# EFFECT OF TENNIS BALL MASS AND SMOOTHING ON PEAK RACKET VELOCITY

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This technical note examined the effect of ball mass and smoothing protocol on the magnitude and timing of peak horizontal velocity of the racket in the tennis forehand. A skilled tennis player stroked ten forehands using three different tennis balls (regular, added mass, foam). Kinematic data were smoothed through impact and interpolating impact. Factorial ANOVA showed a significant main effect for smoothing on the peak racket velocity, but nonsignificant effects for ball mass or the interaction of mass and smoothing. Smoothing protocol had a large ($\varepsilon^2$ = 0.49) effect on peak racket velocity at impact. Ball mass had a significant effect on the timing of peak racket velocity ($\varepsilon^2$ = 0.33) if position data were smoothed through impact. The results confirmed recent studies that sport implement velocities near impact can be distorted by smoothing through impact and the mass of the ball being struck. Studies of striking implement velocities near impact require special data smoothing protocols.

**KEY WORDS:** tennis, forehand, skill, interpolation, accuracy

**INTRODUCTION:** Biomechanical studies of the kinematics of striking sports have often observed peak implement velocity just prior to impact. Peak implement velocities between 10 to 32 ms prior to impact have been reported in batting (McIntyre & Pfautsch, 1982; Messier & Owen, 1984; Welch et al. 1995) and tennis forehands (Elliott et al. 1989; Takashashi et al. 1996). In the past this has been considered a hallmark of skilled striking (Plagenhoef, 1971) or an accuracy enhancing strategy (MacKenzie et al., 1987; Teixeira, 1999). Unfortunately, these observations and hypotheses may be incorrect due to errors in implement velocity measurements near impacts.

The large negative acceleration created by impact when combined with typical data smoothing strategies may distort the position and velocity data before impact (Knudson & Bahamonde, 2001). The other problem is that the mass and material properties of the ball also affect the negative acceleration at impact and the adjacent data points. Tabuchi, Matsuo, and Hashizume (2004) recently reported that balls with mass less than normal baseballs significantly delayed the timing of peak bat velocity, and like tennis players (Knudson & Bahamonde, 2001), skilled batters were increasing bat speed up to ball impact. The purpose of this study was to determine if tennis ball mass and smoothing protocol affected the magnitude peak racket velocity near impact in the topspin forehand. A secondary purpose was to compare changes in the timing of peak racket velocity when using incorrect smoothing-through-impact procedures. These data were needed to improve our understanding of coordination in tennis and the interaction of ball mass and smoothing on measurements of implement velocity near impact.

**METHOD:** One skilled (ITN 4) male tennis player gave informed consent to participate in the study. A midsized tennis racket strung with nylon at 267 N was marked with reflective tape on the lateral edge of the head. Following a warm-up the player stroked flat forehands off balls tossed into a comfortable (waist high) hitting zone. Balls were tossed in underhand and simulated a groundstroke with a slow (5.3 $\pm$ 0.4 m/s), nearly horizontal speed. Three different balls were used: a new tennis ball (TB) with mass of 0.058 kg, a new tennis ball with added mass (TB+) at 0.070 kg, and a 0.013 kg foam tennis ball (FTB). The TB+ ball was made by adding 2 mm plastic beads to the interior of the ball. The balls had similar color and seams and were tossed in a random order from behind a barrier in rallies of three strokes until 10 strokes for each kind of ball were performed.

A high-speed video camera (180 Hz) positioned 9 m lateral to the stroke direction recorded the vertical plane motion of the racket near impact. The experiment took place indoors with 1600 W of additional light. Averaging ten strokes was effective in obtaining reliable data because of the low variability (CV between 3 and 6 %) in racket velocity near impact for advanced players (Knudson 1990: Knudson & Blackwell, in press). The racket and ball were digitized using Peak Motus® 8.3 (Peak Performance Technologies, Inc., Centennial, Colorado) software from fifteen frames before impact to five frames after impact. Two smoothing protocols were utilized, incorrect and interpolated. Incorrect smoothing used a cubic spline to smooth the data through impact with the smoothing parameter automatically selected by the program. Interpolated smoothing inserted a linear interpolation to estimate impact and five padding points (Knudson & Bahamonde, 2001) followed by the same automatic cubic spline smoothing. The peak horizontal racket velocity near impact was analyzed with factorial (ball mass by smoothing) ANOVA with statistical significance accepted at $p < 0.05$. Peak horizontal racket velocity for the interpolated smoothing condition was defined as the velocity at impact. The timing of the peak racket velocity relative to impact across ball masses in the incorrect smoothing condition was also examined with a one-way ANOVA. Comparison of means following significant main effects were conducted with Tukey-Kramer HSD tests at $p < 0.05$. Horizontal racket velocity curves were also ensemble averaged.

**RESULTS:** The ANOVA showed a significant ($F_{1,54} = 60.2$, $p < 0.0001$) main effect for smoothing with interpolated smoothing having 23.5 percent larger mean racket velocity (25.2±2.0 m/s) than incorrect smoothing (20.4 ± 2.9 m/s). The size of this effect was quite large ($\varepsilon^2 = 0.49$). Figure 1 illustrates the ensemble average curves of racket velocity using TB for the two smoothing techniques.

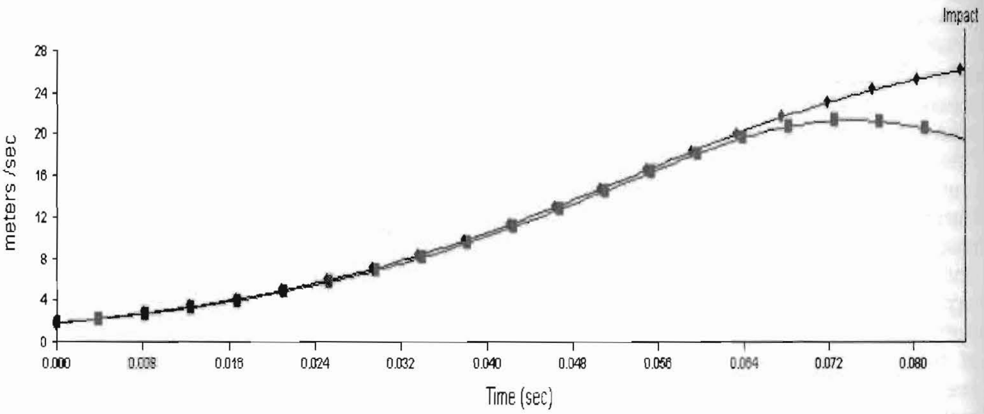


**Figure 1 Effect of smoothing (incorrect ▪and interpolated ♦) on ensemble average horizontal racket velocity pattern with a regular tennis ball.**

The main effect for ball mass ($F_{2,54} = 2.4$, $p = 0.10$) and the interaction ($F_{2,54} = 23.5$, $p = 0.14$) of mass and smoothing were not significant. The statistical power to detect a one meter per second difference in racket velocity for these tests was strong (0.81) so this is not likely a type II error. Descriptive data for peak horizontal racket velocity in all conditions are reported in Table 1.

The timing of horizontal peak racket velocity was significantly ($F_{2,27} = 6.8$, $p < 0.004$) affected by ball mass when data are smoothed through impact. This effect of ball mass was also large ($\varepsilon^2 = 0.33$). Post hoc tests showed that mean peak racket velocity using the FTB occurred significantly closer to impact (- 1 ± 4 ms) than using either the TB (-11 ± 8 ms) or TB+ (-13 ± 9 ms). Timing of peak racket velocity in TB and TB+ were not significantly different. The mass of TB and TB+ combined with the distortion of smoothing through impact created a false peak racket velocity two to three frames before impact with the ball.

**Table 1 Mean (SD) Peak Horizontal Racket Velocity Near Impact (m/s)Smoothing Condition**

| Ball | Incorrect | Interpolated |
|---|---|---|
| FTB | 21.2 (2.9) | 24.3 (2.2) |
| TB | 21.0 (3.0) | 26.3 (1.9) |
| TB+ | 18.9 (2.6) | 25.0 (1.6) |
| Mean (SD) | 20.4* (2.9) | 25.2* (2.0) |

*p < 0.0001

**DISCUSSION:** Momentum has been a key variable in the study of impacts because the masses of the objects, as well as their velocities are analyzed. The negative acceleration of a striking implement during impact is affected by the masses and the material properties of both the implement and ball. Results of the present study were consistent with these laws of physics, but showed that data smoothing had a larger effect than the ball masses examined in tennis forehands. Smoothing racket position coordinates through impact significantly affected the amplitude and timing of the peak velocity of the tennis racket near impact.

In the present study the smoothing protocol accounted for 49 percent of the variance in peak racket velocity. The amplitude of peak racket velocity was not significantly affected by ball mass or the interaction of mass and smoothing. An increased ball mass corresponds to greater ball momentum prior to impact, and consequently a greater reduction in the speed of the racket after impact. Since data smoothing techniques use adjacent data points in determining smoothing, the greater slowing of a striking implement impacting a larger mass ball would tend to decrease the amplitude and shift forward in time the peak velocity. These two distortions were also reported by Knudson and Bahamonde (2000) for incorrect smoothing of tennis forehand data.

The present data did also show a significant effect of ball mass on the timing of peak racket velocity. For the conditions studied, the timing of peak velocity is a variable that was more sensitive to ball mass than the amplitude of peak velocity. The timing of peak racket velocity in the TB and TB+ conditions was significantly shifted forward from impact about 12 milliseconds. The forward shift in peak racket velocity in the TB and TB+ conditions may have been similar because the mass difference (21%) between these balls was not very large. The large reduction (78%) in ball mass in the FTB nearly eliminated the forward shift of peak racket velocity due to the ball/racket collision. This agrees with the observations by Tabuchi, Matsuo, and Hashizume (2004) that hitting very low-mass baseballs (< 5% regular ball mass) had significantly later peak bat velocities compared to regular and higher mass baseballs. Combined these results do not support the hypothesis (Plagenhoef, 1971) that skilled striking involves reaching peak implement velocity prior to impact. This apparent striking coordination is likely an artifact of inappropriate data smoothing or hitting a ball of large mass relative to the implement.

This study was limited by the two-dimensional analysis and the use of a single skilled subject to demonstrate the effect of the data processing and ball mass variables of interest. These limitations have a negligible effect on the extension of the results to other biomechanical striking data because the results were consistent with the laws of physics, similar to three-dimensional studies of tennis forehands (Knudson, 1990; Knudson & Bahamonde, 1999), and confirmed previous observations on smoothing through impact in tennis (Knudson & Bahamonde, 2000) and baseball (Tabuchi, Matsuo, and Hashizume, 2004).

**CONCLUSION:** Sports biomechanics studies focusing on the pattern of striking implement velocity should not smooth data through impact, but should use impact estimation/extrapolation (Knudson & Bahamonde, 2000) or other smoothing techniques

(Knudson, 1990) to obtain accurate implement velocities near impact. Striking implement velocity data in previous studies that smooth through impact are likely affected by the mass of the ball being struck, although this effect may be smaller than the effect of data smoothing. The larger the mass of the ball being struck, relative to the bat/racket, the greater the amplitude reduction and forward shift of the peak implement velocity prior to impact when smoothing through impact. It is likely that the hypothesis that skilled striking involves reaching peak implement velocity prior to impact is incorrect. Knowledge of the correct implement speeds and trajectories through impact can be used to develop more accurate cues to help guide athletes in developing skilled striking.

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