A COMPARISON OF BALL-AND-RACQUET IMPACT FORCE BETWEEN TWO TENNIS BACKHAND STROKE TECHNIQUES

Shyi-Kuen Wu, William E. Prentice[1], Michael T. Gross and Bing Yu
Division of Physical Therapy
[1]Department of Physical Education and Exercise Science
The University of North Carolina at Chapel Hill
Chapel Hill, NC 27599-7135, USA

The purpose of this study is to compare the peak contact force between one-handed backhand stroke with a long backward swing in preparation and one-handed backhand stroke with a short backward swing in preparation. Five advanced and five beginning tennis players participated in this study. Three-dimensional coordinates of critical body and racquet landmarks were obtained. A mathematical model was developed to estimate the contact duration and peak contact force in a stroke. The estimated peak contact forces were reproducible and comparable to those reported in the literature from direct measurements. A one-handed backhand stroke with a short backward swing in preparation had significant shorter contact duration and greater peak contact force than that with a long backward swing in preparation.

KEY WORDS: tennis, backhand stroke, impact, kinetics, injury

INTRODUCTION: The one-handed backhand stroke is a technique commonly used in playing tennis. Poor technique of the one-handed backhand stroke has been suggested as a cause of repetitive overload on the upper extremity and a variety of tennis related upper extremity overuse injuries. A recent extensive review of literature revealed a lack of kinetic studies on the tennis stroke techniques. This lack of kinetic studies prevents our further understanding of tennis-related upper extremity overuse injuries. The major difficulty in studies on upper extremity kinetics in tennis strokes appears to be the measurement of impact forces under game conditions. The purpose of this study was to compare the peak impact force between two one-handed backhand stroke techniques and between different skill levels. The two one-handed backhand stroke techniques compared were: (a) one-handed backhand stroke with long backward swing indicating a good preparation and (b) one-handed backhand stroke with short backward swing indicating a poor preparation. A new mathematical model was developed to estimate the peak ball-and-racquet impact force.

METHODS: Ten healthy volunteers (nine males, one female) were recruited. They were evenly divided into two skill levels according to the skill level rating system of the United States Tennis Association. Five male subjects with a skill level rating greater than 4.5 were selected as the advanced players with an average skill level rating of 5.0. The remaining five subjects were beginning players with an average skill level of 2.2.

 Three S-VHS video camcorders were used to record subjects' performance at a frame rate of 60 frames/second. The three camcorders were synchronized using a light emitting diode box placed in the field of view of each camera. A calibration frame with 24 control points was used to calibrate the locations and orientations of camcorders for a space of 2.5 m long × 2 m wide × 2.5 m high in which backhand strokes were performed.

All subjects used the same Wilson "Pro Staff" 6.7 EB racquet (Hammer system) strung with natural gut under a tension of 212 N (55 lbs.), a mass of 0.3 kg and a grip size of 10.7 cm (4 ¼ inches). Four points on the racquet were marked with white tape to assist in defining the orientation of the racquet in space. A tennis ball machine was used to shoot new standard tennis balls to the subject at a speed of 14.5 m/sec.

Subjects were instructed to hit tennis balls back to a target area on the opposite side of the court using two different one-handed backhand stroke techniques. Subjects were instructed to swing the racquet backward as far as they could during the preparation phase when using the long backward swing technique and to swing the racquet backward approximately to the side of their trunks when using the short backward swing technique. A total of twenty-five

hits were performed in the calibration volume for each technique.

A trial in which the subject hit the ball back to the target area with required preparation was defined as a successful trial. The first five successful trials were digitized for each technique. Seven landmarks on the subject's body, four marked points on the racquet, and the center of the ball were manually digitized for each selected successful trial with the aid of a S-VHS VCR, a 50 cm color monitor, an IBM compatible desktop computer, and the Peak V video data acquisition software (Peak Performance Technologies, Inc., Englewood, CO). The seven body landmarks included the right and left hips, right and left shoulders, right elbow, right wrist, and base of the right third metacarpal bone.

The 3-D trajectory of the ball before the initial ball-and-racquet contact was determined from the 3-D coordinates of the ball in the three consecutive frames immediately before the ball-and-racquet contact was observed. The trajectory of the ball before the initial ball-and-racquet contact was fitted as a linear polynomial function of time in each of the two orthogonal horizontal directions of the global reference frame, and as a second-order polynomial function of time in the vertical direction.

The 3-D trajectory of each of the four marked points on the racquet was determined from the 3-D coordinates in the three consecutive frames immediately before the ball-and-racquet contact was observed. The trajectory of the marker point in the each of the three orthogonal directions of the global reference frame was fitted as a second-order polynomial function of time. The direction vector of the racquet surface was determined from the 3-D coordinates of the four marked points on the racquet.

The actual time of initial ball-and-racquet contact was estimated from the trajectories of the ball and the four marked points on the racquet before the observed ball-and-racquet contact using an extrapolation method with a time interval of 0.001 seconds. The actual time of initial ball-and-racquet contact was defined as the time when the distance between the center of the ball and the racquet surface was less than the radius of the ball before the observed ball-and-racquet contact.

A similar procedure was used to estimate the actual time of the final ball-and-racquet contact. The actual time of final ball-and-racquet contact was defined as the time when the distance between the center of the ball and the racquet surface was greater than the radius of the ball after the observed ball-and-racquet contact. The ball-and-racquet contact duration was estimated as the difference between the final ball-and-racquet contact time and the initial ball-and-racquet contact time.

The ball velocity vectors before and after the ball-and-racquet contact were determined from the 3-D trajectories of the ball considering the effects of the gravitational acceleration. The impulse vector of the impact between the ball and the racquet was computed as the product of the mass of the ball and the change in the velocity vector of the ball due to impact.

We assumed that the magnitude of the impact force in a given direction during ball-and-racquet contact was a second-order polynomial function of ball-and-racquet contact time. Considering that the force on the racquet is zero at the initial ball-and-racquet contact, this polynomial function was expressed as

$$F_t = A_1 t + A_2 t^2 \tag{1}$$

where F is the magnitude of the impact force vector in the given direction; and t is the ball-and-racquet contact time. Integrating equation (1) over time and considering the impulse at the initial ball-and-racquet contact is zero, the magnitude of the impulse in the given direction can be expressed as

$$I_{0-t} = \frac{1}{2} A_1 t^2 + \frac{1}{3} A_2 t^3 \tag{2}$$

where I_{0-t} is the magnitude of the impulse vector in the given direction from initial ball-and-racquet contact to ball-and-racquet contact time t. Function constants A_1 and A_2 can be determined by solving equations (1) and (2) at t = T with known magnitudes of I_{0-T} and F_T.

The peak impact force in the given direction was assumed to occur at the mid-point of ball-and-racquet contact duration and determined as

$$F_{peak} = \frac{1}{2}A_1T + \frac{1}{4}A_2T^2$$

$$(3)$$

The magnitude of the peak resultant impact force was determined from the magnitudes of the three orthogonal components of the peak resultant impact force vector.

The reliability of the estimated ball-and-racquet contact duration, impulse, and peak impact force was evaluated by comparing the corresponding parameters estimated from the originally digitized and re-digitized data. Means and standard deviations of the ball-and-racquet contact duration and peak resultant impact force were estimated for each group of subjects. A two-way ANOVA was used to test the effects of technique and skill level on ball-and-racquet contact duration and peak resultant impact force. A 0.1 level of type I error rate was chosen to indicate statistical significance considering the pilot nature of this study and the consequence of type I and type II errors.

RESULTS: Correlation coefficients of $r = 0.95$, 0.78, and 0.91 were obtained for the ball-and-racquet contact duration, impulse, and peak resultant impact force, respectively, estimated from originally digitized and re-digitized data. The mean errors in these three variables were 0.001 ($\pm$ 0.001) seconds, 0.25 ($\pm$ 0.19) kg-m/sec, and 55.4 ($\pm$ 52.6) N, respectively.

The mean ball-and-racquet contact durations in the one-handed backhand stroke for advanced players were 0.016 ($\pm$ 0.004) seconds with a long backward swing and 0.008 ($\pm$ 0.003) seconds with a short backward swing. The mean durations in the one-handed backhand stroke for beginning players were 0.016 ($\pm$ 0.003) seconds with a long backward swing and 0.009 ($\pm$ 0.002) seconds with a short backward swing. The mean peak resultant impact forces in the one-handed backhand stroke for advanced players were 180.8 ($\pm$ 49.1) N with a long backward swing and 330.0 ($\pm$ 140.7) N with a short backhand swing. The mean peak resultant impact forces in the one-handed backhand stroke for beginning players were 162.1 ($\pm$ 46.5) N with a long backward swing and 276.5 ($\pm$ 104.7) N with a short backward swing.

The ball-and-racquet contact duration in the one-handed backhand stroke with a long backward swing was longer than that with a short backward swing ($p = 0.00$). The peak impact force in the one-handed backhand stroke with long backward swing was lower than that with a short backward swing ($p = 0.00$).

DISCUSSION: The method developed in this study for estimating impact force in tennis stroke from kinematics appears to be valid. The estimated contact durations and peak impact forces are similar to those reported in the literature.

The method developed in this study appears to have reasonable reliability. The error in the estimated peak resultant force was relatively small in comparison to the difference in this variable between different techniques and skill levels. The accuracy of estimated ball-and-racquet contact durations and impact forces can be further improved by appropriately enlarging the calibration volume to obtain more frames to improved the accuracy of estimated ball and racquet movements before and after contact.

The significant difference in the peak resultant impact force between two one-handed backhand tennis strokes suggests that good preparation for the stroke with a long backward swing of the racquet is important for reducing the impact force during the ball-and-racquet contact. The impact force is reduced as the ball-and-racquet contact duration is increased while the impulse remains unchanged. The reduced impact force on the racquet may assist in reducing the risk of tennis-related upper extremity overuse injuries. Those racquets designed for players allow players to use as short swing with a slow swing speed to rely on racquets to generate power for returning the ball should be used with caution.

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