DETERMINING INSTANTANEOUS SHUTTLECOCK VELOCITY: OVERCOMING THE EFFECTS OF A LOW BALLISTIC COEFFICIENT

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Introduction

The badminton shuttlecock has a lower ballistic coefficient, a measure of ability to overcome air resistance, and greater deceleration during flight than any other airborne sporting implement (Nakagawa, Hasegawa, Murakami, & Obayashi, 2012). Indeed, initial shuttlecock velocities of 67 m·s^{-1} have been reported to decelerate in 0.6 s to close to the terminal velocity of approximately 7 m·s^{-1} (Chen, Pan, & Chen, 2009; Hubbard & Cooke, 1997). These rapid decelerations and marker movement due to the spin or flip of the shuttlecock, as well as tracking errors, present researchers with difficulties when seeking to accurately determine post-impact shuttlecock velocity via differentiation (Texier, Cohen, Quéré, & Claneta, 2012).

One study modelling the vertical fall of a shuttlecock found the best model to be one which assumed a resistive force that was quadratic in its relationship with the instantaneous shuttlecock velocity (Peastrel, Lynch, & Armenti, 1980). This caused Chen et al. (2009) to suggest that an equation of shuttlecock motion could be constructed via determination of its terminal velocity. They utilized such an equation to successfully predict the trajectory of a shuttlecock, demonstrating that drag force is proportional to the square of shuttlecock velocity. Similarly, aerodynamic forces calculated experimentally have been used in simulations to predict shuttlecock trajectories, producing mean and maximum errors of 2.5 and 9.1% in vertical distance travelled (Chan & Rossmann, 2012). However, predicting shuttlecock trajectory is less important in many experimental research designs than the accurate calculation of instantaneous velocity from data already collected, without the need for further measures as inputs to a model. Many researchers are also interested in joint kinematics at key sporting instances, such as racquet-shuttlecock impact (Huang, Huang, Chang, & Tsai, 2002; Miller, Felton, McErlain-Naylor, Towler, & King, 2015; Rambely, Osman, Usman, & Abas, 2005). The jump smash is the technique that generates the greatest shuttlecock velocities (Tsai, Huang, & Jih, 1995) and thus the purpose of this study was to develop a method for accurate determination of post-impact instantaneous shuttlecock velocity as well as the identification of racquet-shuttlecock contact timing for the badminton jump smash.

Methods

Twenty-five experienced male badminton players (24.1 ± 7.0 years, 1.83 ± 0.08 m, 77.8 ± 8.6 kg) participated in this investigation. Participants ranging from county to international level of competition were selected so as to provide a large variation in jump smash velocity. The testing procedures were explained to each participant, and informed consent was obtained in accordance with the Loughborough University Ethical Advisory Committee. A thin strip of 3M reflective scotch tape was attached to the shuttlecock base (Yonex AS40; Figure 1). Participants were given the chance to perform a self-selected warm-up and to practice before performing three maximal velocity jump smashes. Trials were recorded using an 18 camera (M^2 MCam) Vicon Motion Analysis System (OMG Plc, Oxford, UK) operating at 400 Hz (Figure 2).

Figure 1. Reflective tape placement on the shuttlecock.

Figure 2. Data collection environment.

The shuttlecock position data were manually labelled and processed. Curves were fit separately to the pre- and post-impact phases (identified from the change in anterior-posterior direction) of the shuttlecock coordinate data in the vertical, anterior-posterior, and medio-lateral planes according to Equation (1) (Figure 3):

$$x = \frac{1}{k} \cdot \ln(1 + k \cdot v_0 \cdot t), \tag{1}$$

where x = displacement; t = time; and k and v_0 are constants.

$$x = \frac{1}{k} \cdot \ln(1 + k \cdot v_0 \cdot t),$$
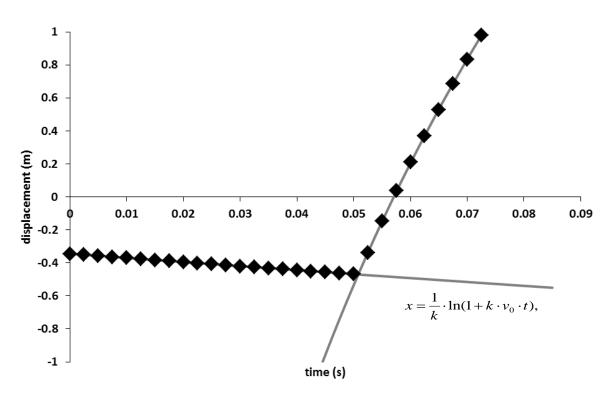
Figure 3. Raw data and the pre- and post-impact curves.

Curves were fitted in MATLAB (Version 8.0, The MathWorks Inc., Natick, MA, 2012) utilizing a Trust-Region-Reflective Least Squares algorithm (Moré & Sorensen, 1983) to determine values for k and v_0. Time of impact was determined as the mean time at which the pre- and post-impact curves intersected in each plane, with differentiation of the post-impact curve equations enabling the calculation of resultant instantaneous velocity at this time (Appendix 1). Shuttlecock velocity was also calculated via differentiation over both one and ten time intervals in order to facilitate comparison with the curve fitting methodology.

Results

The 25 males participating in this study achieved jump smash velocities of 60 - 99 m·s^{-1} (mean 81.9 ± 7.8 m·s^{-1}). R^2 and root mean squared error (RMSE) values for the curves' goodness of fit averaged 0.99 ± 0.03 and 3.5 ± 4.6 mm respectively (Table 1). Differentiation over 1 or 10 time intervals resulted in mean absolute post-impact shuttlecock velocity differences of 4.5 ± 11.0 and 14.8 ± 3.3 m·s^{-1} respectively when compared with those determined via the curve fitting methodology (Figure 4). Data processing time averaged less than a second per trial in MATLAB, with all 75 trials processed in under a minute.

Table 1. Goodness of fit statistics

	R^2	RMSE (mm)
medio-lateral pre.	0.99 ± 0.02	1.3 ± 1.8
medio-lateral post	0.97 ± 0.07	5.4 ± 1.3
anterior-posterior pre.	1.00 ± 0.00	1.3 ± 1.5
anterior-posterior post	1.00 ± 0.00	7.3 ± 9.3
vertical pre.	1.00 ± 0.00	2.0 ± 1.1
vertical post	1.00 ± 0.00	3.5 ± 1.7

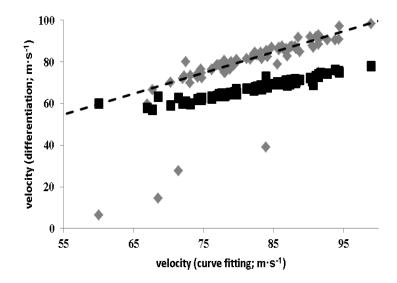Note: RMSE: root mean squared error; pre./post: pre-/post-impact.

Figure 4. Resultant post-impact shuttlecock velocity calculated via differentiation over 1 (gray) or 10 (black) time intervals against that calculated via curve fitting. Dashed line: y = x (via differentiation = via curve fitting).

Discussion

The present study has developed a curve fitting methodology capable of fitting three-dimensional shuttlecock position with a mean R^2 of 0.99 and RMSE of 3.5 mm. This approach enabled both racquet-shuttlecock contact timing and resultant instantaneous shuttlecock velocity to be determined for experimentally recorded jump smashes whilst overcoming the difficulties posed by alternative methodologies. The high mean R^2 values for all pre- and post-impact curves justify the use of the logarithmic equation and demonstrate that such an equation is appropriate for shuttlecock displacement shortly before and after racquet contact. Unlike some previous studies (Chan & Rossmann, 2012; Chen et al., 2009; Cooke, 2002), the purpose was not to predict the shuttlecock trajectory but rather to obtain more accurate velocity and contact timing estimates during the time period for which experimental data was available. This in turn can increase the validity of experimental research investigating the important relationships between kinematic parameters and shuttlecock velocity.

Furthermore, the current curve fitting methodology differs from previous models in that no additional measurements or calculations are required in order to obtain values for terminal velocity or other parameters (Chan & Rossmann, 2012; Chen et al., 2009). This is again advantageous to researchers who require more precise estimates of impact timing and instantaneous velocity from experimentally collected data than is allowed by analyzing the closest frame to impact or through differentiation. Fitting a curve to existing data rather than extrapolation or prediction enables RMSEs in the present study that are much lower in magnitude than the 2.5% errors reported by Chan and Rossmann (2012) or the 5% of Cooke (2002). A further advantage of the curve fitting process is the automated procedure, with the ability to analyze all 75 trials in under a minute.

The lowest mean R^2 and greatest standard deviation were in the medio-lateral plane of shuttlecock motion, with the post-impact medio-lateral R^2 for one trial as low as 0.49. This same curve had an RMSE of 7.5 mm, however, which was similar to the mean value in the

anterior-posterior plane. This highlights that the lower and more variable R^2 values for the medio-lateral curves were simply due to the small displacements in this direction. Shuttlecock displacements were much greater in the anterior-posterior and vertical planes and so the same absolute error (reflected by similar RMSE) resulted in lower R^2 values for the medio-lateral goodness of fit.

When compared to differentiation over one or ten time intervals, the resultant velocities obtained via curve fitting demonstrated absolute differences of the magnitude of 4.5 and 14.8 m·s^{-1} respectively. Figure 3 shows that the velocities obtained over one time interval were mostly close to those via curve fitting, except for a certain number of trials in which differentiation generated unrealistically low velocities. For differentiation over ten time intervals on the other hand, there was a systematic reduction in shuttlecock velocity when compared to the other two methods. It is likely that the errors over one interval (2.5 ms) were caused by noise in the tracking of the shuttlecock. The relatively high mean and standard deviation for the anterior-posterior post-impact RMSE can be explained by the fact that those trials with the highest RMSE values were the same trials in which differentiation over one time interval resulted in unrealistically low velocities. Therefore, these greater RMSE values can be attributed to noise in the displacement data due to tracking errors rather than any failure of the curve to fit the displacement of the shuttlecock. Over ten frames (25 ms) however, the lower velocities were likely caused by the rapid decelerations experienced by shuttlecocks in flight due to their low ballistic coefficients.

The proposed methodology overcomes the limitations associated with noise in the kinematic tracking of the shuttlecock or any consequence of spinning or flipping through the smoothing effect of fitting a curve through the experimentally collected data for the phases either side of the impact. Additionally, determining a curve equation for the trajectory enables the calculation of instantaneous velocity rather than the average velocity over a period of time and so overcomes the problematic rapid decelerations. Assumptions made in this approach include that of an instantaneous impact and the negligible effect of applying the same logarithmic equation in all three planes regardless of the contribution of acceleration due to gravity in the vertical plane. In reality, the duration of racquet-shuttlecock contact is likely to be so short that the calculated post-impact instantaneous velocity is negligibly affected and that there would be insufficient data to split the trajectory into three phases. Likewise, the goodness of fit values for all vertical curves suggest that the equation used was appropriate for the trajectory being fit and able to contribute to valid velocity and impact timing results.

It is important that studies investigating the relationships between kinematic parameters and shuttlecock velocity in badminton techniques obtain accurate data for both the timing of impact and the post-impact instantaneous shuttlecock velocity. A curve fitting methodology enables this to be achieved to a greater degree of accuracy than differentiation methods. Calculation of racquet-shuttlecock contact timing via the curve fitting methodology compared to identifying the nearest frame to contact can result in differences of up to one half of a time interval (± 1.25 ms). This can subsequently cause differences in the kinematics at important joints at this time, especially at fast moving joints such as the wrist or elbow. The wrist has previously been found to be the major contributor to linear racquet head velocity in the smash (26.5%; elbow 9.4%; Rambely et al., 2005) and the more accurate calculation of impact timing and hence of these kinematic parameters will increase the validity of such conclusions.

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