, which has decreased reaction time available to receivers by ~15% [15].

The impact location that maximizes outbound ball velocity, or power spot, was originally defined in a patent by Head [17]. Choppin [6] suggested that “unlike the two sweet spots, which were the node points - the modal shape of racket frame and the center of percussion (COP) - the instantaneous center of rotation, the power spot was not a static point on the string-bed. It was dependent on the momentum upon impact, that is, the physical characteristics of the racket (mass, moment of inertia), its rotational and linear velocity, and the speed of the ball. At a low amount of racket angular velocity, ball speed was maximized for an impact towards the center of mass of the racket, and at higher levels of angular velocity, the power point moved towards the tip. While this has been loosely acknowledged in the literature, specific investigations into the true nature of the power point have been limited.” Brody and Roebert [3] described an impact location that gave maximum rebounding ball speed and suggested that it moved toward the throat as incoming ball speed increased or as racket head speed decreased it moved towards the tip.

A point called the ‘dead spot’ was identified by Cross [7] as a point with an effective mass [9] approximately equal to that of a tennis ball shifted towards the tip of racket. In a classical impact experiment – moving tennis ball towards stationary racket – an impact at the dead spot resulted in a very low rebound velocity. Cross [7] explained that during a serve (i.e., a motion with increased angular velocity) the ‘dead spot’ may be the most appropriate impact point due to its high velocity. This implied that the ‘dead spot’ and previously described ‘power points’ were the same point. This point moved according to shot type and it could be described in terms of the impact point’s effective mass and the velocities of the ball and racket interaction.

A number of authors [1,6,8,12,14,15] have analyzed a simulated ground stroke with stationary racket at rest or at a relatively low speed movement, but the findings are not particularly representative of real tennis first/flat serve at high racket speed. Impact studies so far have not been carried out using a moving racket under laboratory conditions. Tennis GUT by ITF software and Haake et al. [15] have showed the evolution of the tennis racket and various parameters that affect serve speed, but have not identified clearly the maximum ball outbound velocity at various impact locations on the face of racket. Thus, the hypothesis of this study was whether the ball impact location towards the tip
at 60 mm or one tennis ball distance above the center of a tennis racket, so called Geometric String-bed Center (GSC), also known as the “power spot”, would result in maximum ball outbound velocity during a simulated flat serve or not.

This investigation involved trade-offs between apparent coefficient of restitution (\(e_A\)) of racket and radius of flat serve swing speed for an appropriate impact location. The apparent coefficient of restitution is defined as the ratio of the rebound to inbound resultant velocity of the ball of which the ratio is represented by impacts normally to the face of an initially stationary racket and that the transverse fundamental frequency is a function of the stiffness and mass of a racket \([15]\). Thus, the aim of this study was to determine maximum ball outbound velocities and their smash ratios (i.e., ball outbound velocity compared to racket speed at immediate instance before impact) at five typical different impact locations of flat serve actions using tennis strike simulating machine in the laboratory to mimic real flat serve conditions.

METHODS

Simulation Procedure
Flat serve simulation was carried out by using the tennis strike simulating machine at TRECS, Testing and Research Center for Sports Material and Equipment, Faculty of Sports Science, Chulalongkorn University, Bangkok, Thailand. The tennis racket used in simulation was selected as per recommendation and user experience of Thai national youth tennis players. The racket was strung with high-quality string at recommended standard tension, which was measured and monitored throughout the study. The tennis balls were brand new and the bouncing properties were monitored throughout the study. The tennis strike simulating machine was carefully setup to mimic tennis tournament conditions for unbiased comparison. It was calibrated for the highest accuracy and equipped with a high speed, high precision 3D motion capture and analysis system. Simulation results were carefully captured and analyzed to compare various parameters in the experiment.

The Tennis Strike Simulating Machine
The tennis strike simulating machine, as shown in Figure 1, simulated a real tennis striking at the immediate instance of impact between the racket and the ball. The racket was clamped at the handle to the rotating swing arm with counter-weight on the shaft of striker driven by a 5 HP servo-motor. The servo-motor was used to adjust the required angular velocity of the racket by precisely controlling its rotating speed.

Precise impact location on the string-bed of the racket was achieved by adjusting the timing between the ball releasing station above the striker and the angular position of the racket rotating at constant pre-determined speed. It was found that the rotating speed of swing arm at 450 rev·min\(^{-1}\) or at the angular velocity of 47.12 rad·s\(^{-1}\), which generated a steady-state angular velocity of the racket at 49.99 rad·s\(^{-1}\) upon releasing motor power. The angular velocity that was simulated met the required pre-impact velocity of the racket in a tennis tournament situation \([4]\). Also, by adjusting the position and timing of the ball releasing station, ball inbound velocity prior to impact and impact locations could be simulated within the range of real tournament conditions and required impact locations.
Figure 1. The Tennis Strike Simulating Machine Consists of a Striker Driven by 5 HP Servo-Motor and 3D Motion Capture and Analysis System with Two 2,000-Hz High Speed Cameras in the Laboratory. Experimental data were captured and recorded from handle-clamped racket with counter balance to simulate flat serve striking action under controlled testing protocols: (a) front view with camera-1; and (b) left side view with camera-2.

As shown in Figure 2, according to Allen, Haake, and Goodwill [1], the five impact locations on the string-bed used in simulation were at: Position 1 (P1) - at one tennis ball distance above Geometric String-Bed Center (GSC), i.e., at 0 on short axis and at 60 mm on long axis; Position 2 (P2) - at half a tennis ball distance above GSC (0, 30); Position 3 (P3) - at GSC (0, 0); Position 4 (P4) - at half a tennis ball distance below GSC (0, -30); and Position 5 (P5) - at half a tennis ball distance to the right of GSC (30, 0), respectively.

<table>
<thead>
<tr>
<th>Simulation Position</th>
<th>Impact Distance (mm) Along</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Short Axis</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>30</td>
</tr>
</tbody>
</table>

Figure 2. The Five Typical Different Impact Locations on the String-Bed used to determine Parameters and Their Behavior by the Tennis Strike Simulating Machine.
Camera 1 (Front View) was set ~45° to the frontal plane in front view of the machine. Camera 2 (Side View) was set at 10° away from perpendicular line of side view. Calibration frame of 0.5 x 0.5 x 0.5 m with 15 markers was used to calibrate the system for high speed, high precision, and high accuracy with an estimated error of 0.043% (refer to Figure 3).

![Image](image1.png)

**Figure 3. Calibration of DMAS Three Dimensional Motion Capture and Analysis System using Three Dimensional Calibration Frame.**

**The Tennis Racket**

The technical characteristics of the rackets used in this study are described in commercial specification in Table 1. The rectangular shape of the racket head (RR) tennis rackets were recommended (and used) by the elite Thai national youth tennis players. They were selected from a general market place in accordance with the Babolat Racket Diagnostic Center (RDC), except for the racket head size in width by length. The racket head size is 34.0 cm in length where Geometric String-bed Center (GSC) is 17.0 cm away from top or bottom of racket head, according to commercial specification by manufacturer and ITF regulation (18). The data collected included inbound and outbound ball velocities and pre-impact velocity, $v_{\text{pre}}$, of the racket, and were analyzed and compared in efficiency at five typical different impact locations on string-bed of the RR tennis racket.

**The Racket String**

The string type used was Babolat-Pro Hurricane. The racket was strung with initial stringing tension of about 60 lbs, which was continuously monitored by a Gosen string tension tester to ensure “essentially” the same string tension across all simulation protocols throughout the study.

**Table 1. Technical Characteristics of Structural Frame of a New Tennis Racket (RR) of which Brand/Model similar to those used by Elite Tennis Players, according to Babolat Racket Diagnostic Center (RDC), except Racket Head Size in Width by Length.**

<table>
<thead>
<tr>
<th>Model</th>
<th>Composition</th>
<th>Length (cm)</th>
<th>Strung Weight (g)</th>
<th>Head Size (sq in)</th>
<th>Head Size in Width x Length (cm)</th>
<th>Swing Weight (kg·cm²)</th>
<th>Stiffness (Hz-RDC)</th>
<th>Balance (pts HL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RR: Yonex VCORE 95D</td>
<td>Graphite X-Fullerene</td>
<td>68.58</td>
<td>337.36</td>
<td>95</td>
<td>25.5 x 34.0</td>
<td>317</td>
<td>63</td>
<td>7</td>
</tr>
</tbody>
</table>

The Geometric String-bed Center (GSC) of RR racket is 17.0 cm away from top or bottom of racket head.
The Tennis Ball
In this study, only Wilson US open tennis balls were used. The weight of the tennis balls was 57.28 ± 0.04 g with a bouncing height of 139 ± 1.0 cm in accordance with the ITF regulation. Ball bouncing properties were continuously monitored to be within 0.02% deviation from the first measurement values. Each tennis ball was not used by more than 45 impact strikes to ensure consistency of bouncing properties in all simulation protocols.

The Simulation Protocols
To ensure uniform simulating conditions throughout the study, stringing tension of the racket and weight and bouncing height of tennis balls to be used were monitored to be within prescribed range, otherwise the racket was sent for re-stringing, and the ball changed to a new one with known weight and bouncing height within the prescribed range. Newly strung racket was left unused about 3 days for string tension to settle at a stabilized level of about 54 lbs from the initial string tension of about 60 lbs. Thereafter, the string tension remained fairly constant during subsequent striking.

To ensure accurate and precise motion capture, the system was recalibrated before carrying out subsequent simulation to avoid accidental movement of cameras from the prior setting. Simulations were carried out via 10 trials that analyzed a particular impact location from Positions 3, 2, 1, 4, and 5, and, then, 5 out of 10 simulating results at each location were selected as the closest position to target location as possible for final analysis.

Kinematic simulation data were captured only 10 ms before impact and 10 ms after impact. Useful kinematic data of each simulation for analysis needs were well covered within this captured duration. A 0.5 mm width high contrast reflexive marker tape was used to wrap around topmost, bottommost, rightmost, and leftmost positions of the racket head to define plane of racket face and corresponding long axis, short axis, and Geometric String-Bed Center in captured data from the four marker points.

RESULTS

The average of collision transit time at impact locations on the string-bed was about 4 ms. The instance before racket colliding with the ball to determine ball inbound velocity is shown in Figure 4 (a). The instance of impact at the 4th frame of total 8 frames is shown in Figure 4 (b), and the instance first frame of the ball leaving the racket to determine the ball outbound velocity is shown in 4 (c).

![Figure 4. The Precise and Accurate Tracking of Ball and Racket Collision at Location Position 1; (0, 60) on the String-Bed of RR Racket via 2,000-Hz 3D Motion Analysis System.](image)

Figure 4 represents dynamic graphs of the ball outbound acceleration (at red vertical line cursor on the left) and, currently, at maximum ball outbound velocity (the vertical line cursor on the right) at the
GSC using the tennis strike simulating machine at 450 rev-min\(^{-1}\). The left picture (from camera-2) shows the impact of the racket from the rear view, while the right picture was from camera-1 of the 3D motion analysis system. The resultant maximum acceleration in ball outbound from RR racket with string tension of about 53.9 lbs to 53.3 lbs at the end of testing protocol was about 251.83 x 10\(^2\) m\(\cdot\)s\(^{-2}\) at GSC (Position 3). The maximum velocity of ball outbound and current acceleration at the vertical line cursor occurred following after maximum acceleration were 43.84 m\(\cdot\)s\(^{-1}\) and 171.86 x 10\(^2\) m\(\cdot\)s\(^{-2}\) as shown, respectively, while the angular velocity of the racket's steady-state was about 49.97 rad\(\cdot\)s\(^{-1}\).

Figure 5. Graphs of Dynamic Ball Outbound Acceleration and Maximum Velocity (at red vertical line cursor) at the GSC (Position 3) of Five Typical Different Impact Locations using Real Strike Simulating Machine at 450 rev-min\(^{-1}\) via 3D Motion Analysis System, Left Picture from Camera-2 (Rear View of Impact) and Right Picture from Camera-1 (Front View).

In Figure 6, graphs of dynamic velocity at top (M1) and bottom (M2) of racket head before impact at the GSC were 39.92 and 21.99 m\(\cdot\)s\(^{-1}\), respectively, at red vertical line cursor position, which were used to calculate pre-impact velocity of racket at GSC location to be 30.82 m\(\cdot\)s\(^{-1}\). At the instance of impact, the velocity of the racket head at the top and the bottom were 36.13 and 21.26 m\(\cdot\)s\(^{-1}\), respectively, resulting in post-velocity of the impact decrease to 28.69 m\(\cdot\)s\(^{-1}\) (~6.91% reduction).

Figure 6. Graphs of Dynamic Velocity at Top (M1) and Bottom (M2) of Racket Head Before Impact that Represent Pre-Impact Velocity of Racket at GSC (Position 3) using the Real Strike Simulating Machine at 450 rev-min\(^{-1}\) via 3D Motion Analysis System.
Figure 7 shows comparison of the ball outbound acceleration (at red vertical line cursor on left pictures) at the instance of maximum ball outbound velocity of various impact locations on the string-bed of the RR racket: (a) Position 1 (P1), which was 186.59 x 10^2 m·s^{-2} at one tennis ball distance above GSC (0, 60); (b) Position 2 (P2), which was 216.79 x 10^2 m·s^{-2} at half a ball distance above GSC (0, 30); and (c) Position 3 (P3), which was 171.86 x 10^2 m·s^{-2} at GSC (0, 0), using the real strike simulating machine at 450 rev·min^{-1}. While the dynamic graphs of ball outbound velocity at these three locations on the string-bed of the RR racket were nearly similar in pattern after impacts, the maximum ball outbound velocity (on the right pictures) of these locations were 43.48 m·s^{-1}, 44.50 m·s^{-1}, and 43.84 m·s^{-1} at instance on the first frame (one in two-thousandth images of a 2,000-Hz high speed camera) after the ball impact immediately.

Furthermore, the average resultant ball inbound velocity of the five different impact locations on the string-bed of the RR racket at P1, P2, P3, P4, and P5 were gradually increased 2.244 ± 0.235, 2.612 ± 0.153, 3.387 ± 0.273, 3.678 ± 0.121, and 3.329 ± 0.130 m·s^{-1}, respectively, due to gravitational effect of increasing vertical displacement from the ball releasing station of the machine before impact (as shown in Table 2). The mean values of these positions differed statistically at the P<0.05 level of significance, except at P5 with a mean square error of 0.026. Mean values at P5 and P3 were not significantly different due to the same height difference from the ball releasing station of the machine, as P5 is offset 30 mm from P3 to the right.

However, resultant ball outbound velocity of the five different impact locations at P1 to P5 were 43.482 ± 0.245, 44.436 ± 0.226, 43.701 ± 0.194, 43.668 ± 0.161, and 43.578 ± 0.178, respectively, indicating maximum ball outbound velocity of P2, 30 mm distance above Geometric String-Bed Center was shown to be significantly greater than the corresponding value of others. While, pre-impact racket velocity at P1 to P5 were 30.903 ± 0.291, 30.840 ± 0.388, 30.823 ± 0.305, 30.797 ± 0.178, and 30.802 ± 0.332 m·s^{-1}, respectively, which were practically the same for all impact locations resulting from the same initial setting of swing speed at 450 rev·min^{-1} of the tennis strike simulating machine. Although, there were also no significant difference in the ball outbound acceleration both maximum and at the instance of maximum ball outbound speed, the ball outbound acceleration of these values at P2 was likely higher than that of the others as shown in Table 2.
Figure 7. Graphs of Dynamic Ball Outbound Acceleration and Maximum Velocity of Three Locations on the String-Bed of RR Racket at P1, P2, and P3 using the Real Strike Simulating Machine at 450 rev·min⁻¹.

Table 2. Resultant Ball Inbound (Pre) and Maximum Outbound (Post) Velocity, including Maximum and Instance of Acceleration at Maximum Ball Outbound Velocity at Five Typical Different Impact Locations (n = 5), including Pre-Impact Racket Velocity and Smash Ratio (ball_{post}/racket_{pre}), respectively, using the Tennis Strike Simulating Machine at 450 rev·min⁻¹ (mean ± SD).

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Impact Locations (n = 5) of RR Racket</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>P1: (0, 60) (One-Ball Above)</td>
</tr>
<tr>
<td>Ball Velocity (m·s⁻¹)</td>
<td></td>
</tr>
<tr>
<td>Pre-impact</td>
<td>2.244 ± 0.235</td>
</tr>
<tr>
<td>Post-impact (max)</td>
<td>43.482 ± 0.245</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Ball acceleration</td>
<td></td>
</tr>
<tr>
<td>Post-impact (x 10² m·s⁻²)</td>
<td></td>
</tr>
<tr>
<td>Maximum</td>
<td>218.53 ± 14.90</td>
</tr>
<tr>
<td>At instance of max V_{ball}</td>
<td>186.17 ± 14.04</td>
</tr>
<tr>
<td>Racket Velocity (m·s⁻¹)</td>
<td></td>
</tr>
<tr>
<td>Top of racket head</td>
<td>39.167 ± 0.268</td>
</tr>
<tr>
<td>Bottom of racket head</td>
<td>22.638 ± 0.246</td>
</tr>
<tr>
<td>Pre-impact</td>
<td>30.903 ± 0.291</td>
</tr>
<tr>
<td>Smash Ratio</td>
<td></td>
</tr>
<tr>
<td>Ball_{post}/racket_{pre}</td>
<td>1.406 ± 0.015</td>
</tr>
</tbody>
</table>

Significant difference from at GSC impact location. Significant difference from the other impact locations.
The Ball-Racket Interaction of Flat Serve

Figure 8. Comparison in Smash Ratio of Flat Serve at 5-Typical Different Impact Locations, the Maximum Smash Ratio occurred at Position 2 (0, 30) at Half a Tennis Ball Distance above Geometric String-Bed Center of RR Racket with Corresponding Swing Speed of 450 rev-min\(^{-1}\) of the Real Strike Simulating Machine. **Significantly different from other impact locations.

Moreover, the efficiency comparison of different impact locations were made in term of smash ratio, which was defined as ball outbound velocity, ball\(_{\text{post}}\), divided by racket velocity at immediate instance before ball impact, racket\(_{\text{pre}}\), at that impact location. The smash ratio, ball\(_{\text{post}}\)/racket\(_{\text{pre}}\) on the string-bed of RR racket at locations P1 to P5 were 1.406 ± 0.015, 1.444 ± 0.012, 1.415 ± 0.008, 1.414 ± 0.018, and 1.412 ± 0.016, respectively, as presented in Table 2 and as shown in Figure 8. The highest smash ratio occurred at location P2, while the lowest smash ratio was at location P1.

DISCUSSION

The flat serve simulation was carried out by using a tennis strike simulating machine in the laboratory, which was setup to mimic tennis tournament conditions for unbiased comparisons. It was also calibrated for high accuracy and precision with 3D motion capture and analysis. The resultant ball inbound velocities of the five different impact locations on the string-bed of RR racket at P1 - at one tennis ball distance above Geometric String-Bed Center (0, 60); P2 - at half a ball distance above (0, 30); P3 - at the center (0, 0); P4 - at half a ball distance below the center (0, -30); and P5 - at half a ball distance to the right of the center (30, 0) were 2.244 ± 0.235, 2.612 ± 0.153, 3.387 ± 0.273, 3.678 ± 0.121, and 3.329 ± 0.130 m·s\(^{-1}\), respectively, as shown in Table 2. The mean values of these velocities differed statistically at P<0.05 level of significance, except at P5 due to the gravitational effect of increasing vertical displacement of ~30 mm increment from P1 to P4 via ball releasing station of the tennis strike simulating machine. Velocities at P3 and P5 positions were not statistically different due to the same height, as P5 is 30 mm offset to the right of P3. These inbound velocity ranges correspond to the pre-impact ball velocity of a ball tossed by male and female elite tennis players of 3.86 and 4.12 m·s\(^{-1}\), respectively, during the first serve in international tennis tournaments [4]. Thus, this study setup flat serve simulation conditions within the range of ball inbound velocity as reported in international tournament situations.
The pre-impact racket velocities of the racket head before impact during the flat serve striking simulation at impact location P1 to P5 were 30.903 ± 0.291, 30.840 ± 0.388, 30.823 ± 0.305, 30.797 ± 0.178, and 30.809 ± 0.332 m·s⁻¹, respectively. These data are in agreement with the findings of Chow et al. [4] and other international tennis tournament studies [11,19] that reported pre-impact racket velocities in male and female elite tennis players of 38.57 and 30.81 m·s⁻¹, respectively. This study setup the flat serve simulation conditions in terms of the pre-impact racket velocity range by adjusting the rotating speed of the servo motor of the tennis strike simulating machine to 450 rev·min⁻¹ (angular velocity of 47.12 rad·s⁻¹), thus generating the steady-state angular velocity of the racket at 49.99 rad·s⁻¹ to simulate the real strike conditions in the laboratory. Moreover, these pre-impact racket velocities, which slightly declined inversely to the ball inbound velocities, were due to the effects of different vertical position of impact location as pre-impact racket speed at P1 occurred earlier than the others. The other factor was the longer distance along the axis of rotation of the swing at P1 versus the other positions with an absolute speed at P1 of 33.72 ± 0.317 m·s⁻¹, which was higher than that at GSC.

The resulting ball outbound velocities, ball_post, at five typical different impact locations P1 to P5 were 43.482 ± 0.245, 44.436 ± 0.226, 43.701 ± 0.194, 43.668 ± 0.161, and 43.578 ± 0.178 m·s⁻¹ respectively. These findings corresponded to the post-impact ball speed of male and female elite tennis players, which were 51.12 and 42.39 m·s⁻¹, respectively [4,10,11]. Thus, the simulated flat serves by the tennis strike simulating machine with the clamped handle racket are quite realistic in mimicking the player's first serve with regard to the ball and racket interaction via 3D motion analysis system. In fact, when compared with the ball_post at GSC (P3), ball_post at P2 was increased ~1.681% while the others were decreased 0.506% at P1, 0.076% at P4, and 0.281% at P5, respectively. The ball outbound velocities at P1 trended to be the lowest of five different impact locations.

The efficiency comparison of the smash ratio of the ball-racket interaction on striking at the five impact locations via the flat serve simulation are shown in Table 2. While the angular velocity of instance before impact racket velocity, racket_post, was practically equal to steady-state of 49.99 ± 0.04 rad·s⁻¹, the smash ratio (ball_post/racket_pre) on the string-bed of RR racket at impact location at P1 to P5 were 1.406 ± 0.015 (-0.636% compared with the ratio with respect to GSC), 1.444 ± 0.012 (+ 2.049%), 1.415 ± 0.008, 1.414 ± 0.018 (-0.071%), and 1.412 ± 0.016 (-0.212%), respectively. Hence, the smash ratio at P2 was shown to be the highest value while that of at P1 trended to be the lowest (similar to the ball outbound velocities).

The apparent coefficient of restitution (eₐ) is defined as the ratio of the rebound to inbound velocity of the ball [15]. It is normally represented by the impacts to the face of an initially stationary racket at P1 , and is likely to be reduced when compared to P2. The results also corresponded to Brody and Roebert [3] who described an impact location that gave maximum rebounding ball speed as it moved towards tip as incoming racket head speed increased as first serve and that it moved towards throat in inverse scenario. Corresponding to Choppin [6], who stated that the power spot was not a static point on the string-bed of the racket, it was dependent on the momentum at impact given the rotational and linear velocities. At low amounts of racket angular velocity, the ball speed was maximized for an impact towards the center of mass of the racket, and at higher levels of angular velocity, the power point moved towards the tip. Choppin [6] also showed that the racket's angular velocity intersected between the maximum outbound velocity of a forehand shot and the node point of about 40 rad·s⁻¹.

The findings confirm that the appropriate spot of ball-racket interaction of which trade-offs between apparent coefficient of restitution of the racket and string, including pre-impact racket velocity of the flat serve where the smash ratio of location at P2 as the power impact spot yielded the highest ball
velocity compared to others; whereas, that of at location P1, one tennis ball distance above the center, as dead spot [7] likely to be the lowest ball speed among five typical different impact locations during flat serve striking simulation conditions in the laboratory. Therefore, the previous study that described the ‘dead spot’ and the ‘power spot’ as the same point during high velocity of the racket via the flat first serve might not be correct.

CONCLUSIONS

There have been no previous studies of ball-racket interaction at the typical five different impact locations about their maximum ball outbound velocities and smash ratios during flat serving by the tennis strike simulating machine. The findings in this study indicate that half a tennis ball distance (i.e., 30 mm above the Geometric String-Bed Center (P2), known as the power spot of a rectangular shape racket head tennis racket) yielded a maximum ball outbound velocity and corresponding smash ratio, which were approximately 1.68% and 2.04% greater than those at GSC, respectively. These findings about increases in percentage of smash ratio and maximum ball outbound velocity at P2 confirmed that power spot might be the optimal impact location during player’s first serve in tennis. This information could be used to effectively customize a first serve style of a tennis player. Further studies should investigate other frame structures and different model/characteristics rackets for a more in-depth comparison.

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