A kinematic comparison of successful and unsuccessful tennis serves across the elite development pathway

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ABSTRACT

While velocity generation is an obvious prerequisite to proficient tennis serve performance, it is also the only stroke where players are obliged to negotiate a unique target constraint. Therefore, the dearth of research attending to the accuracy component of the serve is surprising. This study compared the body, racquet and ball kinematics characterising successful serves and service faults, missed into the net, in two groups of elite junior female players and one professional female tennis player. Three-dimensional body, racquet and ball kinematics were recorded using a 22-camera VICON motion analysis system. There were no differences in body kinematics between successful serves and service faults, suggesting that service faults cannot be attributed to a single source of biomechanical error. However, service faults missing into the net are characterized by projection angles significantly further below the horizontal, implying that consistency in this end-point parameter is critical to successful performance. Regulation of this parameter appears dependent on compensatory adjustments in the distal elbow and wrist joints immediately prior to impact and also perceptual feedback. Accordingly, coordination of the distal degrees of freedom and a refined perception-action coupling appear more important to success than any isolated mechanical component of the service action.
1. Introduction

During each of the 2011 and 2012 WTA tour seasons, the average percentage of first service points won among the ten leaders in this statistic was 71% (WTA, 2012, 2013). Comparatively, the equivalent average for the top ten leaders in percentage of second service points won was a mere 50%. This disparity implies that, conservatively, a player on the WTA tour is approximately 40% more likely to win a point on their first serve compared with their second serve. In light of this fact, the practical and research attention afforded to the first (generally accepted as a ‘flat’ or ‘power’) serve is understandable.

Biomechanical research has helped to decipher the critical mechanical contributors to racquet velocity in the male first serve (Bahamonde, 2000; Sprigings, Marshall, Elliott, & Jennings, 1994; Tanabe & Ito, 2007), offering coaches instructional direction. While velocity generation is critical to flat serve performance, the unique target constraint (the service box) placed on the stroke necessitates the preservation of an accuracy component. A paucity of research has attended to the preservation of accuracy in the flat serve, wherein ascertaining the common mechanical derivatives of service faults may aid coaches as they endeavour to develop serve performance.

To date, research evaluating serve kinematics with respect to serve outcome has been rather sparse. However, a previous appraisal body kinematics with respect to serve outcome found no differences in ankle, shoulder and elbow angles between successful and unsuccessful serves before, at or after impact (Göktepe, Ak, Söğüt, Karabörk, & Korkusuz, 2009). Unfortunately, this study did not delimit the definition of an unsuccessful serve. Consequently, by grouping all misses (net, long and wide) together, it is likely that more relevant findings were concealed. Further, the study failed to consider several kinematic variables critical to serve performance such as leg drive contribution (Elliott, Fleisig, Nicholls, & Escamilla, 2003) as well as trunk (Bahamonde, 2000) and wrist kinematics (Elliott, Marshall, & Noffal, 1995; Tanabe & Ito, 2007). There was also no attempt to evaluate the end-point parameters (i.e., ball velocity, projection angle and impact location), that ultimately determine the ball trajectory in projectile skills (Kudo, Tsutsui, Ishikura, Ito, & Yamamoto, 2000). A more directed investigation, encompassing specific joint kinematics, as well as end-point parameters would appear to provide a logical extension to this line of research.

Historically, biomechanics research has examined discrete kinematics in the manner of Göktepe et al. (2009). However, founded in the dynamical systems theory, there is now a general appreciation that movement variability and inter-joint coordination play equally important roles in the execution of assorted movement skills (Bartlett, Wheat, & Robins, 2007). Previous work has examined variability in table tennis (Bootsma & van Wieringen, 1990), free throw shooting in basketball (Mullineaux & Uhl, 2010) and underarm throwing (Dupuy, Mottet, & Ripoll, 2000; Kudo et al., 2000). Despite the apparent mechanical disparity between these skills, their critical end-point parameters, such as distal segment (i.e., hand) trajectory, as well as release speed and projection angle of the ball displayed small variability. Bootsma and van Wieringen (1990) proposed a ‘funnel-like’ control pattern of the critical end-point parameter in table tennis (bat direction), wherein movements progressed from gross and imprecise at initiation of the drive to precise at impact. There is also some evidence to suggest that coupling perception and action may augment this process. For example, servers in volleyball (Davids, Kingsbury, Bennett, & Handford, 2001) and tennis (Reid, Whiteside, & Elliott, 2010), as well as batters in cricket (Renshaw, Oldham, Davids, & Golds, 2007) and baseball (Katsumata, 2007) have all been shown to use the position of the incoming ball to regulate consistent temporal execution of their movements. In other words, external information is used as a reference against which players continuously calibrate their mechanics to ensure that desired end-point parameters are consistently attained.

The high consistency of the end-point parameters infers that these are the critical aspects of projectile skills, whose impropriety may compromise task success. Indeed, a consistent projection angle and release speed is considered critical to the successful execution of tennis groundstrokes (Knudson & Blackwell, 2005) and basketball shooting (Mullineaux & Uhl, 2010). By comparison, the distal joint mechanics controlling these end-point parameters are far more variable around the terminal aspect of the skill (i.e., impact/release) (Button, MacLeod, Sanders, & Coleman, 2003; Knudson, 1990). The general interpretation of this disparity is that mechanical variability toward the end of a skill represents
functional compensation (or adjustments) in the distal joints that maintains consistency in the critical end-point parameters. Therefore, serve success is expectedly contingent on a consistent projection angle and ball speed, and less dependent on repeatable distal joint mechanics. However, it has been suggested that variability is only functional within a defined ‘window’ (Dierks & Davis, 2007; Knudson & Blackwell, 2005), deviation from which results in unsuccessful performance (Mullineaux & Uhl, 2010). Therefore, surplus variability in coordinative elbow-wrist mechanics prior to impact may also be seen as a potential source of service faults. The credence of functional variability portrayed in this work presents an interesting paradox between science and practice, as coaches place immense importance on developing a consistent service action (Bollettieri, 2001; Galloway, 2011; Moran, 2006; Saviano, 2003; Smith, 2004; Taylor, 2000; White, 2010).

While the practical emphasis on mechanical consistency seems illogical, so too does the lack of age-specific instruction in tennis. Whether due to the lack of scientific guidance or otherwise, junior instruction is often based on what can be observed from ‘benchmark’ professional models. This philosophy seems inconsistent with both the contention that physicality constrains performance (Haywood & Getchell, 2008; Newell, 1986) and also recent work confirming that serve mechanics change during development (Whiteside, Elliott, Lay, & Reid, in press). With this work advocating development to induce performance changes, the source of service faults may also be expected to change over time. Specifically, where inexperienced performers are thought to restrain degrees of freedom in early learning, developing players may be expected to possess less compensatory potential (Whiteside, Lay, Elliott, & Reid, submitted for publication). Therefore, serve success may be more closely related to differences in isolated joint mechanics, as the potential for correcting these errors is limited in developing movement systems. Regardless, research describing the evolution of service faults would equip junior coaches with the information necessary to tailor appropriate age-specific instruction.

The importance of stabilizing critical end-point parameters is well established in the literature (Dupuy et al., 2000; Kudo et al., 2000), the regulation of which depends on compensatory joint mechanics (Button et al., 2003; Davids, Glazier, Araujo, & Bartlett, 2003; Robins, Wheat, Irwin, & Bartlett, 2006). Historically, these notions have received attention primarily in analyses of successful performance. Coaching texts in tennis often refer to their importance, even going so far to say that service faults are caused by errant spatial impact locations (Bryant, 2003). Such claims can be evaluated by considering successful and unsuccessful performance together in order to identify discrepancies therein. Further, the motor control literature advocates an expectation for performance (and thus, the source of service faults) to change across development. In an effort to better equip elite coaches, this study aimed to determine the mechanical source of service faults by comparing the body, racquet and ball kinematics characterizing successful and unsuccessful serves in two elite junior groups and one professional female tennis player. It is expected that serve success will be most contingent on the critical end point parameters – ball speed, projection angle and impact height. Additionally, relative distal joint mechanics will be more concerned with compensatory function and will therefore not prove repeatable, even in successful serves. Developmentally, younger players’ isolated joint mechanics may differentiate serve outcome as novice movement systems are less adept at correcting for mechanical errors.

2. Methods

2.1. Participants

Eleven elite female tennis players were recruited to participate in this study, which was approved by the University of Western Australia’s (UWA) Human Ethics Committee. Participants were categorized as pre-pubescent, pubescent or adult based on age and menstrual development (as determined by a confidential questionnaire) (Table 1). The two younger categories comprised groups 1 (G1) and 2 (G2) respectively, where players possessed a top 5 Australian ranking for their age group at the time of testing. The adult category was delimited to one player (PRO), who possessed a WTA ranking of 4 at the time of testing. Her success (Grand Slam Championships: 1 singles, 2 doubles, 2 mixed doubles), service statistics (during the WTA Tour season in which testing occurred, she ranked inside the top 10 in aces, service games won and points won on first serve) and recommendations from Tennis
Australia’s High Performance Coaching Group, suggested that her service technique provided an ideal benchmark for female players. Since this study intended to investigate the most proficient servers accessible, the potential for less accomplished servers to dilute her results was prevented by delimiting the adult sample to a single case.

2.2. Protocol

The testing protocol was performed on a full size tennis court constructed at the Australian Institute of Sport indoor biomechanics laboratory. The UWA full body marker set (Besier, Sturnieks, Alderson, & Lloyd, 2003; Chin, Elliott, Alderson, Lloyd, & Foster, 2009; Lloyd, Alderson, & Elliott, 2000) guided the affixation of sixty retro-reflective markers (14 mm diameter) to each player’s body. Ultra-light foam hemispherical markers (radius 7 mm), were placed in three locations on each of the racquet and ball to track kinematics therein. A 10-min warm up with movement (5 min) and serving (5 min) components preceded the testing protocol wherein players performed maximal effort first serves, aiming for a 1x1 m target bordering the T of the service box (right-handers: deuce court; left-handers: advantage court). Five sets of eight serves (for a total of 40 serves) were performed with a 2-min rest period separating successive sets. A 22-camera VICON MX system (VICON Motion Systems, Oxford, UK) operating at 500 Hz tracked three-dimensional (3D) marker trajectories. The junction of the baseline and center mark represented the origin of the global coordinate system, in which positive x pointed rightward along the baseline, positive y pointed to the net and positive z pointed up. The five fastest serves landing in the target area were analyzed as successful serves while the five fastest service faults that missed into the net were analyzed as unsuccessful serves.

2.3. Data treatment

A cubic spline was used to interpolate gaps that existed in the marker trajectories before second-order polynomial extrapolation estimated marker trajectories at impact (Knudson & Bahamonde, 2001; Reid, Campbell, & Elliott, 2012). The data were subsequently filtered using a Woltring filter (Woltring, 1986) where the optimal mean squared error of 2 mm was determined by a residual analysis. Filtered data were then modeled using the UWA full body, racquet and ball models (Besier et al., 2003; Chin et al., 2009; Lloyd et al., 2000; Whiteside, Chin, & Middleton, 2013) to produce kinematic outputs. To maximize accuracy, resultant ball velocity and projection angle were obtained by modeling the raw ball data (Linthorne & Patel, 2011). The ball projection angle was measured as the angular excursion from the horizontal of the vector connecting the ball origin at impact and 10 frames thereafter. Joint rotations were expressed using the Euler zxy sequence, except at the shoulder where a yxy decomposition was used in accordance with the International Society of Biomechanics recommendation. In order to preserve consistency in the statistical analyses, kinematics for the single left-handed player in the study were inverted where appropriate such that all players could be considered together as right-hand dominant.

2.4. Variables and events of interest

The service action was deemed to begin at the instant of ball release from the hand (Fig. 1). Trophy position represented the first peak vertical displacement of the racquet, while the subsequent nadir of vertical racquet displacement was the racquet low point. The time period from racquet low point to
impact was referred to as the ‘forwardswing duration’ and was recorded to gauge time to contact akin to previous work (Bootsma & van Wieringen, 1990).

The variables of interest included several lower, limb, trunk and serving arm kinematics considered to be critical to serve performance (Elliott, 2006; Kibler & van der Meer, 2001). The orientation of the racquet at impact was expressed by its rotation about the global $x$ (backward tilt), $y$ (lateral tilt) and $z$ (polar rotation) axes. Regarding higher order kinematics, linear velocities of the racquet about the three global axes were measured alongside resultant racquet velocity. Consistent with previous descriptions of the tennis serve, the 3D ball position at impact was expressed relative to the first metatarsal of the front foot (Reid, Whiteside, & Elliott, 2011).

Previous work has identified the role of elbow (radio-ulnar) pronation and wrist flexion in orientating the racquet appropriately for impact (Elliott, 2006; Elliott, Reid, & Crespo, 2003). Therefore, the relative motion of these movements was depicted in angle-angle plots during forwardswing, effectively illustrating coordination of the elbow and wrist prior to impact. From these traces, the coefficient of correspondence (CoC) provided a quantitative measure of mechanical variability between 0 and 1 ($0 = \text{no variability}; \ 1 = \text{maximum variability}$) at each event of the serve. The mean CoC curve over the duration of the serve was then calculated for each group and is depicted in Fig. 2. Differences in the CoC, at impact, were determined using a mixed analysis of variance. To gauge the intra-individual consistency of ball toss, the 3D ($X_r$, $Y_r$ and $Z_r$) standard deviations of ball displacement at impact

**Fig. 1.** Key events and phases of the tennis serve.
were calculated for each player and then averaged within groups. The product of these mean values \((X_r \times Y_r \times Z_r)\) provided an ‘impact volume’ that denoted the 3D spatial variability of the impact location.

2.5. Statistical analyses

The single participant in the adult category prevented the application of traditional statistical analyses in this study. Consequently, primary statistical analyses were only performed on the two younger groups using a mixed/split plot ANOVA to determine within group (i.e., successful vs. unsuccessful serves), between group (i.e., G1 vs G2) and interaction effects (i.e., group × serve outcome). To account for the multiple comparisons, statistical significance was fixed a priori at \(p < .01\). The interpretation of these results with respect to the PRO was descriptive.

3. Results

3.1. Discrete kinematics

There were no significant differences in body kinematics between successful and unsuccessful serves in G1 or G2 (see Table 2). The same was true for the ball and racquet kinematics at impact, which did not discriminate successful and unsuccessful serves. The PRO exhibited similar kinematic homogeneity between conditions. Expectedly, projection angle significantly discriminated the two conditions whereby a smaller projection angle was related to service faults hit into the net (Table 3). Irrespective of serve outcome, the projection angle \((F(1,8) = 30.281, p = .001)\) and racquet velocity...
### Table 2
Mean and standard deviation (SD) discrete body kinematics in successful serves (good) and service faults missing into the net (fault).

<table>
<thead>
<tr>
<th>Unit</th>
<th>Good</th>
<th>Fault</th>
<th>G₂</th>
<th>Fault</th>
<th>WG</th>
<th>BG</th>
<th>Int</th>
<th>G₁</th>
<th>Fault</th>
<th>PRO</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean ± SD</td>
<td>Mean ± SD</td>
<td>Mean ± SD</td>
<td>Mean ± SD</td>
<td>p</td>
<td>p</td>
<td>p</td>
<td>Mean ± SD</td>
<td>Mean ± SD</td>
<td>Mean ± SD</td>
</tr>
<tr>
<td><strong>Preparation</strong></td>
<td></td>
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</tr>
<tr>
<td>Peak Separation θ</td>
<td>deg</td>
<td>−29 ± 8</td>
<td>−31 ± 7</td>
<td>−23 ± 6</td>
<td>−23 ± 7</td>
<td>.498</td>
<td>.164</td>
<td>.452</td>
<td>−25 ± 3</td>
<td>−23 ± 2</td>
</tr>
<tr>
<td>Peak Trunk Tilt θ</td>
<td>deg</td>
<td>34 ± 7</td>
<td>28 ± 11</td>
<td>46 ± 8</td>
<td>38 ± 11</td>
<td>.185</td>
<td>.005*</td>
<td>.893</td>
<td>−44 ± 1</td>
<td>47 ± 3</td>
</tr>
<tr>
<td>Peak External Rotation θ</td>
<td>deg</td>
<td>−152 ± 32</td>
<td>−153 ± 32</td>
<td>−138 ± 12</td>
<td>−147 ± 26</td>
<td>.302</td>
<td>.552</td>
<td>.448</td>
<td>−139 ± 1</td>
<td>−138 ± 3</td>
</tr>
<tr>
<td><strong>Propulsion</strong></td>
<td></td>
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</tr>
<tr>
<td>Front Hip Vertical Velocity</td>
<td>m.s⁻¹</td>
<td>1.29 ± 0.18</td>
<td>1.30 ± 0.21</td>
<td>1.55 ± 0.23</td>
<td>1.57 ± 0.30</td>
<td>.563</td>
<td>.102</td>
<td>.911</td>
<td>1.62 ± 0.04</td>
<td>1.69 ± 0.06</td>
</tr>
<tr>
<td>Back Hip Vertical Velocity</td>
<td>m.s⁻¹</td>
<td>1.76 ± 0.25</td>
<td>1.78 ± 0.27</td>
<td>2.02 ± 0.22</td>
<td>2.04 ± 0.26</td>
<td>.591</td>
<td>.129</td>
<td>.995</td>
<td>2.29 ± 0.04</td>
<td>2.39 ± 0.06</td>
</tr>
<tr>
<td>Peak Shldr-over-shldr ω</td>
<td>deg.s⁻¹</td>
<td>−662 ± 51</td>
<td>−678 ± 34</td>
<td>−677 ± 36</td>
<td>−671 ± 37</td>
<td>.509</td>
<td>.889</td>
<td>.152</td>
<td>−705 ± 14</td>
<td>−702 ± 8</td>
</tr>
<tr>
<td>Peak Trunk Twist ω</td>
<td>deg.s⁻¹</td>
<td>817 ± 59</td>
<td>832 ± 33</td>
<td>692 ± 78</td>
<td>751 ± 136</td>
<td>.337</td>
<td>.034</td>
<td>.563</td>
<td>570 ± 128</td>
<td>515 ± 55</td>
</tr>
<tr>
<td>Peak IR ω</td>
<td>deg.s⁻¹</td>
<td>1660 ± 211</td>
<td>1450 ± 362</td>
<td>2113 ± 282</td>
<td>1937 ± 449</td>
<td>.143</td>
<td>.029</td>
<td>.089</td>
<td>2594 ± 225</td>
<td>2429 ± 441</td>
</tr>
<tr>
<td>Peak Elbow Extension ω</td>
<td>deg.s⁻¹</td>
<td>−1365 ± 209</td>
<td>−1435 ± 267</td>
<td>−1563 ± 183</td>
<td>−1626 ± 211</td>
<td>.093</td>
<td>.186</td>
<td>.916</td>
<td>−1365 ± 33</td>
<td>−1378 ± 38</td>
</tr>
<tr>
<td>Peak Wrist Flexion ω</td>
<td>deg.s⁻¹</td>
<td>1170 ± 342</td>
<td>992 ± 210</td>
<td>1764 ± 446</td>
<td>1568 ± 358</td>
<td>.213</td>
<td>.009*</td>
<td>.948</td>
<td>1613 ± 615</td>
<td>1434 ± 312</td>
</tr>
<tr>
<td><strong>At Impact</strong></td>
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<tr>
<td>Shoulder Abduction θ</td>
<td>deg</td>
<td>92 ± 9</td>
<td>101 ± 6</td>
<td>106 ± 8</td>
<td>105 ± 9</td>
<td>.176</td>
<td>.088</td>
<td>.126</td>
<td>108 ± 2</td>
<td>109 ± 3</td>
</tr>
<tr>
<td>Elbow Flexion θ</td>
<td>deg</td>
<td>44 ± 13</td>
<td>44 ± 17</td>
<td>33 ± 5</td>
<td>30 ± 5</td>
<td>.293</td>
<td>.102</td>
<td>.368</td>
<td>39 ± 2</td>
<td>40 ± 3</td>
</tr>
<tr>
<td>Shoulder Facing θ</td>
<td>deg</td>
<td>117 ± 6</td>
<td>104 ± 15</td>
<td>93 ± 15</td>
<td>91 ± 11</td>
<td>.132</td>
<td>.019</td>
<td>.216</td>
<td>81 ± 4</td>
<td>78 ± 5</td>
</tr>
<tr>
<td>Trunk Tilt θ</td>
<td>deg</td>
<td>−24 ± 10</td>
<td>−33 ± 17</td>
<td>−38 ± 10</td>
<td>−38 ± 11</td>
<td>.284</td>
<td>.198</td>
<td>.268</td>
<td>−48 ± 4</td>
<td>−47 ± 3</td>
</tr>
<tr>
<td><strong>Temporal</strong></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Forwardswing Duration</td>
<td>s</td>
<td>0.14 ± 0.02</td>
<td>0.16 ± 0.01</td>
<td>0.12 ± 0.01</td>
<td>0.12 ± 0.01</td>
<td>.028</td>
<td>.001*</td>
<td>.074</td>
<td>0.12 ± 0.01</td>
<td>0.12 ± 0.01</td>
</tr>
</tbody>
</table>

θ: Angle; ω: Angular Velocity; WG: Within groups effect (i.e., good vs fault); BG: Between groups effect (i.e., G₁ vs G₂); Int: Interaction effect (i.e., serve outcome × group). *: significant (p < .01).
(F(1, 8) = 75.716, p < .001) were both significantly greater and lower, respectively in G1 compared with G2. Racquet velocity in the PRO (49.1 m·s⁻¹) was notably larger than both younger groups in both conditions. Service faults appeared to be associated with a longer forward-swing duration in G1, although the same could not be said for G2 (F(1, 8) = 24.811, p = .001).

### 3.2. Serving Arm Variability

Fig. 2 depicts the mean CoC of relative elbow-wrist motion for G1, G2 and the PRO throughout the duration of the forward swing. The variability in relative elbow-wrist motion appeared to increase markedly in the immediate prelude to impact in both successful and unsuccessful serves, in all groups (note the steep increases in the gradients prior to impact). A main effect for serve outcome was noted at impact (F(1, 8) = 20.327, p = .002), indicating that the CoC (i.e., variability) at this time point was significantly greater in successful serves compared with faults. Qualitative interpretation of the PRO curve revealed that variability in her serving arm was similar to what was observed in the younger groups.

### 4. Discussion

The increased likelihood of winning a point on the first serve, as compared to the second serve, seemingly justifies the attention this stroke is afforded in training environments. Ascertain the mechanical causes of first service faults seems the most intuitive step toward helping players improve their first serve percentage and, in turn, increase their likelihood of holding serve. With research showing that serve mechanics evolve during development (Whiteside et al., in press), it follows that the source of faults may also change over time. Understanding this process would extend the applications beyond professional players and aid the cultivation of proficient servers. The present study supports previous contentions that service faults cannot be traced back to any single mechanical variable and extends this assertion across three stages of development. Due to the spatial variability of the ball toss, inter-joint coordination appears an equally critical facet of serve performance at all ages. Ultimately, serve outcome appears most closely related to the projection angle of the ball in all players.

### Table 3
Mean and standard deviation (SD) ball and racquet kinematics at impact and end-point parameters for successful serves and service faults missing into the net (fault).

<table>
<thead>
<tr>
<th>Unit</th>
<th>G1 Good Mean ± SD</th>
<th>G1 Fault Mean ± SD</th>
<th>W G p</th>
<th>B G p</th>
<th>Int p</th>
<th>G2 Good Mean ± SD</th>
<th>G2 Fault Mean ± SD</th>
<th>p p p</th>
<th>PRO Good Mean ± SD</th>
<th>PRO Fault Mean ± SD</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Racquet</strong></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Backward Tilt °</td>
<td>deg 13 ± 2</td>
<td>13 ± 2</td>
<td></td>
<td></td>
<td></td>
<td>10 ± 1</td>
<td>10 ± 2</td>
<td>.830</td>
<td>.027</td>
<td>.488</td>
</tr>
<tr>
<td>Lateral Tilt °</td>
<td>deg -8 ± 8</td>
<td>-5 ± 8</td>
<td>-19 ± 6</td>
<td>-17 ± 7</td>
<td></td>
<td>.015</td>
<td>.039</td>
<td>.233</td>
<td>.31 ± 4</td>
<td>-31 ± 5</td>
</tr>
<tr>
<td>Polar Rotation °</td>
<td>deg 9 ± 2</td>
<td>7 ± 3</td>
<td>15 ± 2</td>
<td>13 ± 2</td>
<td></td>
<td>.087</td>
<td>.001*</td>
<td>.815</td>
<td>19 ± 4</td>
<td>20 ± 6</td>
</tr>
<tr>
<td>X Velocity m.s⁻¹</td>
<td>-2 ± 4</td>
<td>-1 ± 4</td>
<td>3 ± 2</td>
<td>3 ± 2</td>
<td></td>
<td>.365</td>
<td>.057</td>
<td>.706</td>
<td>0 ± 1</td>
<td>-1 ± 2</td>
</tr>
<tr>
<td>Y Velocity m.s⁻¹</td>
<td>31 ± 2</td>
<td>32 ± 2</td>
<td>42 ± 2</td>
<td>42 ± 2</td>
<td></td>
<td>.821</td>
<td>&lt;.001*</td>
<td>.459</td>
<td>48 ± 0</td>
<td>48 ± 1</td>
</tr>
<tr>
<td>Z Velocity m.s⁻¹</td>
<td>3 ± 1</td>
<td>4 ± 1</td>
<td>4 ± 1</td>
<td>5 ± 1</td>
<td></td>
<td>.156</td>
<td>.152</td>
<td>.378</td>
<td>9 ± 1</td>
<td>10 ± 4</td>
</tr>
<tr>
<td>Resultant Velocity m.s⁻¹</td>
<td>32 ± 2</td>
<td>32 ± 2</td>
<td>43 ± 2</td>
<td>43 ± 2</td>
<td></td>
<td>.930</td>
<td>&lt;.001*</td>
<td>.507</td>
<td>49 ± 0</td>
<td>49 ± 1</td>
</tr>
<tr>
<td><strong>Ball Impact Location and End-Point Parameters</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>X Displacement cm</td>
<td>4 ± 20</td>
<td>7 ± 14</td>
<td>-7 ± 19</td>
<td>-9 ± 20</td>
<td>.999</td>
<td>.262</td>
<td>.387</td>
<td>-15 ± 10</td>
<td>-22 ± 11</td>
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</tr>
<tr>
<td>Y Displacement cm</td>
<td>56 ± 8</td>
<td>64 ± 11</td>
<td>62 ± 6</td>
<td>62 ± 6</td>
<td>.244</td>
<td>.650</td>
<td>.259</td>
<td>54 ± 11</td>
<td>57 ± 8</td>
<td></td>
</tr>
<tr>
<td>Z Displacement cm</td>
<td>213 ± 8</td>
<td>214 ± 5</td>
<td>252 ± 6</td>
<td>251 ± 8</td>
<td>.638</td>
<td>&lt;.001*</td>
<td>.847</td>
<td>256 ± 3</td>
<td>258 ± 4</td>
<td></td>
</tr>
<tr>
<td>Impact Volume cm³</td>
<td>514 ± 230</td>
<td>622 ± 517</td>
<td>300 ± 135</td>
<td>253 ± 175</td>
<td>.792</td>
<td>.098</td>
<td>.513</td>
<td>272 ± 3</td>
<td>275 ± 8</td>
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</tr>
<tr>
<td>Resultant Ball Velocity m.s⁻¹</td>
<td>33.3 ± 1.9</td>
<td>33.0 ± 2.0</td>
<td>43.9 ± 1.4</td>
<td>43.3 ± 2.1</td>
<td>.194</td>
<td>.000*</td>
<td>.672</td>
<td>49.2 ± 1.1</td>
<td>47.1 ± 2.6</td>
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</tr>
<tr>
<td>Projection Angle °</td>
<td>-1.6 ± 1.3</td>
<td>-4.1 ± 1.4</td>
<td>-5.4 ± 0.8</td>
<td>-6.7 ± 0.7</td>
<td>.001*</td>
<td>.001*</td>
<td>.116</td>
<td>-6.0 ± 1.2</td>
<td>-6.8 ± 0.6</td>
<td></td>
</tr>
</tbody>
</table>

°: Angle; X: Right(+ – Left(–); Y: Forward(+ – Back(–); Z: Up(+ – Down(–)); WG: Within groups effect (i.e., good vs fault); BG: Between groups effect (i.e., G1 vs G2); Int: Interaction effect (i.e., serve outcome × group), *: significant (p < .01).
4.1. Discrete kinematics

The manner in which players prepared their bodies and generated racquet velocity did not appear to influence serve outcome in any of the groups. This logically accounts for the similarities in trunk and serving arm orientation that were recorded at impact. Consequently, the current findings offer support to the assertion that there are no obvious kinematic sources of service faults (Göktepe et al., 2009). Given that discrete kinematics are often the primary information purveyors for coaches in their evaluation of technique (Elliott & Reid, 2004), any hope of discerning subtle deficiencies in an elite player’s service action through simple observation seems unlikely. Accordingly, there appears an essential role for motion capture and other analytic tools in the evaluation of whole body high-speed movements, such as the tennis serve. One could argue that the complexity of the service action may make it difficult to pinpoint the source of error as this could come from any one of numerous degrees of freedom in each serve. However, the compensatory mechanisms that are an inferred part of the service action (Whiteside et al., submitted for publication) suggest that the movement system is capable of negotiating unsolicited perturbations by adjusting other degrees of freedom accordingly (Davids et al., 2003; Ranganathan & Newell, 2008a, 2008b). Thus, inadequate management of the error may be a greater concern for the coach than the error itself. Practically then, coaches may wish to focus on the acquisition of a highly adaptable movement system instead of a perfectly repeatable service action.

In light of the above, it is perhaps unsurprising that the racquet kinematics also showed no differences between the two conditions, where service faults could not be attributed to either racquet orientation or racquet velocity at impact. Analogous with previous work (Chow et al., 2003), the mean position of the ball at impact appeared variable in both conditions and did not differentiate between successful and unsuccessful serves. This finding counters the practical consideration that an inconsistent ball toss is the source of service faults (Bryant, 2003) and contests the value in trying to refine a perfectly repeatable ball toss. The variable impact location also has implications for the movement system, wherein commensurate variance must then be obligatory. Further, it implies that each serve demands a unique racquet orientation to project the ball into the service box. The practical implications of this concept are substantial as, mechanically, there does not appear to be an optimal service action. Instead the optimal service action is a product of the ball toss and therefore differs with each serve. This interdependence of the ball toss and body mechanics logically explains why previous work has found inconsistencies between the decomposed service action (i.e., practising the ball toss and

![Fig. 3. Overall (within-groups) regression planes for the end-point parameter combinations of successful serves and service faults into the net.](image-url)
racquet swing in isolation of one another) and an actual serve (Reid et al., 2010). In a movement skill where variability is essential, it follows that a practical emphasis on absolute consistency seems counterintuitive.

Unlike ball velocity and impact location, the projection angle was revealed to be the end-point parameter that discriminated successful serves from faults missing into the net. Predictably, the projection angle was significantly further below the horizontal in this type of service fault. Additionally, the converging regression planes in Fig. 3 indicate how, at a given impact height, the margin for error in the projection angle decreases as ball velocity increases. That is to say, small miscalculations in the projection angle are more likely to produce service faults in faster serves compared with slower serves. Sufficient negotiation of these exiguous margins for error (≈1°) at high velocities intuitively requires refined coordination, which is an unlikely feature of young movement systems (Cortis et al., 2009). Therefore, alongside their technical origins, the significantly lower serve velocities observed in junior players (Whiteside et al., in press) may also have a conscious source. In other words, junior players may consciously delimit their racquet velocity in order to afford them better control over the racquet and, in turn, the projection angle. The projection angle in both conditions also exhibited an age effect whereby players in G1 utilized a greater projection angle than those in G2. This parameter is logically constrained by stature, where the smaller stature of younger players commands a more inclined projection angle to overcome the net. Developmentally, the implications of this provision are immense as the serviceable end-point parameter combinations apparently change as players grow. That is, a player’s stature effectively alters the demands of the task, which likely explains why junior and senior players do not possess the same service actions (Whiteside et al., in press). This exemplifies the role of organismic constraints in human performance, where physical maturation has the potential to open up new movement possibilities (Haywood & Getchell, 2008). Three practical considerations can be extracted from this concept where, first, homogenous instruction of junior and senior populations appears questionable. Second, endeavouring to refine consistency in certain junior movement patterns may be impractical given that these patterns cannot functionally persist into adulthood (note the distinct clusters of end-point parameters for G1 to the left and G2/PRO to the right in Fig. 4). As an illustration of this, impact height will logically increase as players develop, necessitating accordant adjustments in projection angle-ball velocity combinations. Therefore, the service action that a pre-pubescent player uses (i.e., one that employs a large projection angle) is rendered futile by physical growth (when, having grown taller, a large projection angle now yields a fault). Third however, appropriate scaling of the court dimensions and net height throughout development would allow
junior players to replicate the projection angles used by adult players. This may promote serve development by alleviating the requisite technical adjustments that would otherwise be enforced by physical maturation.

4.2. Serving arm variability

The magnitude of variability in the coordinative elbow and wrist mechanics that regulate racquet orientation (Elliott et al., 2003) presented an interesting finding. Irrespective of serve success, the relative motion of elbow pronation and wrist flexion looked to be relatively repeatable at ~80–90% of the forwardswing. Thereafter, there was a rapid increase in variability that continued until impact, which was similar to what has been described in free throw shooting (Button et al., 2003) and handball throws (Wagner, Pfusterschmied, Klous, von Duvillard, & Muller, 2011). In these sports, increased terminal variability in the distal joints is considered to be indicative of compensatory movements and this may be also the case in the serve. It therefore appears that players delay the adjustments to the racquet orientation until immediately prior to impact. Although this contradicts the idea of ‘funnel-like’ control, it could be argued that this cunctation is necessary as antecedent adjustments to the racquet face (in other words opening the racquet face early) are thought to impede the generation of racquet velocity (Whiteside et al., submitted for publication). A supplementary explanation is that, due to its variable nature, the impact location cannot be accurately extrapolated until late in the action. Indeed, interceptive actions require perceptual feedback to place the limbs in the appropriate positions at the correct time (Button & Summers, 2002). Therefore, players may initially employ a more ‘schematic’ movement strategy to propel themselves in the general direction of where they expect impact to be. Purposeful mechanical adjustments (i.e., ‘funnelling’) in the serving arm are then initiated late in the action, when they are more confident of where the impact location will lie. This strategy conforms to previous work where consistent pre-impact postures have been noted to precede more variable impact locations (Whiteside et al., submitted for publication). With the ball toss varying between serves, the utilisation of a wholly pre-planned movement pattern seems unlikely, as it would require the pre-programing of an impact location that cannot be definitively determined a priori. Consequently, there is an inferred role of perceptual feedback in the interception process that supports previous work (Bootsma & van Wieringen, 1990; Montagne, Cornus, Glize, Quaine, & Laurent, 2000; Ranganathan & Newell, 2008a, 2008b).

The temporal initiation of propulsive movements is considered vital to the success of various interceptive movements such as hitting in baseball (Katsumata, 2007) as well as serving in both volleyball (Davids et al., 2001) and tennis (Whiteside et al., submitted for publication). Specific to tennis, Whiteside et al. (submitted for publication) perceived the regulation of forwardswing duration as important for successful tennis serve performance. This process was considered to rely on regulating body movements according to the position of the ball – something that pre-pubescent players were comparatively poor at. This inaptitude (Whiteside et al., in press) may therefore account for the increased forwardswing duration that, in turn, contributed to their service faults. The same cannot be said for G2 and the PRO however, whose forwardswing durations remained the same irrespective of serve outcome. In the context of previous work, these players may be able to effectively remove the potential for timing errors within the serve by using the ball to regulate their movements. Within reason, these findings contest coaching ideals that lament players for ‘chasing’ the ball toss (i.e., allowing their movements to be governed by the location of the ball). On the contrary, the literature implies that a refined perception-action coupling allows players’ movements to be continuously calibrated (Bootsma & van Wieringen, 1990), logically reducing the possibility for the ball toss to corrupt the serve. Given that interceptive actions require perceptual feedback to place the limbs in the appropriate positions at the correct time (Button & Summers, 2002), the apparent increase in mechanical variability prior to impact appears functional as players adjust to the location of the ball. Consequently, where closed motor skills are often accompanied by expectations for mechanical consistency, tennis coaches may benefit from appreciating the inherent variability in the ball toss and its functional implications. In this sense, there appears scope for instruction to promote appropriate perception-action couplings from a young age by introducing stochastic perturbations and/or encouraging players to subtly experiment with their ball toss (Davids, Shuttleworth, Button, Renshaw, & Glazier, 2004).
The significantly greater variability recorded in the successful serve condition contrasts with previous observations in free throw shooting (Mullineaux & Uhl, 2010) and golf (Horan, Evans, & Kavanagh, 2011). However, the tennis serve differs from these skills in that it involves significantly faster movements, the ball is not under constant mechanical control throughout the action (as in throwing or basketball) nor is the impact location predetermined (as in golf). Instead, the spatial end-point (i.e., racquet-ball impact) is governed by the ball toss – the dynamics of which are beyond the player’s control after the ball leaves the hand and is therefore more susceptible to variation. It has been established that mechanical adjustments late in the action are imperative as players adjust their bodies to intercept the ball. The smaller distal joint variability recorded in service faults may represent inadequate adjustment, where players have failed to decrypt the ball toss and suitably adapt their schematic pre-impact movement strategy. In this way, prompt anticipation of the impact location would seemingly expedite serve performance. Developing the perceptual system as part of the serve is rarely a noted priority of tennis coaches, and little data exists to guide instruction in this sense. Future research could appraise the perceptual system’s role in the directing of serving arm mechanics immediately prior to impact. Specifically, tracking gaze behavior late in the action or occluding the ball at various intervals prior to impact would provide an indication as to if, and at what point, players are able to accurately forecast impact location. However, given players’ lack of familiarity with these apparatus, their influence on ecological validity would need to be controlled.

It is worth acknowledging the limitations of the small sample sizes utilized in this study and their implications on statistical power. Unfortunately this issue is prevalent in elite level sport where logistical difficulties often prevent the recruitment of professional and/or touring athletes. In the current study, the authors are confident that the participants were among the most accurate and powerful servers in their respective national age groups. Similarly, the foci of the current study limits the generalization of the findings and could be extended by exploring other populations (skill levels), different types of faults (long and wide) or serve types (slice or kick) in the future.

5. Conclusions

Players of all ages appear to prepare their bodies and generate racquet velocity similarly in both successful and unsuccessful serves. The similarity in discrete body kinematics suggests that service faults cannot be attributed to a single source of mechanical error. However, service faults are characterized by projection angles significantly further below the horizontal, suggesting that this parameter is a determinant of serve outcome. Similar to other dexterous skills, compensatory variability in the distal (elbow and wrist) joints immediately prior to impact appears critical to the regulation of projection angle, as it allows players to adjust to the variable impact location. Given that the impact location cannot be predetermined, perceptual feedback may play an important role in the compensation process. For this reason, coordination of the distal degrees of freedom and a refined perception-action coupling appear more important to success than any single kinematic component of the service action. With this in mind, the development of a highly adaptable movement system may be more beneficial to improving serve performance than traditional approaches that decompose and accentuate consistency in the service action. Explicitly, coaches may command varying service performance (speed, spin, location), scale the court dimensions, or administer stochastic perturbations of the ball toss early in development to foster the mechanical and/or perceptual proficiency required in the tennis serve.

Acknowledgments

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References


