Lower Limb and Trunk Function in the High Performance Tennis Serve

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Abstract: The kinematic interrelationships between the lower limbs, pelvis, trunk, and racquet in the performance of the high velocity tennis serve were investigated for 10 participants using a 12 camera opto-reflective Vicon MX system, operating at 250Hz. The average absolute peak racquet centre velocity was 34.0m·s⁻¹, which is comparable to previous studies using high performance players. Peak vertical linear velocity of the right shoulder was highly correlated with this maximum pre-impact racquet resultant velocity (MRV: r = 0.808, p < .001), yet horizontal velocity of the same shoulder shared no relationship with MRV. The vertical drive of the hitting shoulder was strongly associated with drive from both trunk and lower limbs, in particular on the hitting side. The results highlighted the importance of creating a large upward drive of the hitting shoulder in the high performance tennis serve with contributions from both the trunk and the lower limbs playing key roles.

Keywords: Biomechanics, kinematics, leg drive, tennis serve

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Introduction

The tennis serve is the game’s only closed skill and is widely considered its most important stroke. For these reasons, statistics describing serve performance are the centrepiece of tennis match notation, while in player development the stroke is afforded extensive practice. Research that can guide this practice has focused on general descriptions of predominantly upper limb motion and the contributions of select anatomically based movements to racquet velocity (Bahamonde, 1997; Elliott, Marsh, & Blanksby, 1986; Elliott, Marshall, & Noffal, 1995; Sprigings, Marshall, Elliott, & Jennings, 1994). Investigative efforts of lower limb involvement in the serve have preferentially attended to the effect of different types of foot placement and/or “drive phase” knee joint kinematics on various aspects of serving technique (Elliott & Wood, 1983; Bahamonde & Knudson, 2001).

In analysing skill, most biomechanists believe that the observation phase of the analysis process begins at the link between the floor, or court, and the feet (Elliott & Knudson, 2003). It therefore stands to reason that an understanding of the role of the lower limbs in sports movements is essential. More particularly, the linking of “lower limb drive” to pelvis motion and subsequently to trunk rotation is integral to the successful performance of the tennis serve and virtually all other dynamic sporting skills. While the importance of three-dimensional (3D) trunk rotation to the high performance serve has been well established (Bahamonde, 2000), the role of the lower limb and pelvis movements have yet to be investigated.

Therefore, where previous research has described the kinetics and kinematics of selected segments or calculated specific segmental contributions to the serve, the aim of the present study was to examine associations between lower limbs, pelvis, trunk, and racquet kinematics in high performance service actions, which may be monitored from a coaching perspective. Increased knowledge about these areas of the service technique will lead to more informed and therefore more effective coaching and improved player development in this key aspect of the game.

Methods

Participants

Ethics were approved by the Ethics in Human Research Committee at the University of Western Australia. Ten high performance male tennis players with a mean age of 21.7 years (± 3.2), possessing efficient service techniques as described by three high-performance coaches, participated in this study. Mean player height and mass were 183.0 cm (±5.7) and 80.2 kg (±5.1), respectively. All players used the “foot-up” technique (Elliott & Wood, 1983) in their service actions.

Data Acquisition

A Vicon MX opto-reflective motion analysis system with 12 near infrared cameras (Vicon, Oxford Metrics group, UK) operating at 250 Hz recorded the service actions on a tennis court, partially housed within a laboratory environment. Forty-five retro-reflective markers, 16 mm in diameter, were affixed to the racquet, head, thorax, pelvis, and upper and lower limbs at the locations shown in Figure 1. The biomechanical model consisted of two marker sets: the static calibration marker set and the serving marker set, a subset of the static
set. Thirty-seven markers, inclusive of eight “T-bar” three-marker clusters, were affixed to the participants during service trials. The remaining markers identified the position of key anatomical landmarks required for the definition of segment anatomical coordinate systems that were defined in accordance with the standards outlined by the International Society of Biomechanics (Wu & Cavanagh, 1995). These markers were located bilaterally on the medial and lateral ankle malleoli, ulnar and radial styloid processes, and anterior and posterior aspects of the shoulder in line with the estimated glenohumeral joint centres. A calibrated anatomical systems technique (Cappozzo, Catani, Della Croce, & Leardini, 1995) was employed to identify the virtual 3D position of the left and right femoral epicondyles with reference to the technical coordinate systems (TCSs) of marker clusters located on the thighs. This technique was adopted to minimise the error associated with excessive skin movement artefact (Cappozzo et al., 1995). The manufacturer’s (Vicon) generic calibration procedures were used to calibrate the volume and to linearise all 12 cameras. The 3D joint angles were calculated according to the Euler flexion and extension, abduction and adduction, and internal and external convention proposed by Grood and Suntay (1983).

Figure 1. Anterior (a) and posterior (b) views of customised lower limb, pelvis, and trunk marker set.

Testing

Upon arrival, informed consent was obtained from participants and anthropometrical measurements were recorded. Prior to the dynamic service trials, participants were allowed as many warm-up serves as required. Players then performed six “flat first serves” over a net at a target area (1m x 1m) located in the centre corner of the deuce or ad courts depending on the dominant hand of the server (i.e., right-handed players served to the left, or deuce, service court). Serves were required to land within this 1 m x 1 m area, with high velocity (within 5% of their typically recorded match level as indicated by the player) to be considered successful. For simplicity, the serve is discussed as if all players were right-handed.

Data Processing and Analysis

Marker coordinate data were labelled and broken trajectories of less than five frames were interpolated using a cubic spline. Data from the three highest velocity trials were then
filtered using a GCVSPL routine (Woltring, 1986) in Vicon Workstation software. Data were filtered using a mean squared error of 25 as determined by residual analysis (Winter, 1990). Data comprising the phase from the commencement of the swing to one frame pre-impact were time normalised to 101 points and exported to Microsoft Excel.

The vertical and horizontal linear velocities for the right shoulder joint centre, right shoulder joint centre relative to right hip joint centre (a comparative velocity measure at each time point), left hip joint centre, and right hip joint centre were calculated over the service action. The lowest vertical displacement of the right shoulder during the backswing phase and the highest vertical displacement of the right shoulder during the forward swing phase of the service action were also identified. These values were then normalised to each participant's height to allow for computation of a relative, vertical linear distance (between low and high positions of right shoulder), referred to as the vertical displacement range of the right shoulder. The same procedure was carried out to obtain the lowest and highest displacement positions for the right hip joint centre.

![Figure 2. A player near the lowest (a) and highest (b) point of the serve, showing the vertical position of the right hip joint centre (A), right shoulder joint centre relative to right hip (B) and right shoulder joint centre (C).](image)

Pearson correlations were calculated to investigate general associations between all hip and shoulder variables (Tables 1–3) using SPSS for Windows (Version 12.0) software. Prior visual inspection of the data confirmed the presence of no non-linear relationships. A minimum significance level of $p < 0.05$ was established a priori for all analyses.

**Results**

Mean data were generated from three serves, which is consistent with the number of trials recommended by Mullineaux, Bartlett, and Bennett (2001) to accurately represent
movement mechanics. The average maximum resultant pre-impact velocity (MRV) of the racquet centre for the three trials of the 10 players analysed was 34.0 m∙s⁻¹ (±2.50).

Peak vertical linear velocity of the right shoulder (3.4 m∙s⁻¹) was highly correlated with MRV (r = 0.808, p < .001), yet horizontal velocity of the same shoulder (4.1 m∙s⁻¹) shared no significant relationship (r = 0.52) with MRV. Variables that would logically influence the upward drive of the right shoulder as well as have practical significance to coaches were therefore chosen for further analysis (Table 1). Both the peak right shoulder to hip relative vertical velocity as well as the vertical velocity of the right hip were found to share strong relationships with the peak vertical velocity of the right shoulder during the forward swing.

Table 1

<table>
<thead>
<tr>
<th>Correlates with Right Shoulder Vertical Velocity</th>
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<tbody>
<tr>
<td>Variable</td>
</tr>
<tr>
<td>Peak Right Hip Vertical Linear Velocity (m∙s⁻¹)</td>
</tr>
<tr>
<td>Peak Left Hip Vertical Linear Velocity (m∙s⁻¹)</td>
</tr>
<tr>
<td>Peak Right Shoulder to Right Hip Relative Vertical Velocity (m∙s⁻¹)</td>
</tr>
<tr>
<td>Right Shoulder Minimum Vertical Position (cm)^</td>
</tr>
<tr>
<td>Right Shoulder Maximum Vertical Position (cm)^</td>
</tr>
<tr>
<td>Right Shoulder Vertical Displacement Range (cm)</td>
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</tbody>
</table>

*Significance p < 0.05
**Significance p < 0.01
^Relative to participants standing height

While the vertical displacement range of the right shoulder was significantly correlated (r = 0.654) with peak right shoulder vertical velocity, both the lowest right shoulder position during the backswing and the highest vertical right shoulder position during the forward swing did not report an association. That is, the total distance through which the right shoulder travelled (46.7 ± 7 cm), rather than just the lowest or highest vertical position attained alone, permitted a peak vertical right shoulder velocity (3.4 m∙s⁻¹) to be developed. Right hip as well as right shoulder relative to right hip displacement were also analysed (Tables 2 and 3) to provide insight into possible relationships between hip and shoulder kinematics and lower limb and trunk drive. This analysis revealed similar results to the shoulder, with strong associations between vertical hip velocity and vertical hip displacement range reported.
In encouraging players to develop high racquet velocities, coaches can often be heard highlighting the value or need for players to “drive their back hip forcefully upwards” or to “rotate the trunk” at the commencement of the service action. In placing these words in context, coaches will invariably reference (or critique) the horizontal or vertical progression of the trunk’s endpoint—the hitting shoulder—to arrive at an initial diagnosis and garner an appreciation of service improvement. Conceptually, it makes sense to consider the relationships that vertical and horizontal shoulder drive share with racquet velocity; however, there are limitations inherent to this approach given the sophisticated neuromuscular coordination that underpins stroke production. Despite this qualification, the importance of such pedagogical and observational trunk motion feedback by coaches (particularly of the hip and shoulder) is key in facilitating the serve’s analysis or instruction.

The MRV recorded in the current study of 34.0 m∙s⁻¹ was similar to that reported to characterise the flat serves of other high performance male players (35 m∙s⁻¹; Elliott et al., 1986). As described above and with the support of past research (Bahamonde, 2000), coaches teach trunk rotation as being a primary contributor to the development of serve velocity. Devoid of multiple high-speed cameras to accurately appraise the involvement of the trunk, these same coaches “use their eyes” to critique the speed and trajectory of the trunk movements during the serve. In other words, they attend to the horizontal and

**Discussion**

Table 2

*Correlates with Right Shoulder to Hip Relative Vertical Velocity*

<table>
<thead>
<tr>
<th>Variable</th>
<th>Correlation (r)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Right Hip Minimum Vertical Displacement (cm)</td>
<td>0.525</td>
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<tr>
<td>Right Hip Maximum Vertical Displacement (cm)</td>
<td>0.052</td>
</tr>
<tr>
<td>Right Hip Vertical Range (cm)</td>
<td>0.845**</td>
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</table>

**Significance p < 0.01**

Table 3

*Correlates with Right Hip Vertical Velocity*

<table>
<thead>
<tr>
<th>Variable</th>
<th>Correlation (r)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Right Hip Minimum Vertical Displacement (cm)</td>
<td>0.229*</td>
</tr>
<tr>
<td>Right Hip Maximum Vertical Displacement (cm)</td>
<td>0.661*</td>
</tr>
<tr>
<td>Right Hip Vertical Range (cm)</td>
<td>0.876**</td>
</tr>
</tbody>
</table>

*Significance p < 0.05

**Significance p < 0.01**
vertical advance (velocity) of the trunk and, more specifically, the segment end points—shoulder and hip—as a surrogate means of assessing how well players rotate their hips and shoulders. To this end, the findings of this study are of interest, particularly as the vertical but not horizontal drive of the hitting shoulder was shown to significantly and positively relate to MVR. Previously, Elliott et al. (1986) suggested that a greater upward drive of the hitting shoulder drives the racquet downward, eccentrically stretching the racquet arm’s internal rotator musculature, therefore heightening the potential for MVRs. It is likely that the forward rotation of the racquet shoulder in combination with the above also contributes to the creation of MVR, and thus coaches should continue to instruct players to adopt an “up and out” racquet trajectory.

A strong relationship between the upward vertical drive of the right shoulder and the peak vertical velocity of the right shoulder relative to the hip suggests that the trunk plays an important role in the upward drive of the shoulder endpoint. This supports findings of Bahamonde (2000) who highlighted the importance of “shoulder-over-shoulder” trunk rotation as the critical technique feature that differentiated service speed and the transference of angular momentum from the trunk to the racquet arm.

A strong relationship was also found between the peak vertical velocity of the right hip and that of the right shoulder, supporting the mainly anecdotal evidence to date, which asserts that the lower limb plays a key role in creating vertical drive during the serve. It is also important to note that there was a significant positive relationship between the left hip peak vertical velocity and the upward drive of the right shoulder. The relationship, however, was weaker than that found between the hitting side shoulder and right hip despite the two being attached to the same semirigid segment (the pelvis). Coaches often consider the front lower limb as key in lower limb drive because this limb generally supports a larger proportion of a player’s body weight. However, as the back leg corresponds to the racquet side, this limb must also play an equally if not more important role in significantly contributing to an upward and forward drive of the trunk.

The right shoulder kinematic profile, when expressed relative to the right hip joint centre, showed a strong relationship between vertical displacement of the trunk and peak vertical velocity of the shoulder. However, there was no such relationship between the minimum vertical displacement at either the right shoulder relative to hip or the right hip and peak vertical velocity of the same endpoint. Consequently the achievement of lower positions during the backswing does not appear to guarantee more powerful drives during the forward swing.

**Conclusion**

The results of this study highlight the importance of several lower limb and trunk variables to successful high velocity serve performance, which are practically significant to coaches. Specifically, a greater upward vertical drive of the right shoulder during the forward swing is associated with a higher peak racquet velocity. In creating this vertical drive to the hitting shoulder, drive from the lower limbs as well as the trunk have important roles to play. Coaches and sport scientists working in athlete development must emphasise the role of the back leg drive and its contribution to vertical shoulder velocity in the tennis serve. This may lead to the creation of the critical “shoulder-over-shoulder” trunk rotation, a key characteristic of the high performance serve.
References


