Intrasubject Variability of Upper Extremity Angular Kinematics in the Tennis Forehand Drive

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The intrasubject variability of the angular kinematics of the wrist and elbow joints in the tennis forehand drive were studied. Two varsity tennis players were filmed as they performed flat forehand drives. The DLT method of 3-D reconstruction was used to measure the angular motion of the upper extremity for eight strokes to assess the intrasubject variability of selected kinematic variables. Curves were synchronized to impact and averaged. Wrist and elbow angular position data were quite consistent, with curve coefficients of variation (CV) less than 5.9%. The consistent angular positions during the forward stroke did not result from highly consistent patterns of angular velocities or accelerations. For both the wrist and elbow joints, intrasubject variability increased for the angular velocity (CV=90.6%) and angular acceleration (CV = 129.5%) curves. Biomechanical studies comparing derivatives or kinetic variables across subjects may have to be interpreted with reference to intrasubject variability.

It is not unusual for sport biomechanics research to analyze single trials across several performers. The implicit assumptions in these analyses are that one superior performance is representative for that athlete, and intrasubject variability of the mechanical parameters of interest are small.

Recently there has been increased research interest in the variability of biomechanical variables in human motion. Hatze (1986) has proposed a generalized measure of motion variability. Several researchers have begun to report data on the variability of several kinetic variables commonly studied in locomotion (DeVita & Bates, 1988; Winter, 1984), and the importance of this variability is a controversial issue (Bates, 1989). Knudson and Roberts (1989) reported the variability of the 3-D position, velocity, and acceleration of points on the upper extremity in the tennis forehand. The purpose of this paper was to document the intrasubject variability of upper extremity angular kinematics of the tennis forehand.

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Method

Two male Big Ten varsity tennis players stroked flat forehand drives down the center of a tennis court off balls projected from a ball machine at 19.4±0.6 m/s. The motions of the racket, ball, and upper extremity were recorded by two cameras, one operating at 100 fps and the other at 200 fps. The cameras were synchronized by matching every other frame of the faster camera to the slower camera to maximize the synchronization at impact (Dainty et al., 1987). Twenty-three control points defining a 2.44-m³ area were used with the DLT method to reconstruct the points in three dimensions (Abdel-Aziz & Karara, 1971). Mean error in reconstruction of the control points was 4.1 mm. The length of the racket head (0.215 m) was computed during the forward stroke and resulted in dynamic errors of less than 4%. The stroking phase of the forehand drive was documented by digitizing 50 frames, 30 before and 20 after impact. The points digitized were the tip of the racket, top lateral edge of the racket head, racket center of gravity, hand center of gravity, wrist, elbow, shoulder, and ball.

The subjects used the same midsized tennis racket strung with nylon at 245 N (50 lbs) of tension. The first eight strokes qualitatively judged to be flat and down the center of the court were analyzed to calculate the variability of selected angular kinematics. Ball velocity was calculated from raw data because the ball was in the reference space for only a short time.

Resultant (3-D) joint angles were calculated from raw data. The wrist angle was calculated using the dot product of a vector describing the long axis of the racket and the reverse of the longitudinal axis of the forearm. The same procedure was used to calculate the 3-D elbow angle between the forearm and upper arm vectors. Angular positions were smoothed with a Butterworth digital filter using the separation technique to selectively smooth the stroking and impact phases of the stroke (Dowling, 1987; Pour-Manoochehri & Serig, 1985). The discontinuity of the curves at impact precluded the use of splines or Fourier series for smoothing. Wrist angular data were filtered at 10 Hz, the raw data from five frames before to five frames after impact were reinserted into the data, and the data were filtered at 45 Hz to smooth the impact section and transition in the data.

Elbow angular data were smoothed using the same procedure, using 8 and 15 Hz, respectively. The degree of smoothing was selected subjectively by evaluation of residuals relative to dynamic errors observed. Figure 1 illustrates how this procedure fits the low frequency movement data as well as the higher frequency data near impact. Curves were synchronized to impact and averaged. The variability of each curve was evaluated by calculating the curve coefficient of variation using the formula by Winter (1984):

\[ CV = (1/N \sum \sigma^2)^{1/2} / (1/N \sum |M|). \]

Results

Data from both subjects demonstrated similar angular position curves at the wrist but slightly different angular motions at the elbow joint. The wrist angular position curves proved to be very consistent with curve coefficient of variations (CV) of 3.1 and 5.9%. The mean ± standard deviation wrist angle curves for Subject MD are presented in Figure 2.
Figure 1 — Typical raw and piecewise filtered wrist angular position curves.

Figure 2 — Mean and standard deviation wrist angle curves for Subject MD.
Elbow angular position data exhibited a slightly different pattern for the subjects. The variability of the curves, however, were quite similar (CV = 4.2 and 4.7%). Subject SJ used the traditional stroke technique with the arm comfortably extended, while Subject MD used more elbow flexion during the stroke (Figure 3).

The variability of the angular velocity curves for both the wrist and elbow were much higher than the corresponding angular position curves. Figure 4 illustrates the mean elbow angular velocity curve for Subject SJ. Wrist angular velocity curves had CVs of 63.7 and 78.1%, while elbow angular velocity curves had CVs of 135.3 and 85.3%. Variability of angular acceleration curves were 101.4 and 135.1% for the wrist, and 124.2 and 157.1% for the elbow.

![Figure 3](image.png)

**Figure 3 — Comparison of mean and standard deviation elbow angle curves for both subjects.**

**Discussion**

Angular position data were consistent with previous studies of the tennis forehand. For strokes down the center of the court, the mean angles of the wrist at impact were 2.18 and 2.28 radians. These wrist angles indicate wrist hyperextension at impact and were very consistent with a coefficient of variation for that time sample of less than 4.5%. These angles are similar to values reported in previous studies (2.5 to 2.8 rad) of wrist angles at impact in the tennis forehand drive (Ariel & Braden, 1979; Deporte, Van Gheluwe, & Hebbelinck, 1986; Elliott, March, & Overheu, 1989; Plagenhoef, 1970). The mean elbow angles at impact were 1.64 and 2.40 radians and were similar or smaller than previously reported (2.4 to 2.9 rad) values (Deporte et al., 1986; Elliott et al., 1987, 1989;
Gelner, 1965). These elbow angles at impact were also highly consistent with coefficient of variations for that time sample less than 3.1%.

Variability was larger for angular velocity and acceleration curves for the elbow than for the wrist. This trend of increasing variability moving proximally was similar to the results of an analysis of linear kinematics of these same subjects (Knudson & Roberts, 1989).

The issue of intrasubject variability becomes more important when the variables of interest involve derivatives of angular position. Figure 5 illustrates this point well where the mean elbow angle is plotted with the elbow angle from the trial with the fastest rebound velocity for Subject SJ. Angular position curves are relatively close in magnitude prior to impact, but a large difference in slope is apparent near impact. This indicates that angular velocity comparisons across subjects, based on an individual trial for this subject, are not appropriate because of the intrasubject variability.

Previous research has reported mean wrist angular velocities at impact in the tennis forehand drive of 2.6 and 1.4 rad/s for two styles of execution (Elliott et al., 1989), and 0.31 and 4.2 rad/s for two individual tennis players (Deporte et al., 1986). Gelner (1965) reported a range of wrist flexion at impact of 2.3 to 13.7 rad/s in the forehand drives of two tennis players. The mean wrist angular velocities and standard deviations for the subjects in the present study, one frame before impact, were $5.2 \pm 3.4$ rad/s and $6.5 \pm 1.2$ rad/s. This time sample minimized error due to the large acceleration at impact. The large standard deviations suggest that wrist angular velocity near impact is not highly consistent in these subjects.
Figure 5 — Comparison of the mean elbow angle curve to the elbow angle from the trial with the fastest ball velocity for Subject SJ.

Despite using a different racket, these subjects stroked the ball with wrist and elbow positions consistent with previous studies. What previous research has not documented is the larger variability of the higher order kinematic variables commonly studied. Differences in angular velocities at impact could be due to many factors. Subjects, experimental conditions, sampling, and especially smoothing can dramatically affect results. The problem of calculating derivatives near endpoints has been well documented (Phillips & Roberts, 1983; Smith, 1989; Wood, 1982). Regardless of methodological differences, the central issue of the variability of these parameters needs further study. Data from these subjects suggest that biomechanical studies comparing derivatives or kinetic variables across subjects should be interpreted with reference to intrasubject variability.

References


