A Biomechanical Comparison of the Multisegment and Single Unit Topspin Forehand Drives in Tennis

Bruce Elliott, Tony Marsh, and Peter Overheu

Three-dimensional (3-D) high-speed photography was used to compare different forehand techniques of high performance players. Subjects, who hit a topspin forehand drive with the hitting limb moving almost as a single unit (Gs: single-unit group), were compared with players whose individual segments of the upper limb moved relative to each other (Gm: multisegment group) when playing the same stroke. The Direct Linear Transformation method was used for 3-D space reconstruction from 2-D images recorded from laterally placed phase-locked cameras operating at 200 fps. A third Photosonics camera operating at 100 fps filmed from overhead. Significant differences between the groups were recorded at the shoulder and elbow joints at the completion of the backswing. Maximal elbow joint angular velocities occurred 0.06 sec prior to impact, with the Gm group recording a significantly higher mean value for elbow extension than the Gs group. At impact, however, the Gm group recorded a significantly higher level of elbow flexion than the Gs group and achieved a higher mean angular velocity at the wrist joint than the Gs group. The Gm group recorded a higher racket tip linear velocity at impact and higher postimpact ball velocity when compared to the Gs group. The Gm technique of racket movement produced higher racket and ball velocities for this group of high performance players.

The forehand (FH), whether hit from a stationary or running preparation, together with the service and backhand drive, form the cornerstone of tennis stroke production. Successful performance of the forehand drive relies heavily on the player's technique. Unless the stroke mechanics that make up good forehand technique can be identified, it is impossible for the player, coach, or biomechanist involved with elite tennis development to strive for stroke production that integrates appropriate stroke mechanics and individual flair. The forehand technique used by many world ranked players today indicates that individual segments of the

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upper limb are used to generate racket velocity, unlike a conventional forehand in which the upper limb acts more as a single unit. The current quantitative kinematic studies on the forehand drive (Ariel & Braden, 1979; Blievermicht, 1968; Groppel, 1975; Holcomb, 1962) do not clearly identify the mechanical characteristics of either of these FH styles.

This study compared the biomechanical characteristics of two distinctly different topspin forehand techniques of high performance players. Players who hit their forehand with the upper limb moving almost as a single unit (Gs: single-unit group) were compared with players whose individual segments of the upper limb moved relative to each other during the preparation and forward swing phases of the stroke (Gm: multisegment group). The different types of forehand were compared for a stationary FH hit down the line (FH1), and then across court (FH2), and a down-the-line drive hit from a running preparation (FH3). Where applicable, kinematic descriptions of particular aspects of the stroke for both groups were compared with qualitative and quantitative descriptions in the literature.

**Methods and Procedures**

Seven state ranked male tennis players and one internationally ranked female tennis player served as subjects. Their mean age was 22 years. Four of them used the multisegment forehand (Gm group, included female subject) while the remaining four rotated the upper limb more as a single unit during the forehand stroke (Gs group). The number of subjects was qualitatively determined by three state level professional coaches, who indicated that only four players within the state were capable of hitting a high performance multisegment forehand. Players were allowed to use their own rackets (small variations in mass and string tension) to ensure that each player felt comfortable in performing each stroke.

Filming was conducted on a plexipave tennis court using the Direct Linear Transformation (DLT) method for 3-D space reconstruction from 2-D images. Two Photosonics phase-locked cameras operating at 200 fps (exposure time 1/1600 sec) were used to film a reference structure containing markers of known coordinates in space encompassing the field of movement of the forehand action. This structure was then removed and the subject was filmed in the same area with identical camera positions. A third Photosonics camera operating at 100 fps (exposure time 1/800 sec) was positioned above the area from which the ball was hit, perpendicular to the ground (Figure 1). A ball machine was used to propel new tennis balls so that three topspin forehand drives, first down the line and then across court, and three running forehand drives down the line could be hit under a tape strung 60 cm above the net (to negate excessive loop on the ball trajectory) at the target area (Figure 1, right-handed player). The area defined by the reference structure allowed all players to hit each forehand trial at approximately hip height. An electric sweep-hand clock divided into 0.02-sec intervals and positioned in the field of view of all cameras was used to calibrate film speed.

**Analysis and Treatment of Data**

The highest velocity forehand that landed in the target area, provided it was hit from the area outlined by the reference structure and produced a forward ball rotation, was selected for analysis. The film images of each selected forehand
Figure 1 — Filming environment.
were then projected by a NAC 16-mm motion analysis projector via an overhead mirror onto the surface of an analysis table. The 2-D images of both the reference structure (16 points) and subjects (11 points) were digitized, and the unknown 3-D coordinates of each subject’s landmarks were determined using the procedures outlined in Marzan and Karara (1975) and Wood and Marshall (1986). After digitizing, the data were then transferred to a DEC System-10 computer on which 3-D joint angles and angular velocities were calculated. An average mean square error of 5 mm for the calculation of the x, y, and z values of the known points in space from the digitized data was calculated for the eight subjects. Coordinates from the sagittal plane were also used in the calculation of linear and angular kinematics, using procedures outlined by Wood (1977).

An automatic low-pass digital filtering procedure similar to the technique used by Wells and Winter (1980) was developed so that different anatomical landmarks and body segments could be smoothed at different frequencies (range 2 Hz to 15 Hz). A two-way analysis of variance with repeated measures on forehand trials (FH1, FH2, FH3) was used to test for significance. Statistical significance was accepted at an alpha level of 0.05. If no significant interaction was detected, then differences between the main effects were tested. The small sample size was a recognized limitation of this study; however, this was taken into account in the significance tables when deciding what variables were different.

**Results and Discussion**

The data from the Gs and Gm groups for the three trials (FH1, FH2, FH3) were pooled where no significant differences were recorded between the different trials. Differences between the groups will be highlighted where significant variations were recorded. The mean data will be presented in the sections that follow on the various phases of the stroke, beginning with the grip.

**The Grip**

One subject used an Eastern forehand and the other seven used a semi-Western grip. These grips permitted the subjects to contact the ball with a slightly closed (N=8, range = 0.02 to 0.12 rad) or vertical racket face (N=16), irrespective of the type of forehand hit in the three trials (FH1, FH2, FH3). Given that all subjects played regularly on the faster surfaces of grass and hard court (plexipave), an Eastern or semi-Western grip was appropriate since it requires minimal wrist movement to achieve a vertical racket face for a variety of impact heights (Braden & Bruns, 1977; Plagenhoef, 1979; Tilmanis, 1975) and enables a firm grip to be adopted for impact (Elliott & Kilderry, 1983; Groppel, 1984). (See Figures 2 and 3.)

**Backswing**

Preparation. The forehand backswing began with flexion of the knees and hips so that the body was accelerated toward the court with similar mean peak velocities of 0.52 m s⁻¹ (Gm) and 0.49 m s⁻¹ (Gs) (Figure 2). Deceleration of the body for both groups may then have applied stretch to the muscles, which resulted in the subsequent storage of elastic energy in muscles and associated tissues (Komi & Bosco, 1978). This stored energy may then at least partially assist the lower limb drive in moving the player to the vicinity of the ball. Different movement
Figures 2 and 3 — The preparatory phase of the topspin FH1 drive using the youngest subject from the Gm group.

patterns for racket preparation were observed between the two groups. A pivot of the back foot in the Gm group was followed by backward movement of the elbow in synchrony with the shoulder turn so that the racket remained pointed at the oncoming ball (Figure 4a). The racket head was then closed while the elbow was raised (Figure 5a). The forearm and racket then pivoted about the elbow and shoulder (outward rotation of the humerus occurred) and the racket was rotated up to a position above the elbow and shoulder (Figure 6a). This movement was similar to the one described by Van der Meer (in Lott, 1981), who suggested that as the shoulder turn and backswing begin, the elbow should be raised. This closed the racket face, increased the arc of the swing, and produced greater racket acceleration. By contrast, the subjects in the Gs group moved the racket back in synchrony with the shoulder turn (Figure 4b) and rotated the whole racket arm about the shoulder rather than about the elbow joint (Figures 4b, 5b, and 6b).

The backswing, irrespective of style used, was characterized by a loop in all forehand drives. The racket head moved upward to a position higher than the elbow (Figures 6a & 6b) prior to dropping below the intended point of impact at the beginning of the forward swing. Keating (in Braden & Bruns, 1977) theoretically calculated that the racket head gained approximately 2.7 m s⁻¹ for every 30 cm it continuously moved during the backswing. Further, Pecore (1978), in a cinematographic study of female tennis players, found that those using a circular backswing averaged higher racket head velocities at impact compared to players using a straight backswing.

Body Positions at Completion of Backswing. Table 1 presents the mean 3-D joint angles at the backswing position (the point immediately preceding any forward movement of the racket) (Figure 7) and at impact. The alignment of the shoulders taken directly from high-speed film from an overhead camera, and the 2-D trunk angle derived from the 3-D data at the backswing position for the two groups, are presented in Table 2.

No significant differences were recorded in joint angles between the two groups for either the front or back knees or the hip joint at the completion of
Figures 4, 5, and 6 — Backswing phase (a) (left side, top to bottom): using the Gm technique. (b) (right side, top to bottom): using the Gs technique.
Table 1
Mean 3-D Joint Angles at the Completion of the Backswing (BS) and at Impact (I) (rad)

<table>
<thead>
<tr>
<th>Joint</th>
<th>BS</th>
<th></th>
<th>BS</th>
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<tbody>
<tr>
<td></td>
<td>Gm</td>
<td>Gs</td>
<td>Gm</td>
<td>Gs</td>
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<td>Front knee</td>
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<td>2.34</td>
<td>2.65</td>
<td>2.58</td>
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<td></td>
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<tr>
<td></td>
<td>0.27</td>
<td>0.26</td>
<td>0.16</td>
<td>0.15</td>
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<tr>
<td>Back knee</td>
<td>2.19</td>
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<td>Hip</td>
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<td>Elbow</td>
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<td>Wrist</td>
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<td></td>
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<td>0.09</td>
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</tbody>
</table>

†Joint orientations: Posterior angle for knee joints and wrist joint. Anterior angle for hip and elbow joints. Shoulder joint is the angle between the trunk and the arm of the hitting limb. *A significant difference was recorded between Gm and Gs groups.

Note. n = 12 for Gm and Gs groups.

Table 2
Segment Angles at the Completion of the Backswing (BS) and at Impact (I) (rad)

<table>
<thead>
<tr>
<th>Segment</th>
<th>BS</th>
<th>Gm</th>
<th>BS</th>
<th>Gm</th>
<th>I</th>
<th>Gs</th>
<th>I</th>
<th>Gs</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td>Gm</td>
<td>Gs</td>
<td>Gm</td>
<td>Gs</td>
<td>Gm</td>
<td>Gs</td>
<td>Gm</td>
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<tr>
<td>Shoulder alignment</td>
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<td>1.73</td>
<td>0.12</td>
<td>0.15</td>
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<tr>
<td></td>
<td>0.13</td>
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<td>0.05</td>
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<td>1.64</td>
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<td></td>
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<td>0.15</td>
<td>0.13</td>
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</table>

Note. n = 12 for Gm and Gs groups.

The similar trunk angles of 0.17 rad (Gm) and 0.19 rad (Gs) producing a backward lean of the torso were probably related to the distribution of body weight, most of which at this point was presumably over the rear limb. This rear limb was responsible for the production of linear momentum in the forward drive to the ball, hence its flexed position (Groppel, 1984). The hip joint,
which was also flexed for both groups, further enhanced the body’s ability to “lift” during the forward swing.

The shoulders rotated through similar angles of 1.78 rad (Gm) and 1.73 rad (Gs) from an alignment parallel to the net in the ready position to a position past a line drawn perpendicular to the back fence in preparation for the forward swing. A mean shoulder joint angle of 1.19 rad showed that the arm was abducted away from the trunk for the Gs group while a more compact position was recorded for the Gm group (0.80 rad). Similarly, the elbow joint angle for the Gs group of 2.54 rad was significantly larger than the 2.13 rad for the Gm group, which showed that the racket arm was not fully extended in either group; however, the Gm group had a more compact backswing position. The hand was hyperextended at the wrist joint to a similar position for both groups (Gm=2.56 rad; Gs=2.63 rad), which clearly demonstrated that the forearm and racket were not aligned. The 2.09-rad wrist angle reported by Plagenhoef (1970) also supported the concept that the wrist joint was hyperextended at the completion of the backswing. The racket was not pointed at the back fence, as stated in the literature (Braden & Bruns, 1977; Elliott & Kilderry, 1983), but rotated past this orientation by similar angles of 0.91 rad for the Gm group and 0.84 rad for the Gs group.

**Forward Swing to Impact**

*Kinematics of the Forward Swing.* The front knee extended the same amount (0.24 rad) from the backswing position to impact for the two groups while the back knee increased by similar angles of 0.16 rad (Gm) and 0.20 rad (Gs) over the same period (Table 1). These movements, along with the similar levels of hip extension (Gm=0.52 rad; Gs=0.46 rad), raised the hitting shoulder for all subjects, thus assisting the low-to-high trajectory of the racket (Figures 7 to 12).

Rotation of the trunk and lower limb drive increased racket shoulder rotation gradually over the forward swing such that at impact this forward movement was responsible for approximately 10% of final racket velocity for both groups (Figure 13). The shoulders rotated through similar angles of 1.66 rad (Gm) and 1.58 rad (Gs) from the backswing position so that at impact the alignment was 0.12 rad (Gm) and 0.15 rad (Gs) behind a line parallel to the net. Further, the trunk had moved from a backward lean at the backswing position to similar forward leaning positions of 0.11 rad (Gm) and 0.07 rad (Gs) at impact, which suggested that a forward transfer of weight had occurred. The shoulder joint angle decreased during the forward swing for the Gs group and remained relatively constant for the Gm group so that by impact similar angles of 0.83 rad (Gm) and 0.84 rad (Gs) were recorded. The arm therefore remained a comfortable distance from the trunk (Figure 11) during the forward swing to maintain control over the racket head at impact and hit through the ball’s line of flight.

The elbow joint extended for the Gm group from a mean angle for the three trials at the backswing position of 2.13 rad until 0.04 sec prior to impact, where a mean of 2.55 rad was recorded. During this period the Gs group held the elbow joint almost constant. The elbow joint then flexed for the Gm group between this point and impact, while players in the Gs group again maintained their elbow angle. Players from the Gm group recorded a significantly higher maximum elbow extension velocity compared to the Gs group (Gm=4.4 rad s⁻¹; Gs=0.5 rad s⁻¹) prior to flexing the elbow joint at a higher rate at impact (Gm=−3.3 rad s⁻¹; Gs=−0.6 rad s⁻¹).
Figures 7 through 12 — (From top, left to right): The forward swing phase of the topspin FH1 drive using the youngest subject from the Gm group.
Figure 13 — Mean resultant end point velocities for the topspin FH1 drive in the sagittal plane for the Gm and Gs groups.
The wrist angle decreased from the backswing position to 0.12 sec prior to impact for both groups as the racket trailed the forward moving limb. Small wrist joint angular velocities were then generally recorded in the 0.08 sec leading up to impact, showing that these players flexed the wrist to increase racket head velocity over this period. Significantly higher angular velocities of the wrist joint were recorded at impact by the Gm group (2.6 rad s\(^{-1}\)) compared to the Gs group (1.4 rad s\(^{-1}\)). However, this should not be interpreted as a wrist flick. The increase in racket tip velocity was well coordinated with the forward movement of the forearm so that a near maximal velocity was recorded at impact. Much of the increase in racket velocity occurred because of the increase in linear velocity produced by the sequential segment end points (elbow, wrist, racket tip) being further away from the axis of rotation (the shoulder).

Maximum racket velocities of 23.3 m s\(^{-1}\) (Gm) and 20.2 m s\(^{-1}\) (Gs) were recorded 0.01 sec prior to impact, levels that were reduced to a significantly higher velocity of 22.5 m s\(^{-1}\) for the Gm group when compared to the 19.3 m s\(^{-1}\) recorded for the Gs group at impact (Figure 13). Plagenhoef (1971) also noted that this phenomenon was apparent in many activities that involved an impact, such as judo, golf, squash, and boxing. The suggestion was that the body segments slow down just prior to contact to prepare for the force of the impact. The shoulder, elbow, wrist, and racket all decelerated for both groups after reaching maxima prior to impact.

**Racket Trajectory.** Topspin has been identified by Braden and Bruns (1977), Elliott and Kilderry (1983), and Groppel (1984) as the most effective method of increasing the margin of error over the net while still having the ball land inside the baseline. These authors identified the following critical factors for the production of topspin: (a) a movement of the racket head from below the level of the ball to above the point of impact during the forward swing and follow-through (Figures 8 to 11), and (b) a vertical or near vertical racket face at the moment of impact (Figure 11).

The racket head moved on similar upward paths with respect to the court of 0.30 rad (Gm) and 0.29 rad (Gs) (Figures 8 to 10) prior to impact for the three trials, which was in agreement with the angle of 0.30 rad proposed by Braden and Bruns (1977). This upward trajectory was increased dramatically between 0.005 sec prior to impact and 0.005 sec postimpact to 0.83 rad (Gm) and 0.81 rad (Gs). These data suggest that these players, irrespective of technique used, first aligned the racket and ball and then, once impact was assured, increased the trajectory to impart an off-center force to the ball. At impact the racket face was vertical (N= 16) or slightly closed (0.02 to 0.12 rad, N=8) irrespective of technique used, which supported data by Brody (1985), Groppel (1975), and Groppel, Dillman, and Lardner (1983).

**Impact**

**Kinematics at Impact.** The 3-D joint angles at impact are presented in Table 1. There were no significant differences between the groups for either technique at this most critical point of the stroke. Neither group fully extended the front (Gm=2.65 rad; Gs=2.58 rad) or back knee (Gm=2.35 rad; Gs=2.32 rad) at impact. Hip angles for the dominant side of 2.69 rad (Gm) and 2.62 rad (Gs) showed that the trunk was angled slightly forward toward the ball for both groups. Similar shoulder angles (Gm=0.83 rad; Gs=0.84 rad) meant that the arm was
a comfortable distance from the trunk, and the elbow angles (Gm=2.42 rad; Gs=2.44 rad) showed that the upper limb was not fully extended. Wrist angles of 2.76 rad (Gm) and 2.72 rad (Gs) were of a similar magnitude to those reported by Plagenhoef (1970—2.62 rad), Ariel and Braden (1979—2.79 rad and 2.48 rad), and Van Gheluwe (1983—2.76 rad), and clearly showed that the hand was hyperextended at the wrist joint at impact irrespective of technique used.

Wrist joint and racket angle data from the Gm and Gs groups were pooled for the stationary down-the-line and across-court strokes so that the wrist and racket angles could be compared at impact. The racket was angled significantly further forward (0.13 rad) in the FH2 impact as opposed to a mean of −0.03 rad in the FH1 trials (0 rad was a line parallel with the net). The wrist angles of 2.86 rad (Gm) and 2.85 rad (Gs) for the across-court trials were significantly larger than the wrist angles for FH1 trials (Gm=2.66 rad; Gs=2.59 rad). Overhead film data revealed that FH2 trials were impacted further in front of both the racket shoulder (14 cm) and front foot (17 cm) than the FH1 trials (Figure 14). The larger wrist angle at impact, then, allowed the ball to be hit further forward in the across-court stroke than in the down-the-line drive to direct the ball across court.

**Racket/Ball Relationships.** Table 3 summarizes the racket and ball interaction at pre- and postimpact for the two forehand techniques. The consistent velocity with which the ball machine delivered the ball to be hit assisted the study by allowing the subjects to perform under similar conditions. A fourfold increase in the postimpact ball velocity occurred in all trials, with a loss of only 20% in the postimpact racket velocity. In this study, racket mass and flexibility were relatively constant across all subjects; however, no attempt was made to standardize string tension, a variable that influences resultant ball velocity (Elliott, 1982b; Groppel, Shin, Spotts, & Hills, 1987). Impacts, although generally centrally located, were at times off center in a vertical orientation with the center of percussion. This emphasized the need for a firm grip at impact (Elliott, 1982a).
Table 3
Racket/Ball Interaction for the Gm and Gs FH Techniques (m s⁻¹)

<table>
<thead>
<tr>
<th></th>
<th>Gm</th>
<th>Gs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preimpact ball velocity</td>
<td>7.9</td>
<td>8.0</td>
</tr>
<tr>
<td>Preimpact racket velocity</td>
<td>23.3</td>
<td>20.2</td>
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<tr>
<td>Postimpact ball velocity</td>
<td>34.5</td>
<td>32.3</td>
</tr>
<tr>
<td>Postimpact racket velocity</td>
<td>17.8</td>
<td>16.0</td>
</tr>
<tr>
<td>Ball ratio out/in</td>
<td>4.4</td>
<td>4.0</td>
</tr>
<tr>
<td>Racket ratio out/in</td>
<td>0.8</td>
<td>0.8</td>
</tr>
</tbody>
</table>

**Follow-through**

The racket retained approximately 80% of its velocity after impact. Therefore, in order to avoid injury a follow-through was required to slow the racket and body segments (Broer, 1966). During the period after impact the segments underwent a gradual deceleration (Figure 13), while a recovery step was made by the rear leg which was brought forward to a position level with the front foot (Figure 12). This action prepared the player for movement to the next shot.

**Conclusion**

There were no major differences between the Gm and Gs groups in grip or in initial footwork. A qualitative analysis of the film revealed that players in the Gm group, after a pivot of the back foot, moved the racket elbow back in synchrony with the shoulder turn so that the racket remained pointed at the oncoming ball. The racket and forearm then rotated about the elbow and shoulder. In contrast, players in the Gs group moved the racket back in synchrony with the shoulder turn and rotated the whole racket limb about the shoulder rather than about the elbow joint.

At the backswing position, the Gm group was characterized by a more compact arm with significantly smaller shoulder and elbow joint angles (0.80 rad, 2.13 rad, respectively) than the Gs group (1.19 rad, 2.54 rad, respectively). Similar shoulder rotations of 1.78 rad (Gm) and 1.73 rad (Gs) showed that the shoulder rotated past a line drawn perpendicular to the back fence in preparation for the forward swing. Further, the racket was not pointed at the back fence but rotated past this position for both groups (Gm=0.91 rad; Gs=0.84 rad).

In the forward swing, the shoulders rotated through angles of 1.66 rad (Gm) and 1.58 rad (Gs) so that at impact they were 0.12 rad (Gm) and 0.15 rad (Gs) behind a line parallel to the net. Although movement at the shoulder joint during the forward swing was minimal in both groups, the Gm group was able to produce a higher racket head velocity at impact (Gm=22.5 m s⁻¹; Gs=19.3 m s⁻¹),
and subsequently greater ball velocities ($G_m = 34.5 \text{ m s}^{-1}$; $G_s = 32.3 \text{ m s}^{-1}$), due to increased movement at the elbow and wrist joints. Players from the $G_m$ group recorded a significantly higher maximum elbow extension in the forward swing compared to the $G_s$ group ($G_m = 4.4 \text{ rad s}^{-1}$; $G_s = 0.5 \text{ rad s}^{-1}$) prior to flexing the elbow joint at a higher rate at impact ($G_m = -3.3 \text{ rad s}^{-1}$; $G_s = -0.6 \text{ rad s}^{-1}$).

In addition, significantly higher angular velocities at the wrist joint were recorded at impact by the $G_m$ group ($2.6 \text{ rad s}^{-1}$) compared to the $G_s$ group ($1.4 \text{ rad s}^{-1}$).

There were no significant differences between the two groups for 3-D joint angles at impact.

The data suggested that the direction of the shot, whether across court or down the line, was greatly determined by the alignment of the racket at impact, not by the technique used in the stroke. The racket was angled significantly further forward ($0.13 \text{ rad}$) in the FH2 impacts compared to the FH1 trials ($-0.03 \text{ rad}$). Further, the FH2 trials were impacted further in front of both the racket shoulder ($14 \text{ cm}$) and front foot ($17 \text{ cm}$) than were FH1 trials.

**References**


