Comparison of Endpoint Data Treatment Methods for the Estimation of Kinematics and Kinetics Near Impact During the Tennis Serve

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Tennis stroke mechanics have attracted considerable biomechanical analysis, yet current filtering practice may lead to erroneous reporting of data near the impact of racket and ball. This research had three aims: (1) to identify the best method of estimating the displacement and velocity of the racket at impact during the tennis serve, (2) to demonstrate the effect of different methods on upper limb kinematics and kinetics and (3) to report the effect of increased noise on the most appropriate treatment method. The tennis serves of one tennis player, fit with upper limb and racket retro-reflective markers, were captured with a Vicon motion analysis system recording at 500 Hz. The raw racket tip marker displacement and velocity were used as criterion data to compare three different endpoint treatments and two different filters. The 2nd-order polynomial proved to be the least erroneous extrapolation technique and the quintic spline filter was the most appropriate filter. The previously performed “smoothing through impact” method, using a quintic spline filter, underestimated the racket velocity (9.1%) at the time of impact. The polynomial extrapolation method remained effective when noise was added to the marker trajectories.

Keywords: tennis, biomechanics, methods, data endpoint treatment

The accurate biomechanical analysis of certain human movements is complicated by collision events. The heel strike in gait, the foot striking the ball in football and the ball striking the racket in tennis all represent collisions that result in rapid deceleration of the colliding objects. This segment deceleration and preceding acceleration are important from both performance and injury perspectives; however, data at and near impact are often compromised or misrepresented by data treatment methods.

The analysis of tennis stroke mechanics, from both of the abovementioned perspectives, has been the source of considerable investigative interest. Past and contemporary data treatment has included the use of a variety of filters: a necessary and accepted practice to remove oscillations in the data that disturb higher order kinematic calculation (Elmer & Martin, 2009). The selection of inappropriate filtering has been demonstrated to misrepresent data around the collision event (Bisseling & Hof, 2006; Knudson & Bahamonde, 2001). No previous research has investigated the appropriateness of different approaches to filtering in the tennis serve.

The effect of the collision between the racket and ball in tennis is often negotiated by “smoothing” through impact or “cropping” the data one frame before impact (creating an endpoint in the data set) and/or extrapolating (Reid, et al., 2007). To this end, the study of Knudson and Bahamonde (2001) represents a stand-alone research effort in tennis aimed at evaluating the conundrum of “endpoint error,” practically described by Vint and Hinrichs (1996). Knudson and Bahamonde (2001) illustrated that wrist kinematics near impact in the tennis forehand were best represented by linear and polynomial extrapolation methods. As the selection of data treatment method depends on the variable and skill of interest (Giakas et al., 1998; Tabuchi et al., 2007), it is uncertain whether these methods are suitable for the other tennis strokes. For example, the momentum of the ball in the tennis forehand and serve can be very different such that the associated impact kinematics are likely disparate. Further, determining the most appropriate method to minimize “endpoint error” is complicated by a lack of gold standard measurement. While Knudson and Bahamonde (2001) used goniometry at the wrist, under dynamic conditions this instrumentation is confounded by large cross-talk errors (Hansson et al., 2004). The use of a body segment or joint, such as the wrist, to quantify the error associated with impact also misleads as the instrumental error,
defined as any error originating from the measurement system itself, cannot be interpreted independent of the error associated with soft tissue artifact. Therefore, in the current investigation, the criterion data are proposed as untreated (raw) racket tip marker positions. The rationale for this decision was threefold. First, the most pronounced effects of impact occur at the site of collision, the racket. Second, the racket data are not affected by soft tissue artifact error; therefore, marker perturbation will represent instrumental error and the impact event. For the purpose of this investigation the racket was assumed to be rigid. Finally, the raw data were collected at 500 Hz with a 12 camera VICON motion analysis system (Vicon, Oxford Metrics Inc.) focused on the racket and upper limb ensuring accurate, consistent tracking of the racket and upper limb at and near impact of the tennis serve. Vicon is one of the most accurate motion analysis systems currently available and has been used to validate two-dimensional motion recording systems in vivo (Elliott et al., 2007).

This article has three aims: (1) to identify the best method of estimating the displacement and velocity of the racket at impact during the tennis serve, (2) to demonstrate the effect of different treatment methods on upper limb kinematics and kinetics and (3) to report the effect of increased noise on the most appropriate endpoint treatment method.

Methods

Ethics were approved by the University of Western Australia. A 12-camera Vicon 612 system (Oxford Metrics Inc.), operating at 500 Hz, recorded the service motion of one internationally ranked player at the School of Sport Science, Exercise and Health’s biomechanics laboratory. Retro-reflective markers were affixed to the player’s racket, hand, wrist, forearm, upper arm and thorax, as previously detailed (Reid et al., 2007). Static and dynamic calibrations were conducted to set up the global reference system and calibration volume. The wrist joint center, elbow joint center and shoulder joint center were identified following a static trial in line with past research (Reid et al., 2007).

The player performed five successful flat serves on a replica tennis court, with a net and service box. For serves to be considered successful, they were required to land in a 1 m x 1 m box bordering the “T” of the deuce service court, within 95% of a previously recorded “maximum” ball velocity. The serve selected for analysis was that with the highest ball velocity and also that which the player indicated to be his best serve.

Data Treatment Methods

Smoothing through impact and two polynomial extrapolation methods were compared, along with two different filters. The two filters selected for comparison were the Woltring filter, a quintic spline that is commonly recommended for the filtering of human motion data (Giakas et al., 1998), and the Butterworth filter, which has been shown to effectively manage impact during the tennis forehand (Knudson & Bahamonde, 2001). The selection of polynomial extrapolations was consistent with those previously used in tennis (Knudson & Bahamonde, 2001).

The data from one trial was copied and treated with all combinations of data treatment (smooth through impact [STI], 2nd-order extrapolation [Extra 2nd] and 5th-order extrapolation [Extrap 5th]) and filters (Butterworth digital filter [DF] and Woltring quintic spline filter [QSF]). Customized Matlab operations were used to perform a 5th- and 2nd-order polynomial extrapolation. The start of the impact phase was identified as the time point coinciding with the maximum horizontal velocity of the racket tip marker in the raw data. Each algorithm used the 10 frames before impact to predict impact and 10 subsequent frames. To determine the optimal cut-off frequency for each filter, a residual analysis was performed (Winter, 1990). This analysis revealed an optimal low pass cut off frequency of 17 Hz for the recursive 4th-order DF. A mean square error (MSE) of 25 for the QSF was set (Reid et al., 2007).

Calculation of Racket and Body Kinematics

The racket tip displacement and velocity were output relative to the global reference frame in Vicon customized software, Bodybuilder. A customized mathematical model, the UWA model (Lloyd et al., 2000) was used to calculate the kinematics and kinetics. The wrist and racket angles were calculated with a ZXY Euler order of rotations, while the shoulder internal rotation angle was output using a YXY decomposition to avoid gimbal lock errors. The shoulder moments were calculated from the angular velocity of the segment and the estimated mass and moment of inertia information from cadaveric studies (De Leva, 1996), as has been previously detailed (Reid et al., 2007).

Noise Analysis

Subsequent to establishing preferred data treatment methods, Gaussian noise was added to the raw racket tip marker at three amplitudes; 2 mm, 4 mm and 6 mm. This was undertaken to illustrate the robustness of the preferred treatment methods among data that are collected by systems more susceptible to artificial error (Ehara et al., 1994).

Results

Racket Tip Marker Analysis

The comparison of the horizontal progression of the racket tip marker (relative to the global origin), using different endpoint treatments and filters, are delineated in Tables 1 and 2. Both endpoint treatments (Extrap 5th and Extrp 2nd) appeared suitable for estimating impact displacements, yet the Extrp 2nd best approximated the criterion velocity data (Table 1).
The two endpoint treatment conditions as well as STI reported racket tip displacements that were comparable (2–4% lower) to the criterion data, when filtered with the QSF (Table 2). Data from the Extrap 2nd QSF were most similar to the criterion data. The influence of the DF was pronounced with the horizontal displacement and velocity of the racket being under-reported by between 5 and 40% compared with the criterion (Figures 1 and 2). With the Extrap 2nd QSF considered to best estimate the velocity data, it provided a comparative baseline to illustrate the effect of different endpoint treatment and filtering techniques on selected racket and upper limb kinematics and kinetics relevant to the tennis serve (Table 3: Elliott et al., 2003; Reid et al., 2007). The sizeable percent differences highlight the effect of the different treatment procedures on the variables of interest. This variation is most evident in the higher order kinematic and moment calculations.

**Effect of Noise on Data Extrapolation and Filtering**

As the unfiltered Extrap 2nd and Extrap 2nd QSF best approximated the criterion racket displacement and velocity data, the effect of noise was investigated on the racket trajectories estimated using those procedures.
Figure 2 — Comparison of different endpoint treatments and filters to criterion racket tip velocity data near impact.

Table 3  Effect (% change from criterion measure) of different endpoint treatment and filter methods on the calculation of wrist, racket, and shoulder kinematics, and shoulder kinetics at impact of the tennis serve

<table>
<thead>
<tr>
<th>Criterion Measure</th>
<th>Extrap 2nd QSF</th>
<th>STI DF</th>
<th>Extrap 2nd DF</th>
<th>STI QSF</th>
<th>Extrap 2nd Raw</th>
<th>Extrap 5th DF</th>
<th>Extrap 5th QSF</th>
<th>Extrap 5th Raw</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wrist Flexion</td>
<td>–56.54</td>
<td>20%</td>
<td>2%</td>
<td>16%</td>
<td>7%</td>
<td>11%</td>
<td>12%</td>
<td>7%</td>
</tr>
<tr>
<td>Wrist Flexion Velocity</td>
<td>214.45</td>
<td>–125%</td>
<td>10%</td>
<td>–147%</td>
<td>–300%</td>
<td>–23%</td>
<td>–111%</td>
<td>–251%</td>
</tr>
<tr>
<td>Wrist Flexion Acceleration</td>
<td>–20,936.6</td>
<td>64%</td>
<td>40%</td>
<td>106%</td>
<td>894%</td>
<td>43%</td>
<td>90%</td>
<td>469%</td>
</tr>
<tr>
<td>Racket Flexion</td>
<td>–40.053</td>
<td>9%</td>
<td>–14%</td>
<td>9%</td>
<td>33%</td>
<td>–11%</td>
<td>8%</td>
<td>–2%</td>
</tr>
<tr>
<td>Racket Flexion Velocity</td>
<td>1,145.75</td>
<td>61%</td>
<td>76%</td>
<td>55%</td>
<td>71%</td>
<td>81%</td>
<td>44%</td>
<td>51%</td>
</tr>
<tr>
<td>Racket Flexion Acceleration</td>
<td>28,777.04</td>
<td>41%</td>
<td>60%</td>
<td>96%</td>
<td>675%</td>
<td>72%</td>
<td>60%</td>
<td>469%</td>
</tr>
<tr>
<td>Shoulder Internal Rotation Angle</td>
<td>–54.52</td>
<td>3%</td>
<td>–15%</td>
<td>–7%</td>
<td>–11%</td>
<td>–16%</td>
<td>–3%</td>
<td>–11%</td>
</tr>
<tr>
<td>Shoulder Internal Rotation Moment</td>
<td>–34.6</td>
<td>–6%</td>
<td>–242%</td>
<td>–40%</td>
<td>–714%</td>
<td>–175%</td>
<td>–20%</td>
<td>–306%</td>
</tr>
<tr>
<td>Shoulder Flexion Moment</td>
<td>–119.6</td>
<td>–100%</td>
<td>–85%</td>
<td>–109%</td>
<td>73%</td>
<td>–159%</td>
<td>–65%</td>
<td>251%</td>
</tr>
<tr>
<td>Shoulder Abduction Moment</td>
<td>241.85</td>
<td>–92%</td>
<td>–44%</td>
<td>–100%</td>
<td>–119%</td>
<td>–64%</td>
<td>–96%</td>
<td>–244%</td>
</tr>
</tbody>
</table>
Table 4  Effect of noise on racket tip horizontal displacement and velocity at impact of the tennis serve

<table>
<thead>
<tr>
<th></th>
<th>2 mm Noise</th>
<th>4 mm Noise</th>
<th>6 mm Noise</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Unfiltered</td>
<td>Extrap 2nd</td>
<td>Extrap 2nd</td>
</tr>
<tr>
<td>Racket tip position error</td>
<td>0</td>
<td>0.3%</td>
<td>0.2%</td>
</tr>
<tr>
<td>Racket tip velocity error</td>
<td>5%</td>
<td>1%</td>
<td>1%</td>
</tr>
</tbody>
</table>

(Table 4). The results generally supported the need to extrapolate and filter, particularly for velocity data and as the magnitude of noise increased. The extrapolation and the extrapolation/filter combination were typically more effective in estimating racket displacement and velocity at impact than the unfiltered noisy data.

Discussion

This investigation had three aims. The first was to determine the optimal method of estimating the position and velocity of the racket tip at impact during the tennis serve. For this purpose, the racket tip’s horizontal displacement and velocity were analyzed.

Results revealed both extrapolation polynomials (Extrap 5th and Extrap 2nd) to effectively estimate racket position at impact but the Extrap 2nd to better represent racket velocity. The use of the DF with both extrapolations as well as the STI appeared erroneous in estimating racket displacement at impact. This would seem to preclude the use of this type of filter in the interpretation of racket kinematics near impact in the serve. The Extrap 2nd combined with the QSF best approximated the criterion velocity data, where the combination of the Extrap 5th or STI and the QSF were less analogous and prone to increasing error.

These findings are not altogether dissimilar to those reported by Knudson and Bahamonde (2001), where five point linear and polynomial extrapolations were shown to be more effective than STI in estimating the angular displacement and velocity of the wrist at impact in the tennis forehand. Noteworthy is that the relatively lower percentage decreases in velocity introduced by STI in this study may relate to the difference in “oncoming” ball momentum between the forehand and serve. Nonetheless, it would appear probable that recent VICON investigations on serve mechanics have underestimated racket velocity (i.e., Reid et al., 2007).

The Extrap 2nd QSF was used as baseline data against which the effects of different endpoint treatment and filtering techniques on selected racket and upper limb kinematic and kinetic variables could be compared. This undertaking proved instructive in underlining the importance of standardizing endpoint and filtering techniques in appraising the mechanics of the tennis serve.

For instance, displacement measures like shoulder joint internal rotation were affected by 5–10% depending on the treatment method. However, as expected, the effects of this disparate data treatment were most pronounced in the acceleration and kinetic data—where variations in the order of 200% were recorded.

The potential utility of the Extrap 2nd QSF among different data sets was further illustrated by its management of the systematic addition of Gaussian noise to the raw racket marker. This proves useful to other researchers interested in examining the mechanics of the tennis serve, particularly through analysis systems that are more susceptible to artificial error.

The magnitude of the differences demonstrated in this paper may vary depending on the momentum of the objects involved and the duration of the collision, however the results clearly demonstrate that standardized impact treatment is required for all collisions in biomechanics. In tennis, this may mean that data treatment differences exist between the groundstrokes, volleys and serve. This research has demonstrated that to effectively estimate the data around impact of the tennis serve, a polynomial (2nd-order) extrapolation followed by a QSF can be performed.

References


