JOURNAL OF APPLIED BIOMECHANICS, 1993, 9, 143-148

Effect of String Tension and Impact Location on Ball Rebound Accuracy in Static Tennis Impacts

Duane Knudson

The rebound accuracy of tennis impacts was studied by measuring the vertical angles of approach and rebound of tennis balls projected in a vertical plane at a clamped racket. Three identical oversized tennis rackets were strung with nylon at 200, 267, and 334 N of tension. Ten impacts were filmed at 200 Hz for each string tension with the ball impacting the strings centrally and 8 cm off-center. A two-way ANOVA revealed significant ($p < .01$) main effects for string tension, impact location, and the interaction of string tension and impact location. Treatment–Contrast Interactions demonstrated one significant ($p < .01$) difference: The decrease in rebound accuracy from a string tension of 200 to 334 N was significantly different for central versus off-center impacts.

The accuracy of shot placement is of primary importance in the game of tennis, and string tension may be a key factor in determining the accuracy of ball rebound. The selection of a string tension in order to improve shot accuracy has been based largely on opinion because of a lack of experimental evidence (Knudson, 1991a).

Groppel (1984) hypothesized that higher string tensions improved stroke accuracy. He theorized that the greater ball deformation on the strings (Groppel, Shin, Thomas, & Welk, 1987) and the shorter dwell time (Brody, 1979, 1987; Groppel, Shin, Thomas, & Welk, 1987) allowed the ball to be directed more accurately. Brody (1987) outlined how string tension may either increase or decrease tennis rebound accuracy based on the laws of physics.

The first study to examine stringing and rebound accuracy in tennis reported that string type, string tension, and the interaction between the two have significant effects on ball rebound accuracy for midsized tennis rackets (Knudson, 1991a). The more accurate rebounds observed in lower string tensions were hypothesized to be related to their greater elasticity (Knudson, 1991a). Studies have clearly demonstrated that lower string tensions have greater elasticity than higher string tensions (Baker & Wilson, 1978; Brannigan & Adali, 1981; Elliott, 1982a; Ellis, Elliott, & Blanksby, 1978; Groppel, Shin, Thomas, & Welk, 1987).

Duane Knudson is with the Department of HPER, Baylor University, P.O. Box 97313, Waco, TX 76798-7313.

A study was needed that tested the effect of string tension on rebound accuracy using oversized rackets because studies have shown significantly greater ball rebound speeds for oversized rackets compared to smaller racket heads (Elliott, Blanksby, & Ellis, 1980; Groppel, Shin, Thomas, & Welk, 1987). Impact conditions would also be more realistic if off-center impacts were studied because research has shown that most impacts occur off-center (Knudson, 1991b; Ohmichi, Miyashita, & Mizumo, 1979; Plagenhoef, 1979) and off-center impacts have been observed to have nonsignificant and significant reductions in ball rebound velocity compared to central impacts (Elliott, 1982a, 1982b; Elliott et al., 1980; Ellis et al., 1978). Controlled impact conditions are needed to make comparisons across string tensions because the intraindividual variation of hand-held rackets is quite large (Hatze, 1992; Knudson & White, 1989).

The purpose of this study was to examine the effect of three string tensions and two impact locations on ball rebound accuracy in a vertical plane for an oversized racket. If ball rebound accuracy data from different racket head size and impact location conditions supported the hypothesis of greater rebound accuracy for lower string tensions (Knudson, 1991a), the choice of string tension to maximize accuracy in flat shots like volleys would be more clear.

Method

Three identical Prince oversized tennis rackets were strung alternately with Prince Synthetic Gut (nylon) strings (16 gauge) at three string tensions (200, 267, and 334 N). String tensions represented the range of typical tensions and corresponded to the more common English units of 45, 60, and 75 lb, respectively. Each racket was marked with 3M reflective tape strips and a round wooden bead (15 mm in diameter) that was covered with reflective tape and glued to the racket (Figure 1). Strips (5 mm wide) of tape marked the tip of the racket head and the center of the throat, while the reflective bead marked the top, lateral geometric center of the racket head. The rackets were secured in a horizontal position to a wooden arm by three C clamps. Nine new tennis balls were bounce tested and projected from a distance of 2.29 m by a Lobster ball machine stabilized with weights and elastic cords. Impact locations on the racket face were central and 0.08 m superior to the geometric center of the racket face. Mean (±*SD*) preimpact ball velocities were $28.9 \pm 1.9\ m \cdot s^{-1}$ at an angle of $25.4 \pm 1.8°$ to the horizontal. The balls had negligible rotation prior to impact ($<10\ rad \cdot s^{-1}$).

Ten central impacts for each condition were filmed at 200 fps by a Photo-sonics 1PL camera placed 7.92 m from the center of the racket face. Camera speed was established by internal timing lights set at 100 Hz. A mirror was placed at a 45° angle to the racket to record impact location in the longitudinal direction of the racket face. Data were digitized on a Numonics 1224 digitizer interfaced to a Zenith 128 computer. Trials were digitized for ±3 frames before and after impact for the following points: top (lateral geometric center) of the racket head, tip of the racket head, center of the ball, mirror image of the tip of the racket, mirror image of ball position, and the mirror image of the throat of the racket.

Kinematic data were not smoothed because the greater accuracy of a small field size limited the number of images of the ball in the field of view (Hudson, 1990). Also, there were no smoothing procedures that handled very small data

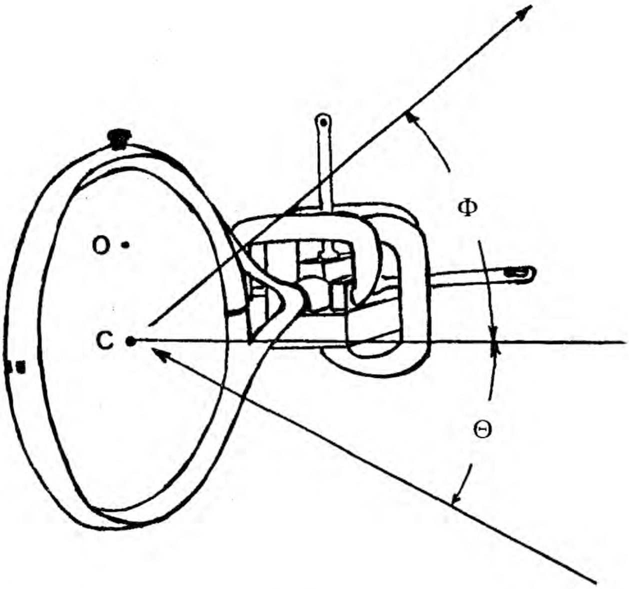

Figure 1 — Schematic of the racket, reflective markers, impact locations, and angles of interest. The angle of approach (Θ), angle of rebound (Φ), central impact location (C), and off-center impact location (O) are illustrated.

sets, eliminated the effect of adjacent points on the smoothed data, and were unaffected by boundary effects (D'Amico & Ferrigno, 1992; Smith, 1989; Woltring, 1985; Wood, 1982). To minimize errors in angle and velocity calculations two analysis procedures were used. First, position data for each trial were established by averaging three digitizations by one skilled operator (Groppel, Shin, Spotts, & Hill, 1987; Looney, Smith, & Srinivasan, 1990). Second, the angles and velocities of ball approach and rebound were determined from the mean of two finite difference calculations between the three samples before and after impact. The racket angle at impact was calculated from the frame prior to impact to avoid detection of motion of the frame caused by impact.

The vertical plane angles of approach (Θ) and rebound (Φ) relative to the horizontal were calculated to monitor the consistency of the impact conditions (Figure 1). So rebound accuracy across trials could be compared, an accuracy ratio (AR) representative of a tennis volley was calculated as the angle of rebound divided by the angle of approach, both measured relative to an axis normal to the racket face. An accurate rebound in a vertical plane was defined as an angle of rebound close to normal to the racket face, since the study simulated a primarily flat shot, like a volley, with a target at right angles to the racket. An AR of unity corresponded to equal angles of approach and rebound, so the smaller the AR, the more accurate the ball rebound. Data were analyzed by a two-way ANOVA (2 × 3—Location × String Tension) with statistical significance accepted at the .01 level of probability.

Results

Impact locations measured from film were consistent. Across all trials, the mean impact location was 0.8 ± 1.8 cm proximal to the geometric center of the racket face. Mean impact locations in the vertical dimension were 0.08 ± 0.9 cm above geometric center for central impacts, and 0.80 ± 1.8 cm above for the off-center trials. Due to timing variations in the projection of the ball by the ball machine, not all conditions had 10 observations.

Mean and mean–standard deviation accuracy ratios (AR) for all conditions are plotted in Figure 2. A smaller AR corresponds to greater accuracy or a rebound more in line with normal to the racket face. The unequal frequencies and different variances (Figure 2) of the AR data required the variances in the data to be equalized with a square-root transformation prior to ANOVA analysis (Kirk, 1982). The two-way ANOVA revealed significant main effects for impact location, $F(1, 44) = 84.2$, $p < .01$; string tension, $F(2, 44) = 11.8$, $p < .01$; and the interaction of string tension and location, $F(1, 44) = 6.2$, $p < .01$.

Treatment–Contrast Interactions were calculated since the significant interaction precluded valid post hoc comparisons between means (Kirk, 1982). Treatment–Contrast Interactions demonstrated that the interaction between impact location and the difference in string tension from 200 to 334 N was significant, $F(2, 44) = 5.75$, $p < .01$. In other words, the change in AR (slope in Figure 2) across string tensions from 200 to 334 N was different for central versus off-

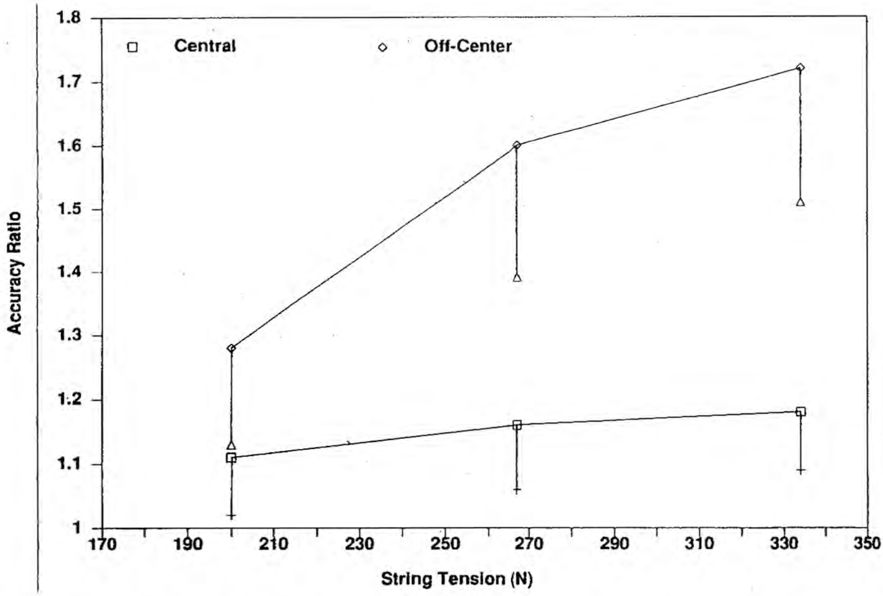

Figure 2 — Mean and mean–standard deviation rebound accuracy ratios. The accuracy ratio is the angle of reflection divided by the angle of approach. A smaller accuracy ratio corresponds to a more accurate rebound (more in line with normal to the racket face).

center impacts. Off-center impacts showed a greater loss in accuracy as string tension was increased.

Discussion

Results of the present study supported previous research demonstrating that the increased elasticity of lower string tensions tends to improve rebound accuracy in static tennis impacts (Knudson, 1991a). The oversized racket strung with 200 N of tension had the most accurate rebounds (AR = 1.11 ± 0.09) in central impacts. This was more accurate than a study of central impacts on a midsized racket (AR = 1.50 ± 0.16) strung with nylon at a slightly higher tension of 222 N (Knudson, 1991a). It appears that oversized rackets may provide more accurate rebounds because the oversized racket strung at 267 N was more accurate (AR = 1.16 ± 0.1) than the previous study (Knudson, 1991a) of a midsized racket in the same string tension and impact location conditions (AR = 1.52 ± 0.2). Similar to the previous study of rebound accuracy (Knudson, 1991a), the present study found that the typical standard deviation for mean ARs was 0.1, which corresponded to a variance of ± 2.5° in rebound angle for these impact conditions.

How these results relate to players attempting to impart large amounts of spin is not clear. Stroking a tennis ball with a slightly open/closed racket face and using a steep racket path less aligned with the target, in order to generate spin, may place different demands on the strings and the frame. Future studies should utilize high-speed videography (2000 Hz) to make higher sampling rates and larger samples cost-effective. Data are needed in a variety of stroking conditions to establish whether it is the effect of string elasticity or the combined effect of dwell time and racket displacement that has the greatest influence on ball rebound accuracy when string tension is varied.

It was concluded that string tension, impact location, and the interaction of tension and location significantly affect ball rebound angle in static tennis impacts. Results supported previous research (Knudson, 1991a) demonstrating that higher string tensions have less accurate rebounds in a vertical plane. Off-center impacts showed less accurate vertical plane rebounds and a greater loss of accuracy as string tension increased. The oversized rackets in this study created more accurate rebounds in central impacts than midsized rackets in similar string tension and impact conditions.

References

Baker, J., & Wilson, B. (1978). The effect of tennis racket stiffness and string tension on ball velocity after impact. *Research Quarterly*, **49**, 255-259.

Brannigan, M., & Adali, S. (1981). Mathematical modelling and simulation of a tennis racket. *Medicine and Science in Sports*, **13**, 44-53.

Brody, H. (1979). Physics of the tennis racket. *American Journal of Physics*, **47**, 482-487.

Brody, H. (1987). *Tennis science for tennis players*. Philadelphia: University of Pennsylvania Press.

D'Amico, M., & Ferrigno, G. (1992). Comparison between the more recent techniques for smoothing and derivative assessment in biomechanics. *Medical and Biological Engineering and Computing*, **30**, 193-204.

Elliott, B.C. (1982a). The influence of racket flexibility and string tension on rebound velocity following dynamic impact. *Research Quarterly for Exercise and Sport*, **53**, 277-281.

Elliott, B.C. (1982b). Tennis: The influence of grip tightness on reaction impulse and rebound velocity. *Medicine and Science in Sports and Exercise*, **14**, 348-352.

Elliott, B., Blanksby, B., & Ellis, R. (1980). Vibration and rebound velocity characteristics of conventional and oversized tennis rackets. *Research Quarterly for Exercise and Sport*, **51**, 608-615.

Ellis, R., Elliott, B., & Blanksby, B. (1978). The effect of string type and tension in jumbo and regular sized rackets. *Sports Coach*, **2**(4), 32-34.

Groppel, J. (1984). *Tennis for advanced players*. Champaign, IL: Human Kinetics.

Groppel, J., Shin, I., Thomas, J., & Welk, G. (1987). The effects of string type and tension on impact in midsized and oversized tennis rackets. *International Journal of Sport Biomechanics*, **3**, 40-46.

Groppel, J., Shin, I., Spotts, J., & Hill, B. (1987). Effects of different string tension patterns and racket motion on tennis racket-ball impact. *International Journal of Sport Biomechanics*, **3**, 142-158.

Hatze, H. (1992). Objective biomechanical determination of tennis racket properties. *International Journal of Sport Biomechanics*, **8**, 275-287.

Hudson, J. (1990). Problems in data reduction: Tracking a round object. In M. Nosek, D. Sojka, W.E. Morrison, & P. Susanka (Eds.), *Proceedings of the VIIIth International Symposium of the Society of Biomechanics in Sports* (pp. 351-355). Prague: Conex.

Kirk, R.E. (1982). *Experimental design* (2nd ed.). Pacific Grove, CA: Brooks/Cole.

Knudson, D.V. (1991a). Effect of string type and tension on ball vertical angle of rebound in static tennis impacts. *Journal of Human Movement Studies*, **20**, 39-47.

Knudson, D.V. (1991b). Factors affecting force loading on the hand in the tennis forehand. *Journal of Sports Medicine and Physical Fitness*, **31**, 527-531.

Knudson, D.V., & White, S.C. (1989). Forces on the hand in the tennis forehand drive: Application of force sensing resistors. *International Journal of Sport Biomechanics*, **5**, 324-331.

Looney, M.A., Smith, S.L., & Srinivasan, S. (1990). Establishing reliability of biomechanical data using univariate and multivariate approaches. *Research Quarterly for Exercise and Sport*, **61**, 154-160.

Ohmichi, H., Miyashita, M., & Mizumo, T. (1979). Bending forces acting on the racquet during the tennis stroke. In J. Teradus (Ed.), *Science in racquet sports* (pp. 89-95). Del Mar, CA: Academic.

Plagenhoef, S. (1979). Tennis racket testing related to tennis elbow. In J. Groppel (Ed.), *A national symposium on the racket sports* (pp. 291-310). Urbana–Champaign, IL: University of Illinois Press.

Smith, G. (1989). Padding point extrapolation techniques for the butterworth digital filter. *Journal of Biomechanics*, **22**, 967-971.

Woltring, H.J. (1985). On optimal smoothing and derivative estimation from noisy displacement data in biomechanics. *Human Movement Science*, **4**, 229-245.

Wood, G.A. (1982). Data smoothing and differentiation procedures in biomechanics. *Exercise and Sport Science Reviews*, **10**, 308-362.

Acknowledgments

This research was supported in part by a grant from the United States Tennis Association. The support of Prince Manufacturing Inc. and the Baylor Institute of Graduate Statistics is gratefully acknowledged.