Comparison of Ball-and-Racquet Impact Force Between Two Tennis Backhand Stroke Techniques

Shyi-Kuen Wu, PT, MS
Michael T. Gross, PT, PhD
William E. Prentice, ATC, PT, PhD
Bing Yu, PhD

Study Design: A mixed design for kinetic comparison of 2 types of one-handed backhand strokes and 2 skill levels in tennis.

Objectives: To develop and evaluate a model to estimate the impact force on the racquet during tennis stroke, and to compare the peak impact force between one-handed backhand stroke with a long backswing and one-handed backhand stroke with a short backswing and between the beginning and advanced players.

Background: A one-handed backhand stroke is commonly used in tennis and may be associated with many upper extremity over-use injuries. An understanding of kinetics of the backhand stroke is essential for understanding injury mechanisms and prevention.

Methods and Measures: Five male advanced tennis players and 4 male and 1 female beginning tennis players participated. Mean age was 32.2 ± 7.0 years. Each subject was instructed to use the 2 types of one-handed backhand strokes to hit balls from a tennis ball machine. Three-dimensional coordinates of critical body and racquet landmarks were obtained. A mathematical model was developed to estimate the contact duration and the peak impact force during a stroke.

Results: The estimated peak impact forces were reproducible and comparable to those reported in the literature from direct measurements. A one-handed backhand stroke with a short backswing had a significantly shorter contact duration (0.008 ± 0.003 seconds) and a greater peak resultant impact force (330.0 ± 140.7) than that with a long backswing (0.016 ± 0.004 seconds and 180.8 ± 49.1 N). Skill level did not significantly affect the peak resultant impact force.

Conclusion: A long backswing in a one-handed backhand stroke may reduce the load on the upper extremity and may assist in reducing the risks of tennis-related upper extremity over-use injuries.

Key Words: over-use injury, tennis, upper extremity load

The one-handed backhand stroke is a technique commonly used in playing tennis. A one-handed backhand stroke consists of: (a) a preparation phase with a backswing of the tennis racquet, (b) an acceleration phase with a forward swing of the racquet towards the ball, (c) an impact phase with a ball-and-racquet contact, and (d) a follow through phase with a continuous forward movement of the racquet following the ball (Figure 1).

Hatze reported a peak impact force of 348.7 N during ball-and-racquet impact. The torque applied to a player’s wrist in impact force ranged from 17 to 22 N-m. Poor technique of the one-handed backhand stroke has been suggested as a cause of increased ball-and-racquet impact force.
One-handed backhand stroke and repetitive overloads have been concerned only with the kinematics of the stroke. Ilfeld\(^9\) observed 57 novice tennis players either on the tennis court or in the clinic and concluded that incorrect tennis strokes seemed to be the main etiology of their lateral humeral epicondylitis symptoms. Elliott and Christmas\(^6\) used 3-dimensional, high-speed cinematography to compare high and low backspin backhand strokes using different grips. They reported that the mean elbow joint angle was 15 degrees flexion at ball impact instead of full extension. They reasoned the elbow joint angle might have an important influence on the kinetics and thus the risk for injuries at the elbow. Blackwell and Cole\(^2\) reported that the wrist flexion pattern of novice tennis players might predispose them to conditions that facilitate wrist extensor muscle injuries.

The preparation phase of a one-handed backhand stroke may have significant effect on the impact force during the stroke. A long backswing during the preparation assists in increasing the racket speed before the ball-and-racquet impact.\(^6\)\(^,\)\(^7\) A high racket speed before the ball-and-racquet impact may assist in increasing the ball-and-racquet contact duration and reducing the impact force.

Although these kinematic studies provide significant information regarding tennis stroke techniques, the 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 purposes of our study were (a) to develop a method to estimate impact forces during tennis strokes from kinematics, and (b) to compare the peak impact force between 2 one-handed backhand stroke techniques and between different skill levels. The 2 one-handed backhand stroke techniques compared were: (a) one-handed backhand stroke with long backswing and (b) one-handed backhand stroke with short backswing.

**METHODS**

**Subjects**

Ten healthy right-handed volunteers (9 men and 1 woman) were recruited both from the men’s tennis team of the University of North Carolina at Chapel Hill and local tennis clubs. The exclusion criteria included: 1) incidence of upper quadrant pathology in the past 6 months which restricted normal performance of tennis play for more than 2 days; 2) history of elbow or forearm surgery; 3) recent pain at the el-
bow or forearm within 2 weeks; and 4) use of the left hand or 2 hands to perform the backhand stroke. The subjects ranged in age from 22 to 45 years, with a mean age of 32.3 ± 7.0 years. They were assigned to 2 groups 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 group. The average skill level rating of the advanced players was 5.0. This group of players had a dependable stroke and began to master the use of power and spins in strokes with sound footwork. Four of the players in this group were collegiate tennis players with intensive training for collegiate tournaments. The remaining 5 subjects were beginning tennis players. Their average skill level was 2.2. This group of players had basic stroke skills with obvious weaknesses. They could get the ball into play in slow pace. Age and sex were not controlled variables in our study. The skill levels of the subjects were rated by National Tennis Rating Program verifiers. The only female player was a beginning player with a skill level rating of 2.5. The experimental protocol was approved by the Committee for the Protection of the Rights of Human Subjects at the School of Medicine of the University of North Carolina at Chapel Hill. Written consent was obtained from each subject before the study and rights of all subjects were protected throughout the entire course of the study.

Instrumentation

Three S-VHS video camcorders (Figure 2) were used to record subject performance at a frame rate of 60 frames/sec. The 3 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. The calibration frame covered a space of 2.5 m long × 2 m wide × 2.5 m high (calibration volume) in which backhand strokes were performed (Figure 2). A light emitting diode box was also placed in the field of view of each camcorder for synchronization purpose.

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. Four points on the racquet were marked with white tape to define 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. The mass of the tennis balls was 0.057 kg (2 ounces).

Procedures

Subjects were instructed to hit tennis balls back to a 2 m long × 2 m wide target area (Figure 2) on the opposite side of the court using 2 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 backswing technique and to swing the racquet backward to the side of their trunks when using the short backswing technique. Each subject performed a total of 25 one-handed backhand strokes in the calibration volume with each technique.

Data Reduction

A trial in which the subject hit the ball back to the target area with the required technique was defined as a successful trial. In the selection of successful trials, the one-handed backhand stroke technique with long backswing and the one-handed backhand stroke technique with short backswing were quantified using the ball velocity and racquet angle (Figure 3). The ball velocity and racquet angle was defined as the angle between the horizontal velocity vector and the horizontal projection of the longitudinal axis of the racquet at the maximum backswing. A one-handed backhand stroke with a ball velocity and racquet angle greater than 180° was considered as the one-handed backhand stroke with long backswing. A one-handed backhand stroke with a ball velocity and racquet angle less than 120° was considered as the one-handed backhand stroke with short backswing.

The first 5 successful trials of each technique were digitized for each subject. The 4 marked points on the racquet and the estimated center of the ball were manually digitized for each selected successful trial with the aid of a S-VHS VCR, a 50-centimeter color monitor, an IBM compatible desktop computer, and the Peak V video data acquisition software (Peak Performance Technologies, Inc, Englewood, Colo). The camera calibration, mathematical time synchronization of digitized 2-D coordinate data, and the direct linear transformation of 2-D digitized coordinates to real life 3-D coordinates were conducted using the 3DVA system version 4.0 (MotionSoft Inc, Chapel Hill, NC).

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 3 consecutive frames immediately before the ball-and-racquet contact was observed. We assumed that the ball was moving with a constant horizontal velocity and a constant vertical acceleration. 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 2 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 4 marked points on the racquet was determined from the 3-D coordinates in the 3 consecutive frames immediately before
the ball-and-racquet contact was observed. The trajectory of the marker point in the each of the 3 orthogonal directions of the global reference frame was fitted as a second-order polynomial function of time. The actual initial ball-and-racquet contact in each trial occurred between the last video frame in which there was no ball-and-racquet contact (frame m - 1) and the first video frame in which the ball-and-racquet contact was observed (frame m). At least 5 frames before frame m - 1 were used to determine
the trajectories of the 4 markers on the racquet and
the center of the tennis ball before frame m − 1 as
second-order polynomials of time. The positions of
the 4 markers and the center of the tennis ball be-
tween frame m − 1 and frame m were estimated us-
ing their estimated trajectories before frame m − 1
with a time interval of 0.001 seconds. The actual
time of initial ball-and-racquet contact was defined as
the first time when the distance between the center
of the ball and the racquet surface was equal to or
less than the radius of the ball between frames m −
1 and m. The direction vector of the racquet surface
at any given time was determined from the 3-D co-
ordinates of the 4 marked points on the racquet at the
corresponding time.

A similar procedure was used to estimate the ac-
tual time of the final ball-and-racquet contact. The ac-
tual final ball-and-racquet contact in each trial oc-
curred between the last video frame in which the
ball-and-racquet contact was observed (frame n) and
the first video frame in which there was no ball-and-
racquet contact (frame n + 1). The actual time of fi-
nal 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 between frames n and n + 1. The ball-and-
racquet contact duration (T) 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 corre-
sponding 3-D trajectories of the ball considering the
effects of the gravitational acceleration. The impulse
vector of the impact between the ball and the rac-
quet was computed as the product of the mass of the
ball and the change in the velocity vector of the ball
due to impact.

Brannigan and Adali10 modeled the impact force
during tennis stroke as a sine function of ball-and-
racquet contact time based on the experimental data
reported by Hatze.10 For mathematical convenience,
we assumed that the magnitude of the impact force
during ball-and-racquet contact was a second-order
polynomial function of ball-and-racquet contact time,
which has a similar shape as the sine function. Con-
sidering that the force on the racquet is zero at the
initial ball-and-racquet contact, this polynomial func-
tion was expressed as:

\[ F_t = A_1 t + A_2 t^2 \]  

where \( F \) is the magnitude of the impact force vector
in the given direction and \( t \) is the ball-and-racquet
contact time. The impact forces at the beginning
and the end of the contact are zero (\( F_0 = 0 \) and \( F_T = 0 \)).
Integrating equation 1 over time and consider-
ing the impulse at the initial ball-and-racquet contact
is zero, the magnitude of the impulse in the given
direction was expressed as:

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

where \( I_{0-t} \) is the magnitude of the impulse vector in
the given direction from initial ball-and-racquet con-
tact 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 midpoint of
ball-and-racquet contact duration and determined as:

\[ F_{peak} = \frac{1}{2} A_1 T + \frac{1}{4} A_2 T^2 \]  

The magnitudes of the 3 orthogonal components
of the impact force vector were used to determine
the magnitude of the resultant impact force. The
above described data reductions were conducted us-
ing a customized computer program (MotionSoft
Inc, Chapel Hill, NC).

Data Analysis

All selected trials were digitized twice by the first
author. The reliability of the estimated ball-and-rac-
quet contact duration, impulse, and peak impact
force was evaluated by comparing the corresponding
parameters estimated from the originally digitized
and redigitized data.12 Pearson correlation coeffi-
cients and mean absolute mean errors were used to
represent the correspondence and agreement com-
ponents of reliability.16

Means and standard deviations of the ball-and-rac-
quet contact duration, impulse, and peak resultant
impact force were estimated for each group of sub-
jects. A 2-way ANOVA with mixed design was used to
test the effects of technique (repeated measure) and
skill level (independent measure) on each of the
ball-and-racquet contact duration, impulse, and peak
resultant impact force. A 0.05 level of type I error
rate was used to indicate statistical significance.

RESULTS

The linear and second order polynomial fits of the
ball and racquet movement trajectories had a mini-
imum regression determinant of \( r^2 = 0.94 \). Correla-
tion coefficients of \( r = 0.95, 0.78, \) and \( 0.91 \) were ob-
tained for the ball-and-racquet contact duration, im-
pulse, and peak resultant impact force, estimated
from originally digitized and redigitized data. The
mean errors in these 3 variables due to digitizing er-
ror were 0.001 (± 0.001 seconds), 0.25 (± 0.19
kg·m/s), and 55.4 (± 52.6 N), respectively.

The mean ball-and-racquet contact durations in
the one-handed backhand stroke for advanced play-
ers was 0.016 (± 0.004) seconds with a long backsw-
ing and 0.008 (± 0.003) seconds with a short back-
swing (Figure 4). The mean durations in the one-handed backhand stroke for beginning players was 0.016 (± 0.003) seconds with a long backswing and 0.009 (± 0.002) seconds with a short backswing (Figure 4). A significant technique effect on the ball-and-racquet contact duration was detected. This technique effect indicates that, on average, the ball-and-racquet contact duration in the one-handed backhand stroke with a long backswing was longer than that with a short backswing ($F_{1,9} = 43.06, P = 0.00$). Skill level did not significantly affect the ball-and-racquet contact duration ($F_{1,8} = 1.16, P = 0.29$).

The mean impulses in the one-handed backhand stroke for advanced players were $1.88 \pm 0.28$ kg·m/s with a long backswing and $1.72 \pm 0.28$ kg·m/s with a short backswing (Figure 5). The mean impulses in the one-handed backhand stroke for beginning players was $1.63 \pm 0.34$ kg·m/s with a long backswing and $1.55 \pm 0.26$ kg·m/s with a short backswing (Figure 5). A trend of skill level effect on the impulse was observed. This trend suggests that, with the same one-handed backhand stroke technique, the impulse for the advance players was greater than that for the beginning players ($F_{1,9} = 4.15, P = 0.07$). Technique did not significantly affect the impulse ($F_{1,8} = 3.01, P = 0.14$).

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 backswing and $330.0 \pm 140.7$ N with a short backswing (Figure 6). 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 backswing and $276.5 \pm 104.7$ N with a short backswing (Figure 6). A significant technique effect on the peak resultant impact force was detected. This technique effect indicates that the peak resultant impact force in the one-handed backhand stroke with a short backswing was greater than that with a long backswing ($F_{1,9} = 49.1$ N, beginning players with long backswing ($180.8 \pm 49.1$ N), beginning players with long backswing ($162.1 \pm 46.5$ N), advanced players with short backswing ($330.0 \pm 140.7$ N), and beginning players with short backswing ($276.5 \pm 104.7$ N). The peak impact force of the one-handed backhand stroke with short backswing significantly greater than that with long backswing for both groups of players. $P = 0.00$. 

---

**FIGURE 4.** Mean contact durations in one-handed backhand stroke of advanced players with long backswing ($0.016 \pm 0.004$ seconds), beginning players with long backswing ($0.016 \pm 0.003$ seconds), advanced players with short backswing ($0.009 \pm 0.002$ seconds), and beginning players with short backswing ($0.009 \pm 0.002$ seconds). The contact duration of the one-handed backhand stroke with long backswing significantly longer than that with short backswing for both groups of players. $P = 0.00$.

**FIGURE 5.** Mean impulses in one-handed backhand stroke of advanced players with long backswing ($1.88 \pm 0.28$ kg·m/s), beginning players with long backswing ($1.63 \pm 0.34$ kg·m/s), advanced players with short backswing ($1.72 \pm 0.28$ kg·m/s), and beginning players with short backswing ($1.55 \pm 0.26$ kg·m/s).

**FIGURE 6.** Mean peak impact forces in one-handed backhand stroke of advanced players with long backswing ($180.8 \pm 49.1$ N), beginning players with long backswing ($162.1 \pm 46.5$ N), advanced players with short backswing ($330.0 \pm 140.7$ N), and beginning players with short backswing ($276.5 \pm 104.7$ N). The peak impact force of the one-handed backhand stroke with short backswing significantly greater than that with long backswing for both groups of players. $P = 0.00$. 

---
49.17, \( P = 0.00 \)). In addition, a trend of skill level effect on the peak resultant impact force was observed. This trend of skill level effect indicates that, with the same one-handed backhand stroke technique, the peak resultant impact force for the advanced players was greater than that for the beginning players \( (F_{1,8} = 4.96, P = 0.06) \).

**DISCUSSION**

The method developed in our study for estimating impact force in tennis stroke from kinematics appears to be valid. Bernhang et al.\(^5\) estimated ball-and-racquet contact durations in tennis forehand and backhand strokes using strain gauges. He reported that the average ball-and-racquet contact duration ranged from 0.006 to 0.012 seconds, which are very similar to the average ball-and-racquet contact durations estimated in our study. Hatze\(^10\) measured the peak impact force using a strain gauge on a fixed tennis racquet and expressed the peak impact force as a function of ball velocity before the impact. His results suggest a peak impact force of 377 N for a ball velocity of 14.5 m/s before the impact, which is notably similar to the estimated peak resultant impact force for the advanced players with short backswing in our study. The peak impact forces reported in Hatze’s study,\(^10\) however, were consistently greater than the peak impact forces under the other condition in our study. This discrepancy is likely due to the difference in testing conditions between the Hatze study\(^10\) and our study. Hatze measured the peak impact forces on stationary tennis racquets while the peak impact forces in our study were estimated during actual play. The contact duration for a ball velocity of 14.5 m/s before the impact was reported as 0.004 seconds in Hatze’s study,\(^10\) consistent with those reported by Brannigan and Adali\(^6\) and Groppel et al.\(^8\) under similar conditions. On the other hand, Bernhag\(^1\) reported the ball-and-racquet contact duration of the ball on the racquet during actual play ranged from 0.006 to 0.012 seconds. The results of previous studies suggest that the ball-and-racquet contact duration of the ball on a stationary racquet was shorter than that during actual play. This indicates that the difference in ball-and-racquet contact duration may explain the greater peak impact forces reported by Hatze\(^10\) compared to the mean peak resultant impact forces in our study.

The method developed in our 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. The reliability test showed that the correlation coefficient for the estimated impulse between originally digitized and redigitized data was lower than that for the estimated ball-and-racquet contact duration. This means that the error in the estimated peak resultant impact force may be mainly due to the error in estimated velocity vectors of the ball before and after the impact. The error in the estimated peak resultant impact force may be reduced by increasing sampling rate and enlarging the calibration volume and the field of view. Increasing sampling rate will increase the number of samples that can be used to estimate motion patterns of the ball and racquet and reduce the time interval for extrapolation. Appropriately enlarging the field of view will increase the travel distances of the ball before and after impact and can be used to estimate the ball velocity vectors before and after impact. The increased travel distance used to estimate the ball velocity vector may improve the accuracy of the estimated ball velocity and thus the accuracy of impulse and peak impact force; however, the possible reduction in digitizing resolution that may increase digitizing error should be considered before enlarging the field of view.

The significant difference in the peak resultant impact force between 2 one-handed backhand tennis strokes suggests that good preparation for the stroke with a long backswing of the racquet is important for reducing the impact force during the ball-and-racquet contact. A good preparation for the stroke with a long backswing of the racquet allows the racquet to follow the ball after the initial ball-and-racquet contact and thus increases the ball-and-racquet contact duration. As the ball-and-racquet contact duration is increased, the impact force is reduced while the impulse remains unchanged. This explanation is supported by the significant difference in the ball-and-racquet contact duration associated with the difference in the peak resultant impact force between the 2 one-handed backhand tennis strokes (Figure 4).

The results of our study also show a trend of increased peak resultant impact force for the advanced players in comparison to the beginning players. The most likely explanation for this trend is that the advanced players hit balls harder with increased impact forces to return the ball to the given target area with increased velocity. This explanation is supported by the trend of increased impulse for the advanced players in comparison to the beginning players. The increased impulse indicates an increased ball returning velocity because the ball in-coming velocity was controlled by the tennis ball machine and the positions in which the backhand strokes were performed relative to the tennis ball machine were essentially the same for all subjects. However, the differences in the peak impact force and impulse between skill levels are within the range of digitizing error. Considering the small sample size of this study, further studies are needed to confirm this result.

Reducing the impact force during ball-and-racquet contact of the one-handed backhand stroke may assist tennis players in preventing some tennis-related conditions. The method developed in our study should be tested on tennis players in preventing some tennis-related conditions.
upper extremity injuries, especially lateral humeral epicondylitis. Lateral humeral epicondylitis is the most common tennis-related upper extremity injury. The direct cause of this injury is the accumulated microtears of the tendinous attachment of the wrist extensor muscles near the lateral epicondyle due to repetitive overloads on these muscles in one-handed backhand strokes.15 The stress on the upper extremity due to the ball-and-racquet impact during one-handed backhand stroke can be transferred to the large shoulder and trunk muscles if the wrist extensor muscles are contracted to firmly lock the wrist during the ball-and-racquet impact.15 However, the wrist extensor muscles may fail to lock the wrist if the external torque on the wrist, due to the ball-and-racquet impact force, is greater than the torque these muscles can produce in one-handed backhand stroke. The failure to lock the wrist during a one-handed backhand stroke may cause an eccentric wrist extensor muscle contraction that can generate a force up to 130% of that in their maximum isometric contractions.8 Muscle tension may increase the stress on the tendinous attachment of these muscles near the epicondyle. Reducing the ball-and-racquet impact force can significantly reduce the external torque on the wrist in the one-handed backhand stroke. The reduced external torque on the wrist may enable the wrist extensor muscles to stabilize the wrist joint and thus reduce the stress on the tendinous attachment of wrist extensor muscles near the epicondyle. Based on these results, we recommend one-handed backhand stroke with long backswing for all tennis players for the purpose of prevention of lateral humeral epicondylitis and other tennis related upper extremity overuse injuries.

As the results of our study indicate, the backswing significantly affects the ball-and-racquet contact duration and impact force, but it is not the only factor affecting the ball-and-racquet contact duration and impact force. Other factors, such as ball velocity before the ball-and-racquet impact, racquet string tension, and spinning, may also significantly affect the contact duration and impact force.5,4 The method for estimating ball-and-racquet impact force during actual play may be a useful tool in future studies to quantify the effects of these factors on the ball-and-racquet impact force.

CONCLUSION

A valid method for estimating impact force in tennis stroke from kinematics has been developed with good reliability. The preparation phase has a significant influence on the peak resultant impact force for the one-handed backhand stroke. A long backswing during the preparation phase can significantly reduce the peak resultant impact force and may reduce the risk for tennis-related upper extremity overuse injuries for both advanced and beginning players.

REFERENCES