# PRE- AND POST-IMPACT BALL AND RACQUET CHARACTERISTICS DURING TENNIS SERVES PERFORMED BY ELITE MALE AND FEMALE PLAYERS

John Chow, Les Carlton, Woen-sik Chae, Young-tae Lim, and Jae-ho Shim
Department of Kinesiology, University of Illinois, Urbana, Illinois, USA

This study quantified the pre- and post-impad 3-D kinematics of a tennis ball and racquet. Data were collected during the tennis competition of the 1996 Atlanta Olympic Games using two high-speed cameras (200 Hz). Two first serves were analysed for each subject. A one-way ANOVA for the factor of sex ($p < .05$) was performed for each parameter. The results indicate that, regardless of sex, the ball travelled forward and to the left during the flight phase before impact and the ball was hit near the peak height of the racquet. The males had significantly higher height of ball impact, greater pre-impact racquet velocity and greater post-impact ball velocity than their female counterparts. It is not certain whether the techniques used by males and females contributed to the differences in racquet speed observed.

KEY WORDS: kinematics, tennis serve, gender difference

INTRODUCTION: Among all tennis strokes, the serve is the only stroke that is completely under a player's control because the ball is tossed by the server. On the other hand, the selection and execution of the other strokes depend on the player's position and the trajectory of the oncoming ball. Although the serve is a stroke that is completely under a player's control, it is one of the most difficult strokes to master because a skilled service motion requires intricate coordination of different parts of the body. Although the mechanics of the serving motion are discussed in many tennis texts, very limited quantitative data describing the serving motion, especially three-dimensional (3D) data, are available. A review of literature indicates that only a handful of biomechanical studies have been conducted on the tennis serve. Furthermore, it is noteworthy that the data reported in most previous studies were collected in non-competition conditions and limited attempts have been made to collect kinematic data of serves performed by elite tennis players (i.e., top-ranked professional players).

The purpose of this study was to determine the kinematic characteristics of the ball and racquet immediately before and after the ball-racquet impact for serves performed by elite male and female tennis players in competition conditions.

METHODS: Based on principles of projectile motion, the displacement of the ball, between the instant it leaves the server's racquet and the instant it lands on the service court, is governed by its location of release, its velocity immediately after impact, the fluid force that acts upon it during its flight, and the acceleration due to gravity. The first two factors are dependent upon the trajectory of the ball from hand release to impact and some mechanical characteristics of the ball and racquet immediately before impact, respectively. These mechanical characteristics include the masses of the ball and racquet, the coefficient of restitution for the ball-racquet impact (e), friction force, the orientation and location of the racquet at impact, and the velocities of the ball and racquet at impact. These characteristics (except e and friction force) were the prime focus of this study.

Data **Collection:** With the approval from the International Olympic Committee (IOC) Subcommission on Biomechanics and Physiology of Sports and the Atlanta Committee for the Olympic Games (ACOG), data were collected during the 1996 Atlanta Olympic Games. Data collection sessions were conducted in the stadium court of the Stone Mountain Tennis Center from July 23-29, 1996. Two synchronized high-speed video systems (JC Labs, Inc., Mountain View, CA 94043, field rate 200 Hz) were used to record the serving motions of the subjects performed on the deuce side (right side of the baseline). To determine the landing locations of the balls delivered by the servers, a Panasonic AG-450 S-VHS (60 Hz) camcorder was used to record the overview of the whole court. All cameras were mounted on brackets that were fixed on permanent structures in the spectator area.

A 2 m x 2 m x 2.3 m calibration frame (Peak Performance Technologies, Inc., USA) was used to obtain three calibration volumes. Two of these volumes (V1 and V2) were at approximately the same location immediately behind the baseline except that V2 was about 0.9 m higher than V1. The third volume was located in front of V2 and was used to cover the ball-racquet impact. A plumb line hung on the calibration frame and two markers placed on the baseline were used for vertical and horizontal references.

All matches completed in the stadium court were recorded. In addition, the speeds of the serves, as determined by radar devices displayed at court sides, were manually recorded. Although more than 300 legal serves performed by 16 females and 14 males were available, the trials from only nine of these players were usable for the purpose of this study (left-handers were excluded). The subjects in this study included four females (world singles ranking ranged from 2 – 28, age 24±3 yrs, height 1.73±0.11 m, mass 61.3±8.8 kg) and five males (ranking 3 – 137, 24±2 yrs, 1.83±0.5 m, 76.8±6.1 kg). Two first serves performed by each subject, one landing near the centre line and the other landing near the sideline were selected for subsequent analysis. When there was more than one trial available for each landing location, the one with the highest speed (determined by a radar device) was used. For each subject, the average values over two trials were used in subsequent analyses.

**Data Reduction:** A Peak Motion Measurement System was used to obtain two-dimensional (2D) coordinate data from the video recordings. For the selected trials, the ball and four points defining the orientation of the racquet (top, bottom, left, and right of the racquet head) were digitized starting 10 fields before and ending 10 fields after the impact. In addition, the left toe and ball were also digitized from the field showing the instant of ball release from hand. The time elapsed between ball release from hand to impact was determined from the identification numbers of the fields showing these two instants and the time interval between consecutive fields (1/200 s). The multi-phase calibration procedure (Challis, 1995) for the Direct Linear Transformation (DLT) method (Abdel-Aziz & Karara, 1971) was used for 3D space reconstruction from the 2D images. The calibration errors (i.e., the root-mean-square error between the computed locations of the control points and their known locations) for the combined calibration space for different sessions ranged from 8.86 to 9.99 mm. The 3D coordinates were transformed to a trial specific coordinate system – principal axes parallel to the sideline (x-direction, pointing away from the server toward the net), baseline (z-direction, pointing from left to right when viewing from behind the server), and the vertical (y-direction, pointing upward), respectively, and the origin located at the vertical projection of the left toe (LT) on the court at the instant of ball release from hand. In other words, the antero-posterior and medio-lateral locations of the ball reported are locations relative to the LT. For each trial, the 3D coordinates before and after the impact were smoothed separately using a second-order polynomial.

The velocity of the ball at hand release was determined using the locations of the ball at release and at impact, the known elapsed time, and the equations for uniformly accelerated motion. The pre- and post-impact velocities of the ball and racquet head (intersection of the line joining the left and right and the line joining the top and bottom of the racquet head) were determined by the first and second locations before and after the impact, respectively. Specifically, a velocity was obtained by dividing the distance between the first and second locations (last and second to last locations for a pre-impact velocity) by a time of 0.005 s. The orientation of the racquet head was represented by a unit vector perpendicular to the racquet face and pointing away from the side making contact with the ball. This unit vector was obtained by the cross product of two vectors formed by the line joining the left and right edges and the line joining the top and bottom edges of the racquet head.

**Data Analysis:** Group means for males and females and standard deviations were computed for each of the parameters measured. For each parameter, a one-way analysis of variance (ANOVA) were used to test for significant differences between the two sexes.

**RESULTS AND DISCUSSION:** The speeds of the serves, as recorded by a radar device, were 180.9±12.4 and 140.7±9.6 km/h for the males and females, respectively. Results of the statistical analysis are given in Table 1.

Kinematics of the Ball During the Flight Phase Before Impact: The ball location when it was released from the hand has not been studied previously. All the subjects in this study released the ball at heights close to their standing heights (Table 1). Although not statistically significant, females seemed to release the ball at a more forward location as compared to the males. For both sexes, the ball location at impact was about 0.8 m in front of the LT. The males had significantly higher pre-impact ball height than the females and the differences were probably due to the differences in stature (to a great extent) and jumping ability (to a lesser extent). The heights of the ball at impact recorded in this study are comparable to those reported by Elliott et al. (1986) but lower than those reported by Elliott (1983). From an overhead view, the ball traveled forward and to the left during the flight phase before impact. When viewed from behind the server, the ball was released on the right side and was hit in front or on the left side of the LT for all subjects. The trajectory of the ball tossed by elite players is quite different from the straight up (or up and slight forward) toss recommended by authors of most tennis texts (Gould, 1993, p. 24; Murphy, 1982, p. 24).

Ball Velocity: The pre-impact ball vertical velocities found in this study are greater than the corresponding values reported by Elliott et al. (1986) suggesting that elite players may release the ball with greater vertical velocities (higher toss as a result) than players of lower skill levels. It is worth noting that, on average, the ball was moving forward at a speed of approximately 0.8 m/s immediately before impact. Assuming that the same amount of momentum is transferred to the ball during the impact, a ball with forward velocity at pre-impact will have a greater post-impact velocity when compared to a ball that has no pre-impact forward velocity (i.e., straight up toss).

As expected, a significant difference was found between males and females in post-impact ball velocity. The average post-impact ball velocity attained by the females was about 82% of the same parameter exhibited by the males. In general, the post-impact ball velocities found in this study are higher than those reported by Elliott et al. (1986) and similar to those reported by Elliott (1983). On average, the ball was projected at an angle of 6.2 and 5.3 degrees below the horizontal for males and females, respectively. These projection angle values were greater than the range of values (0 to 2 degrees) reported by Elliott (1983).

Racquet Kinematics: The males had significantly greater pre- and post-impact ball velocities than the females. The signs of the pre- and post-impact vertical velocities indicate that the racquet was moving upward before and downward after the impact. This implies that the racquet was rotating forward and the ball was hit when the racquet was located near its highest position. It was very likely that the contact was made before the racquet reached its peak height because Elliott (1983) has found a topspin on the ball in the so-called "flat serve." The small vertical component found in the unit vector that represented the pre-impact racquet head orientation suggests that the racquet was tilted slight upward immediately before impact. Because the racquet was rotating forward at that instant, it is reasonable to speculate that the racquet was in a near vertical position at impact.

CONCLUSION: The tossing technique used by elite players is quite different from the ones suggested in most tennis texts. For beginners, tossing the ball upward may be recommended because it is easy to execute while learning to coordinate the movements of both arms – one for the ball tossing and the other for the racquet upswing. However, once coordination and consistency are established, the player can add power to his/her serve by tossing the ball forward and to the left and at the same time jumping upward and forward to strike the ball. Significant gender differences in pre-impact ball height, post-impact ball velocity, and pre- and post-impact racquet velocities were found. In addition to the factors of physique and strength, future studies should examine whether the techniques used by males and females also contribute to the differences in racquet speed observed between the two sexes.

Table 1 **Mean±SD** of ball and racquet kinematics

| | Male | Female | | Male | Female |
|---|---|---|---|---|---|
| Ball Location at Ball Release (m) | | | Pre-impact Ball Location (m) | | |
| Antero-posterior | 0.00f0.03 | 0.16f0.17 | Antero-posterior | 0.79±0.17 | 0.76f0.14 |
| Vertical | 1.79f0.08 | 1.76k0.14 | Vertical' | 2.77±0.11 | 2.64k0.10 |
| Medio-lateral | 0.37k0.08 | 0.26k0.09 | Medio-lateral | -0.17k0.35 | -0.15k0.15 |
| Ball Displacement before Impact (m) | | | Ball Velocity at Ball Release (m) | | |
| Antero-posterior | 0.79k0.18 | 0.59±0.27 | Antero-posterior | 0.83f0.21 | 0.72±0.29 |
| Vertical | 0.9820.10 | 0.88f0.13 | Vertical | 5.72k0.34 | 5.34k0.83 |
| Medio-lateral | -0.54k0.41 | -0.41k0.22 | Medio-lateral | -0.57f0.41 | -0.59k0.52 |
| | | | Resultant | 5.82f0.31 | 5.46k0.72 |
| Pre-impact Ball Velocity (m/s) | | | Post-impact Ball Velocity (m/s) | | |
| Antero-posterior | 0.83f0.21 | 0.72±0.29 | Antero-posterior | 49.36k.74 | 40.94f1.24 |
| Vertical | -3.66f0.49 | -3.00±1.90 | Vertical | -5.42f1.55 | -3.86f1.05 |
| Medio-lateral | -0.5720.41 | -0.59f0.52 | Medio-lateral# | -8.90k1.68 | -5.48±1.47 |
| Resultant | 3.83±0.45 | 3.36f1.45 | Resultant' | 50.66k.12 | 41.66f1.44 |
| Pre-impact Racquet Velocity (m/s) | | | Post-impact Racauet Velocity (m/s) | | |
| Antero-posterior' | 35.02Q.71 | 29.40Q.46 | Antero-posterior* | 25.81f1.98 | 20.29Q.47 |
| Vertical | 15.15±3.51 | 12.13±2.88 | Vertical | -5.68Q.22 | -4.92f1.86 |
| Medio-lateral' | -3.74k2.64 | 1.68f3.14 | Medio-lateral | 7.33f3.14 | 7.62f5.18 |
| Resultant' | 38.63Q.66 | 32.14Q.28 | Resultant# | 27.71Q.03 | 22.69f3.46 |
| Pre-impact Racquet Orientation | | | | | |
| Antero-posterior | 0.82f0.04 | 0.87f0.06 | | | |
| Vertical | 0.06f0.09 | 0.06±0.15 | | | |
| Medio-lateral | -0.55f0.06 | -0.44f0.14 | | | |

Significantly different between males and females for p < .01(*) and p < .05(#)

REFERENCES:

Abdel-Aziz, Y.I., & Karara, H.M. (1971). Direct linear transformation from comparator coordinates into object space coordinates in close-range photogrammetry. Proceedings of the Symposium on Close-Range *Photogrammetry* (pp. 1-18). Falls Church, VA: American Society of Photogrammetry.

Challis, J. H. (1995). A multi-phase calibration procedure for the Direct Linear Transformation. *Journal* of Applied Biomechanics. **11**, 351-358.

Elliott, B.C. (1983). Spin and the power serve in tennis. Joumal of Human Movement Studies, 9, 97-104.

Elliott, B., Marsh, T., & Blanksby, B. (1986). A three-dimensional cinematographic analysis of the tennis serve. International Journal of *Sport* Biomechanics, 2, 260-271.

Gould, D. (1993). Tennis, Anyone? Mountain View, CA: Mayfield Publishing Company.

Murphy, C. (1982). Advanced tennis. Dubuque, IA: Wm. C. Brown Co. Publishers.

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