Contributions of Upper Limb Segment Rotations During the Power Serve in Tennis

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In the high-velocity tennis serve, the contributions that the upper limb segments' anatomical rotations make to racket head speed at impact depend on both their angular velocity and the instantaneous position of the racket with respect to the segments' axes of rotation. Eleven high-performance tennis players were filmed at a nominal rate of 200 Hz by three Photosonics cameras while hitting a high-velocity serve. The three-dimensional (3-D) displacement histories of 11 selected landmarks were then calculated using the direct linear transformation approach, and 3-D individual segment rotations for the upper limb were calculated using vector equations (Sprigings, Marshall, Elliott, & Jennings, 1994). The major contributors to the mean linear velocity of the center of the racket head of 31.0 m·s⁻¹ at impact were internal rotation of the upper arm (54.2%), flexion of the hand (31.0%), horizontal flexion and abduction of the upper arm (12.9%), and racket shoulder linear velocity (9.7%). Forearm extension at the elbow joint played a negative role (−14.4%) and reduced the forward velocity of the center of the racket at impact.

As every rally in tennis is started with a serve, it is logical to assume that this stroke plays an important role in determining the final outcome of a match. Players of all levels certainly seek to develop a high-speed serve as an integral part of their game.

Sport scientists and coaches agree that the speed of the racket and therefore the postimpact speed of the ball, the height of impact, and the amount of forward rotation of the ball are the key factors determining the angle the ball should be directed for a successful serve (e.g., Elliott, 1983). The speed of the racket head at impact is therefore a critical feature of a successful serve that can be varied considerably by the player, particularly through the individual movements of the upper limb segments. As such, the role of the angular velocity vectors of the upper arm, forearm, and hand in generating maximum racket impact point speed...
is of considerable interest to sport scientists, coaches, and players. There is, however, a paucity of scientific data on the contributions that the individual segments of the hitting limb play in the development of racket speed at impact.

The proximal-to-distal sequencing of motion in the service action has been clearly described (Adrian & Enberg, 1971; Elliott, Marsh, & Blanksby, 1986; Plagenhoef, 1971; van Gheluwe & Hebbelinck, 1985). Jack, Adrian, and Yoneda (1979) used electrogoniometry to calculate aspects of segment contributions to racket speed for average level performers. Van Gheluwe, de Ruysscher, and Craenhals (1987) used three-dimensional (3-D) cinematography to further describe the rotation of the upper arm and pronation of the forearm during the service action of high-performance players. Sprigings, Marshall, Elliott, and Jennings (1991) developed an algorithm that calculated the contribution that the anatomical rotations of each segment of the upper limb made to racket head velocity, with due consideration to both the segment’s angular velocity and the instantaneous position of the racket head with respect to each axis of rotation. In an analysis of one player of average service ability, Sprigings et al. (1994), using 3-D cinematography, showed that the greatest contribution to racket head velocity at impact was produced by internal rotation of the upper arm. Forearm pronation, although recording the highest level of angular rotation, played only a relatively minor role in the development of racket velocity because of the position of the racket with reference to the axis of rotation.

The purpose of this study was to identify the role of the lower body and trunk, upper arm, forearm, and hand in a high-velocity tennis serve. The relative importance of the linear motion of the shoulder as well as each of the possible segmental rotations (upper arm flexion/extension, adduction/abduction, internal/external rotation; forearm flexion/extension, pronation/supination; hand flexion/extension, radio/ulnar flexion) during the service action will also be identified.

Methods and Procedures

Subjects

Eleven male right-handed tennis players of mean age 22 years, who were deemed by two professional coaches as having a high-velocity serve, were used as subjects. Players were filmed using their own rackets (small variations in mass, string tension, and flexibility) to ensure that each player felt comfortable performing each stroke.

Filming Procedures

Three Photosonics phase-locked cameras operating at a nominal rate of 200 Hz and positioned in accordance with camera locations described by Wood and Marshall (1986) were used to film a reference structure containing markers of known coordinates in space that encompassed the field of movement of the service action. Each subject had nine markers attached to the upper limb, and a further two markers were attached to the sides of the racket at the central axis.
Markers on the anterior and posterior aspects of the shoulder were used to identify the glenohumeral joint, while those on either side of the distal end of the humerus were used to identify the elbow joint. In an attempt to better estimate wrist and forearm movements, markers at the distal end of the forearm and on the hand were fitted to rigid rods that were extended beyond the anatomical borders of the respective segment to amplify forearm pronation/supination, hand flexion/extension, and radio/ulnar flexion (Figure 1). These rods did not inhibit the players' natural swing during the serve, and only very small amounts of marker displacement were observed during the action because of skin movement.

We then filmed each player hitting three high-speed serves from close to the center mark of the baseline so that the ball successfully landed in a 1.5-m square positioned in the center corner of the deuce service court, in the above reference area, with identical camera positions.
Analysis and Treatment of the Data

The highest velocity successful trial, as measured from film, was selected for analysis. The film images of each selected serve were then projected by a NAC 16-mm motion analysis projector via an overhead mirror onto the surface of the analysis table. The 2-D images of both the reference structure (24 points) and each subject (11 points) were digitized, and the unknown 3-D coordinates of each subject's landmarks were determined using the direct linear transformation procedures outlined by Marzan and Karara (1975). The forward swing sequence, commencing at the first forward movement of the upper arm and finishing approximately 5 frames past ball contact, was digitized from a projected image 1/9 of life size. An average mean square error of 4 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 11 subjects.

Orthogonal unit vectors defining each local segment coordinate system were constructed for each of the three segments of the upper limb. Anatomical descriptions of the axes of movement of the upper limb segments (upper arm flexion/extension, adduction/abduction, internal/external rotation; forearm pronation/supination, flexion/extension; hand flexion/extension, radio/ulnar flexion) were chosen because they reflect the joint rotations over which a player has control through muscle actions and are terms traditionally employed by coaches to describe the joint movement patterns in tennis. The absolute angular velocity vectors of the three segments were computed so that the relative angular velocity vectors of each segment with reference to its more proximal attachment could be calculated (Sprigings et al., 1994). The anatomically oriented angular speeds of the upper limb segments were then determined from the scalar (dot) product between the relative angular velocity vectors and their appropriate unit vectors. The vector cross products between the relative angular velocity vectors and their respective position vectors to the center of the racket head were then used to determine the effectiveness of these joint rotations in producing racket head velocity. This procedure was previously verified for the tennis serve (Sprigings et al., 1991).

Because the upper arm axis frame is attached to the limb and not the shoulder, the flexion/extension and abduction/adduction axes change with respect to conventional anatomical descriptions when the upper arm internally or externally rotates. As a result it is difficult with the previously mentioned algorithm to accurately delineate contributions to racket head speed from the flexion/extension- or abduction/adduction-based rotations when the upper arm movement includes substantial internal/external rotation. Because substantial internal rotation of the upper arm occurs immediately prior to impact in the tennis serve, we decided to report the combined contribution of upper arm flexion and abduction with respect to racket head speed.

The displacement histories of the 11 digitized markers were filtered using an optimally regularized quintic spline procedure (Woltring, 1986).

Results and Discussion

At impact, a mean velocity of 31.0 m \( \cdot \) s\(^{-1} \) (in a line perpendicular to the baseline toward the opponent: x axis) for the center of the racket head was higher than
the 27.0 m · s⁻¹ reported for the player filmed by Sprigings et al. (1994) and similar to the mean values reported by Elliott et al. (1986) and van Gheluwe and Hebbelinck (1985) for high-performance college and international level players, respectively. The average peak velocity of the center of the racket head (32.9 m · s⁻¹) was recorded a mean 0.005 s prior to impact.

The contribution of trunk rotation along with the forward drive from the lower limbs (see Figure 2, a and b) produced a mean x-direction velocity of 3.0 m · s⁻¹ for the racket shoulder at impact (Table 1). This value, which was reduced from a peak of 3.6 m · s⁻¹ recorded 0.056 s prior to impact, contributed 9.7% to the impact velocity of the center of the racket head. The 3.0 m · s⁻¹ impact velocity for the racket shoulder shows the marginally higher effect of trunk rotation and forward body movement for this group of high-performance players compared to the 2.0 m · s⁻¹ (7.4% contribution: Sprigings et al., 1994), 2.4 m · s⁻¹ (approximate 8% contribution: van Gheluwe & Hebbelinck, 1985), and 2.5 m · s⁻¹ (8% contribution: Elliott et al., 1986) x-direction shoulder velocities at impact. The computed anatomical rotational velocities for the upper arm, forearm, and hand at impact then accounted for the remaining 90% of racket head velocity.

A mean peak angular velocity of 36.5 rad · s⁻¹ was recorded for internal rotation of the upper arm (Figure 2, d–f) just 0.005 s prior to impact (Table 2). This motion contributed 54.2% to the impact linear velocity of the racket head (Table 1). Van Gheluwe et al. (1987) previously identified upper arm inward rotation as a characteristic of a high-velocity serve, and Sprigings et al. (1994)

<table>
<thead>
<tr>
<th>Shoulder and upper limb segment movements</th>
<th>Peak velocity (m · s⁻¹)</th>
<th>Time prior to impact (s)</th>
<th>Impact velocity (m · s⁻¹)</th>
<th>Contribution (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shoulder</td>
<td>3.6 0.3</td>
<td>0.056 0.018</td>
<td>3.0 0.6</td>
<td>9.7 1.8</td>
</tr>
<tr>
<td>Upper arm</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inward rotation</td>
<td>19.0 4.4</td>
<td>0.005 0.004</td>
<td>16.8 4.0</td>
<td>54.2 14.1</td>
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<td>Horizontal flexion and abduction</td>
<td>6.7 1.9</td>
<td>0.013 0.013</td>
<td>4.0 2.1</td>
<td>12.9 5.9</td>
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<tr>
<td>Forearm</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pronation</td>
<td>5.6 2.0</td>
<td>0.060 0.011</td>
<td>1.6 2.4</td>
<td>5.2 4.1</td>
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<tr>
<td>Extension</td>
<td>0.9 1.3</td>
<td>0.036 0.006</td>
<td>−4.4 3.1</td>
<td>−14.2 6.4</td>
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<tr>
<td>Hand</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flexion</td>
<td>12.6 3.5</td>
<td>0.005 0.004</td>
<td>9.5 4.4</td>
<td>30.6 9.1</td>
</tr>
<tr>
<td>Ulnar flexion</td>
<td>0.2 0.8</td>
<td>0.001 0.002</td>
<td>0.2 0.8</td>
<td>0.6 1.2</td>
</tr>
<tr>
<td>Center of racket head</td>
<td>32.9 2.5</td>
<td>0.005 0.003</td>
<td>31.0 1.9</td>
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</tr>
</tbody>
</table>

Note. All values refer to the velocity in the x-direction (the velocity perpendicular to the baseline toward the opponent’s court).
d. Time = 0.120  e. Time = 0.135  f. Time = 0.150 (impact)

Figure 2 — Selected photographs from a service action shot at 200 fps.
Table 2  Maximum and Impact Angular Velocities of the Upper Limb Segments in the Tennis Serve (N = 11)

<table>
<thead>
<tr>
<th></th>
<th>Peak (rad · s⁻¹)</th>
<th>Time prior to impact (s)</th>
<th>Impact (rad · s⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>M</td>
<td>SD</td>
<td>M</td>
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<tr>
<td>Upper arm</td>
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<tr>
<td>Internal rotation</td>
<td>36.5</td>
<td>5.7</td>
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<tr>
<td>Forearm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pronation</td>
<td>16.4</td>
<td>8.2</td>
<td>0.055</td>
</tr>
<tr>
<td>Extension</td>
<td>21.5</td>
<td>3.1</td>
<td>0.040</td>
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<tr>
<td>Hand</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flexion</td>
<td>30.0</td>
<td>10.1</td>
<td>0.006</td>
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<tr>
<td>Ulnar flexion</td>
<td>11.1</td>
<td>23.3</td>
<td>0.003</td>
</tr>
</tbody>
</table>

reported that this movement contributed 30% of the racket head velocity at impact. Chandler, Kibler, Stracener, Ziegler, and Pace (1992), in testing muscle strength and power in a simulated tennis service action, reported 25% higher values for the internal rotator muscles of the upper arm for the preferred compared to the nonpreferred upper limbs. Mont, Cohen, Campbell, Gravare, and Mathur (1994) showed that serving velocity increased by approximately 11% for groups who trained the internal and external rotators of the upper arm either concentrically or eccentrically on an isokinetic machine when compared to a control group, who improved by 1%. Specific training of a segment movement identified as playing a role in the generation of racket speed was therefore shown to be beneficial for performance, although the study did not show that the improved serving velocity was a result of higher internal angular velocity of the upper arm. Internal rotation of the upper arm would therefore appear to be the dominant contributor to racket head velocity at impact in the tennis serve.

Horizontal flexion and abduction (Figure 2, a–c) of the upper arm played a significant (12.9%) yet lesser role in the development of racket head velocity at impact when compared to the influence of internal rotation of the upper arm. The mean linear velocity of 4.0 m · s⁻¹ for these two upper arm movements recorded in this study was less than the 7 m · s⁻¹ reported by Sprigings et al. (1994) for a server of average ability.

Forearm pronation (Figure 2, c–e) about the radioulnar joint and extension (Figure 2, c and d) at the elbow joint also had important, albeit conflicting, influences on racket velocity for impact. A mean peak forearm pronation of 16.4 rad · s⁻¹ was similar in value but occurred earlier in the forward swing phase (0.055 s prior to impact) than was reported by Sprigings et al. (1994). Figure 2e shows that the server who produced the highest racket head velocity had completed most of the pronation action prior to impact. By impact, a mean angular speed of 6.8 rad · s⁻¹ contributed 1.6 m · s⁻¹ (5.2%) to the impact linear velocity of the racket. For 2 of the 11 serves we recorded very small forearm supination values at impact, a characteristic identified by van Gheluwe et al. (1987). Forearm
pronation therefore plays a dual role in developing racket speed prior to impact while also positioning the racket head for impact.

Mean peak forearm angular speed at the elbow joint of 21.5 rad \cdot s^{-1} recorded approximately 0.04 s prior to impact was similar to the 21 rad \cdot s^{-1} reported by Vorobiev, Ariel, and Dent (1993) for Andre Agassi and the 25 rad \cdot s^{-1} reported by Sprigings et al. (1994) for a server of average ability but was less than the peak value of 44.1 rad \cdot s^{-1} reported for British county-level players (Buckley & Kerwin, 1988). At impact, a mean elbow angular speed of 8.3 rad \cdot s^{-1} was less than the 15 rad \cdot s^{-1} (Sprigings et al., 1994) and 27.8 rad \cdot s^{-1} (Buckley & Kerwin, 1988) reported for other high-performance players. It is interesting, however, to note that the 8.3 rad \cdot s^{-1} elbow angular speed had a negative effect on racket head linear velocity, reducing by −14.2% the x-direction velocity of the center of the racket at impact. This negative effect from elbow angular speed was also reported by Sprigings et al. (1994). The explanation for this negative contribution lies in the fact that as the racket head approached ball contact, the upper arm internally rotated to the extent that elbow extension produced a lateral and slightly backward movement of the racket head.

Hand flexion and ulnar flexion at the wrist joint completed the movement sequence. A mean peak hand flexion angular speed of 30.0 rad \cdot s^{-1} recorded 0.006 s prior to impact was reduced to 26.5 rad \cdot s^{-1} at impact. This flexion movement produced a linear velocity for the racket head of 9.5 m \cdot s^{-1} at impact, which represented 30.6% of the final velocity. This important role of hand flexion was previously identified by Jack et al. (1979) and Sprigings et al. (1994) as being a desirable characteristic of the power serve.

Ulner flexion of the hand played only a minor role in the development of racket head velocity. The small angular speed produced a 0.2 m \cdot s^{-1} (0.6%) contributory effect to racket head velocity at impact. These results in general supported data reported by Sprigings et al. (1994).

Conclusions

The computed contributions that each of the anatomical rotations made to racket head velocity clearly reveal that knowledge of a segment’s angular velocity alone is insufficient for assessing the resulting benefits to racket speed. Certainly the mean internal rotation velocity of the upper arm of 33.0 rad \cdot s^{-1} at impact, the highest recorded for any segment, produced the greatest contribution (54.2%) to racket head velocity. However, any increases in forearm extension velocity at impact may produce even greater reductions in the forward movement of the racket than were recorded in this study. Hand flexion, trunk rotation, and upper arm flexion and abduction were also identified as significant contributors to the high-velocity tennis serve.

References


**Acknowledgment**

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