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A Correlational Analysis of Shuttlecock Speed Kinematic Determinants in the Badminton Jump Smash

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Featured Application: The findings suggest that players and/or coaches should focus on proximal segment movements: specifically, producing greater pelvis-thorax separation during the retraction phase and greater shoulder internal rotation at shuttle contact to increase shuttlecock speed.

Abstract: The forehand jump smash is an essential attacking stroke within a badminton player's repertoire. A key determinate of the stroke's effectiveness is post-impact shuttlecock speed, and therefore awareness of critical technique factors that impact upon speed is important to players/coaches. Three-dimensional kinematic data of player, racket and shuttlecock were recorded for 18 experienced players performing maximal effort forehand jump smashes. Joint angles and X-factor (transverse plane pelvis-thorax separation) were calculated at key instants: preparation, end of retraction, racket lowest point, turning point and shuttlecock contact. Peak shoulder, elbow, and wrist joint centre linear velocities, phase durations and jump height were also calculated. Correlational analyses were performed with post-impact shuttlecock speed, revealing significant correlations to peak wrist joint centre linear velocity ($r = 0.767$), acceleration phase duration ($r = -0.543$), shoulder internal/external rotation angle at shuttlecock contact ($r = 0.508$) and X-factor at the end of retraction ($r = -0.484$). Multiple linear regression analysis revealed 43.7% of the variance in shuttlecock speed could be explained by acceleration phase duration and X-factor at the end of retraction, where shorter acceleration phase durations and more negative X-factor at end of retraction caused greater shuttlecock speeds. These results suggest that motions of the proximal segments (shoulder and pelvis–thorax separation) are critical to developing greater distal linear velocities, which subsequently lead to greater post-impact shuttlecock speed.

Keywords: velocity; technique; overhead; racket; swing; stroke

1. Introduction

The forehand smash is an effective attacking shot in badminton, accounting for 54% of "unconditional winner" and "forced failure" shots in international matches [1]. Success of the stroke is dependent upon two components: speed and direction, where speeds as high as 89.3 ± 7.2 m·s^{-1} have been reported in the literature for elite Malaysian players [2], whereas the competition world record is 118 m·s^{-1} [3]. A shuttlecock with a greater post-impact speed will give an opponent less reaction time, while directing the shuttlecock away from the opponent requires them to make fast reactive movements in order to return the shuttlecock.

Several studies have determined that both linear and angular velocities of distal segments (hand and racket) are strong positive correlates with shuttlecock speed [2,4], which is unsurprising due to higher velocities causing greater transfer of linear momentum to the shuttlecock. Explaining what kinematic parameters determine this greater distal velocities may be more useful for players, coaches and practitioners, as the greater joint powers associated with distal segments are not fully generated by the muscles associated with these segments, but transferred between segments through reaction forces of a proximal-to-distal nature, e.g., shoulder–elbow–wrist [5]. Varied experimental set-ups and methodologies of quantifying joint contributions have generated conflicting results, where Rambely et al. [4] suggested that a distal-to-proximal order of wrist, followed by the elbow and shoulder are the major contributors to racket head speed (26.5%, 9.4% and 7.4%, respectively). In contrast, Liu et al. [6] reported that a proximal-to-distal order of shoulder internal rotation, forearm pronation and wrist palmar flexion contribute 66%, 17% and 11%, respectively, towards racket head speed. Rambely et al. [5] captured video data at 50 Hz and calculated the resultant linear velocities of the shoulder, elbow and wrist joint centres at impact, and expressed the segment contributions as these velocities represented as percentages of the racket head centre resultant velocity at impact. Conversely, Liu et al. [6] used a three-dimensional kinematic method developed by Sprigings et al. [7] and calculated the relative angular velocities of distal segments by removing contributions from the adjacent proximal segment. Data were captured using high-speed video (200 Hz) and processed using direct linear transformation [8]. Teu et al. [9] found no specific proximity order using a dual Euler angles method with high-speed video (200 Hz), and reported torso rotation, shoulder internal rotation, forearm pronation and wrist abduction contributed 57%, 3%, 27% and 10% to resultant racket head velocity, respectively.

In summary, previous research has reported that linear velocities of the distal segments best explain variation in shuttlecock speed/racket head speed, however it is unclear how the distal segment velocities and subsequent racket head and shuttlecock speeds are generated. Additionally, use of low frame rates and unclear methodology for defining both shuttlecock speed and racket head speed mean that it is difficult to compare results. The present study therefore aims to identify full-body kinematic parameters that best explain the generation of post-impact shuttlecock velocities in the badminton jump smash, such that coaches/practitioners can advise players how best to increase smash speeds through technique and/or strength training. It is hypothesised that positions (joint angles) of proximal segments and linear velocities of more distal segments will best explain variation in post-impact shuttlecock speed.

2. Materials and Methods

2.1. Participants

Eighteen male badminton players (mean ± SD: age 24.3 ± 7.1 years, height 1.84 ± 0.08 m, mass 79.6 ± 8.8 kg) of regional (n = 9), national (n = 4) and international (n = 5) standards participated in this study, each performing a series of twelve forehand jump smashes from a racket-fed lift via an international coach/player, representative of match conditions. A range of abilities were used to provide a variety of maximal smash speeds, facilitating an investigation into causal factors associated with this variation. Testing procedures were explained to each participant, and informed written consent was obtained in accordance with the guidelines of the Loughborough University Ethical Advisory Committee (SSEHS-1959).

2.2. Data Collection

An eighteen-camera Vicon Motion Analysis System (400 Hz; OMG Plc, Oxford, UK) was used to collect three-dimensional kinematic data of the participant, racket and shuttlecock on a mock badminton court within a hall of sufficient height. Forty-seven 14 mm retroreflective markers were attached to the participant (Figure 1), where joint centres were calculated from a pair of markers placed across the joint so that their midpoint coincided with the joint centre [10]. Hip, thorax, neck and head joint centres were calculated according to Worthington et al. [11]. A further marker was placed on the bottom of the racket handle, seven pieces of 3M Scotchlite reflective tape were attached to the racket frame and a single piece of reflective tape was attached around the base of the cork of the shuttlecock (Figure 2). Participants used their own racket and new Yonex AS40 shuttlecocks throughout, where misshapen or broken shuttlecocks were removed.

Figure 1. Participant marker locations.

Figure 2. Racket and shuttlecock marker locations.

2.3. Data Reduction

Position data were labelled within Vicon Nexus 1.7.1 where gaps within marker trajectories were filled using the "pattern-filled" function where possible, and "spline-filled" function thereafter. All position data were then imported into Matlab v.2018b (The MathWorks Inc., Natick, MA, USA) for all further processing. Position data of all body markers were filtered using a fourth-order, zero-phase, low-pass Butterworth filter with a cut-off frequency of 30 Hz, determined through residual analysis [12]. Racket and shuttlecock markers remained unfiltered to avoid double-filtering during subsequent curve-fitting methodologies.

Joint angles were calculated using three-dimensional rotation matrices, defining the rotation applied to the proximal segment coordinate system to bring it into coincidence with the coordinate system of the distal segment [12]. An XYZ rotation sequence was used, representing flexion–extension, adduction–abduction and longitudinal axis rotation, respectively. When describing humerothoracic motion, a YZY rotation sequence was used as recommended by ISB [13], using a different coordinate system for the humerus segment where xyz represented adduction–abduction, longitudinal axis rotation and flexion–extension, respectively. Wrist angles were normalised based on the player adopting their normal grip within a static trial, which was considered the neutral position. The mean offset was 28.8 ± 8.4° and 7.1 ± 7.4° of palmar extension and ulnar deviation, respectively. X-factor referred to the separation angle between vectors connecting the right and left shoulder joint centres and, the right and left hip joint centres, respectively, in the transverse plane [14]. Centre of mass was calculated using segment inertial values from de Leva [15], where the body was modelled as fourteen segments. Jump height was defined as the difference between the maximum centre of mass height and the height of that during a static standing trial. Table 1 details the joint angles calculated.

Table 1. Calculated joint angles, with their relative zero positions and positive directions.

Joint	Motion	Anatomical Position (°)	Positive Direction
Shoulder	Internal/External Rotation	†	Internal Rotation
Elbow	Flexion/Extension	0	Extension
	Pronation/Supination	0	Supination
Wrist	Palmar Flexion/Extension	180	Extension
	Ulnar/Radial Deviation	0	Ulnar Deviation
Trunk	X-Factor (Transverse Plane)	0	‡

† For further details on motion of the shoulder joint as a result of the ISB rotation sequence recommendations, see Wu et al. [13]. ‡ Positive direction relates to the direction of rotation during the forward swing of the movement, i.e., anticlockwise for a right-handed player. Note transverse plane is viewed from above.

Instantaneous post-impact shuttlecock speed and racket–shuttlecock contact timing were determined using a logarithmic curve-fitting methodology [16] with minor adjustments for the application to the badminton smash. The time of impact was derived from the intersection of pre- and post-impact shuttlecock displacement curves in the global anterior–posterior direction (dominant direction of the smash), and an intermediate 1 ms contact period [17] was added between the pre- and post-impact shuttlecock curves, where the racket face and shuttlecock velocity were assumed equal. Post-impact shuttlecock speed was determined via differentiation of the post-impact logarithmic shuttlecock displacement curve. Racket head speed was the component of the linear racket head centre linear velocity acting perpendicular to the racket stringbed. The pre-impact racket head speed data was then interpolated to the calculated time of initial shuttlecock contact.

Based upon previous literature within badminton, the movement was defined around two phases, defined as backswing and acceleration phases [18]. Five discrete instants were identified such that trials could be compared appropriately: preparation (P) was defined as the point at which centre of mass height was minimal [2]; end of retraction (ER) was defined as the point at which the racket was most medio-laterally positioned towards the non-dominant side of the participant within the global coordinate system; racket lowest point (RLP) when the racket tip was at its lowest vertical point [19]; and turning point (TP) was defined as the point, after minimum (most negative), at which the racket head speed became positive [4] and shuttlecock contact (SC) was defined as the closest motion capture frame to the previously defined instant of racket-shuttlecock contact. The backswing phase (BSP) was defined as the time between PP and TP, whereas the acceleration phase (AP) was defined as the time between TP and SC.

Five joint angles (Table 1) were calculated for each trial, describing the elements of badminton smash technique which have previously been linked to shuttlecock velocity in literature or thought to be linked to shuttlecock velocity. Joint angles were defined at each key instant and their maximum range of motion through to SC calculated, e.g., maximum external rotation angle through to angle at contact. Furthermore, post-impact shuttlecock speed; racket head speed at impact; jump height; and peak shoulder, elbow and wrist joint centre linear velocities were calculated for each trial. Length of phases (BSP and AP), as well as total swing time, were also calculated for each trial. All kinematic variables for each player's trial with the greatest shuttlecock speed were entered into subsequent correlation analyses.

2.4. Statistical Analysis

All statistical correlational analyses were performed in Matlab v.2018b (The MathWorks Inc., Natick, MA, USA). Pearson product moment correlation analyses were performed between each kinematic (independent) variable and shuttlecock speed. Pearson product moment correlations (r) and their 95% confidence intervals (CI) were interpreted as negligible < 0.3; $0.3 \leq$ low < 0.5; $0.5 \leq$ moderate < 0.7; $0.7 \leq$ high < 0.9; very high ≥ 0.9 [20]. An alpha value of 0.05 was used to determine significance. Correlates were then entered as "candidate" variables into a forwards stepwise multiple linear regression model to identify key kinematic parameters that best explain variation in shuttlecock speed. Entry requirements for inclusion of a parameter were $p < 0.05$, with a removal coefficient of $p > 0.10$. The regression model was rejected if the 95% CI coefficients included zero, the residuals of the predictor were heteroscedastic or if the bivariate correlations, tolerance statistics or variance inflation factors showed any evidence of multicollinearity [21–25]. The normality of the standardised residuals in the regression model was also confirmed using the Shapiro–Wilk test. The percentage of variance in the dependent variable explained by the independent variables (predictors) within the regression equation was determined by Wherry's adjusted R^2 value [26]. Multiple linear regression analysis was performed in IBM SPSS Statistics 23 (IBM, Armonk, NY, USA).

3. Results

Maximal shuttlecock speeds for the cohort were 89.6 ± 5.3 m·s^{-1} (range: 80.1–99.8 m·s^{-1}). Racket head speeds at SC achieved during these trials were 56.3 ± 4.0 m·s^{-1} (range: 46.7–64.6 m·s^{-1}). Five kinematic variables were significantly correlated with shuttlecock speed, where a greater racket head speed, greater peak wrist joint centre linear velocity and shorter acceleration phase duration were associated with greater shuttlecock speeds. Likewise, greater shoulder internal rotation at SC and more negative X-factor at ER produced greater shuttlecock speeds. No other variables were significantly correlated to shuttlecock speed (Tables 2–4). Means and standard deviations, as well as a time-normalized comparison between the "fastest" and "slowest" participant for shoulder internal rotation angle, X-factor and racket head speed are shown in Figures 3–5, respectively.

Table 2. Pearson product moment correlation (r) between each of racket head speed, jump height, phase durations, joint centre linear velocities and ranges of motion, and shuttlecock speed.

Kinematic Variable	Key Instant/Phase	Mean (SD)	r	95% CI	p
Racket Head Speed ($m{\cdot}s^{-1}$)	SC	56.3 (4.0)	0.903	0.753, 0.964	<0.001 *
Jump Height (cm)		31.6 (9.2)	0.454	−0.017, 0.760	0.059
Phase duration (ms)	BSP	509.0 (94.8)	0.412	−0.067, 0.737	0.089
	AP	38.1 (5.2)	−0.543	−0.805, −0.101	0.020 *
	TS	547.1 (92.5)	0.392	−0.092, 0.726	0.108
Peak Shoulder JC LV ($m{\cdot}s^{-1}$)		3.5 (0.4)	0.177	−0.316, 0.595	0.482
Peak Elbow JC LV ($m{\cdot}s^{-1}$)		8.3 (0.8)	0.353	−0.136, 0.704	0.151
Peak Wrist JC LV ($m{\cdot}s^{-1}$)		14.2 (1.7)	0.767	0.467, 0.908	<0.001 *
Shoulder IR ROM (°)	Peak−SC	98.1 (20.7)	0.403	−0.079, 0.732	0.097
Elbow Flexion ROM (°)	Peak−SC	106.0 (7.9)	0.016	−0.454, 0.479	0.950
Elbow PRO ROM (°)	Peak−SC	21.2 (14.9)	0.298	−0.197, 0.671	0.230
Wrist Flexion ROM (°)	Peak−SC	40.4 (12.5)	−0.242	−0.254, 0.637	0.333
X−Factor ROM (°)	Peak−SC	46.0 (9.4)	0.208	−0.287, 0.615	0.408

Abbreviations: CI: confidence interval, BSP: backswing phase, AP: acceleration phase, TS: total swing, JC LV: joint centre linear velocity, IR: internal rotation, ROM: range of motion, PRO: pronation. * Significant ($p < 0.05$) .

Table 3. Pearson product moment correlation (r) between joint angles of the shoulder and elbow at key instants and shuttlecock speed.

Kinematic Variable	Key Instant/Phase	Mean (SD)	r	95% CI (Lower, Upper)	p
Shoulder INT/EXT Rotation Angle (°)	P	102.4 (29.8)	0.324	−0.168, 0.678	0.189
	ER	1.9 (8.8)	0.013	−0.457, 0.477	0.959
	RLP	−33.6 (8.2)	0.161	−0.331, 0.584	0.523
	TP	−29.2 (13.7)	0.299	−0.195, 0.672	0.228
	SC	58.7 (20.0)	0.508	0.054, 0.788	0.031 *
Elbow Flexion Angle (°)	P	88.4 (19.8)	0.329	−0.163, 0.690	0.183
	ER	64.9 (8.0)	−0.206	−0.614, 0.289	0.413
	RLP	74.2 (9.8)	0.161	−0.648, 0.236	0.298
	TP	120.6 (10.5)	0.225	−0.271, 0.626	0.370
	SC	166.1 (4.3)	0.243	−0.252, 0.638	0.331
Elbow Pronation Angle (°)	P	−61.6 (17.5)	0.398	−0.084, 0.730	0.102
	ER	−99.4 (20.0)	−0.180	−0.597, 0.313	0.475
	RLP	−84.0 (13.2)	0.120	−0.556, 0.368	0.636
	TP	−95.4 (15.4)	−0.376	−0.717, 0.111	0.125
	SC	−101.5 (19.0)	−0.420	−0.741, 0.059	0.083

Abbreviations: KI: key instant, CI: confidence interval, INT: internal, EXT: external, P: preparation, ER: end of retraction, RLP: racket lowest point, TP: turning point, SC: shuttlecock contact. * Significant ($p < 0.05$).

Table 4. Pearson product moment correlation (r) between joint angles of the wrist and X-factor at key instants and shuttlecock speed.

Kinematic Variable	Key Instant/Phase	Mean (SD)	*r*	95% CI (Lower, Upper)	*p*
Wrist Flexion Angle (°)	P	191.0 (13.0)	0.368	−0.120, 0.712	0.133
	ER	208.2 (10.6)	−0.134	−0.565, 0.356	0.598
	RLP	225.4 (9.9)	0.146	−0.344, 0.574	0.563
	TP	225.8 (9.3)	0.021	−0.451, 0.483	0.935
	SC	187.8 (8.9)	0.190	−0.304, 0.603	0.451
X−factor (°)	P	0.8 (8.6)	0.024	−0.448, 0.485	0.926
	ER	−33.3 (5.8)	−0.484	−0.775, −0.022	0.042 *
	RLP	−23.5 (7.1)	−0.362	−0.709, 0.126	0.140
	TP	−5.2 (7.6)	−0.175	−0.593, 0.318	0.489
	SC	7.9 (7.9)	−0.077	−0.525, 0.404	0.760

Abbreviations: KI: key instant, CI: confidence interval, P: preparation, ER: end of retraction, RLP: racket lowest point, TP: turning point, SC: shuttlecock contact. * Significant ($p < 0.05$).

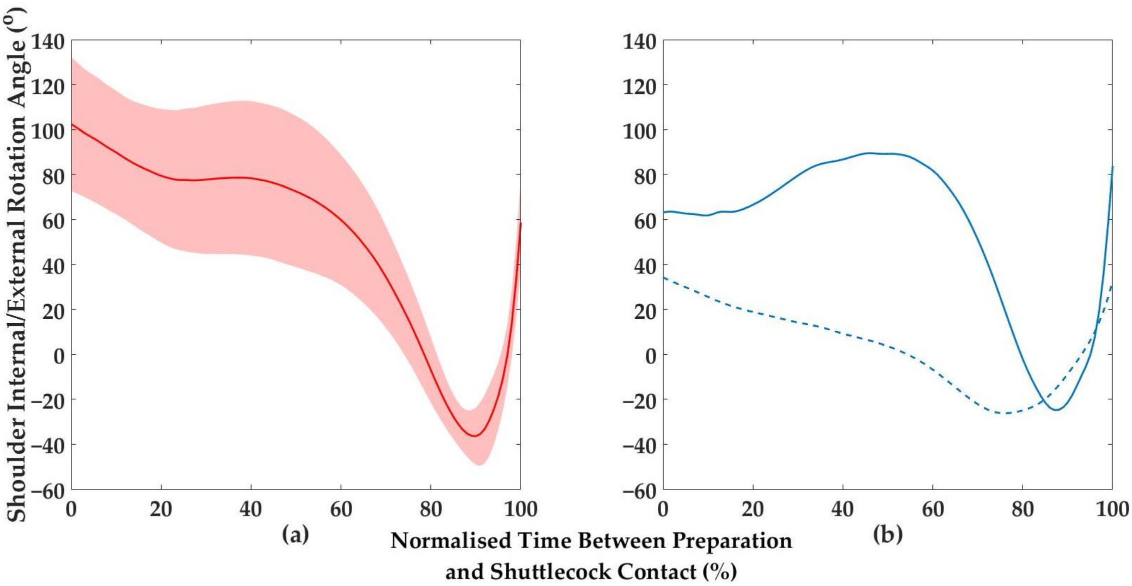

Figure 3. (**a**) Mean (solid line) ± SD (shaded area) for the normalised racket arm shoulder internal/external rotation angle between preparation and shuttlecock contact key instants. (**b**) Normalised racket arm shoulder internal/external rotation angle between preparation and shuttlecock contact key instants, for participants with the fastest (solid line) and slowest (dashed line) participant's smash. Internal rotation (positive); external rotation (negative). A significant correlation between shuttlecock speed and shoulder internal rotation angle was present at shuttlecock contact.

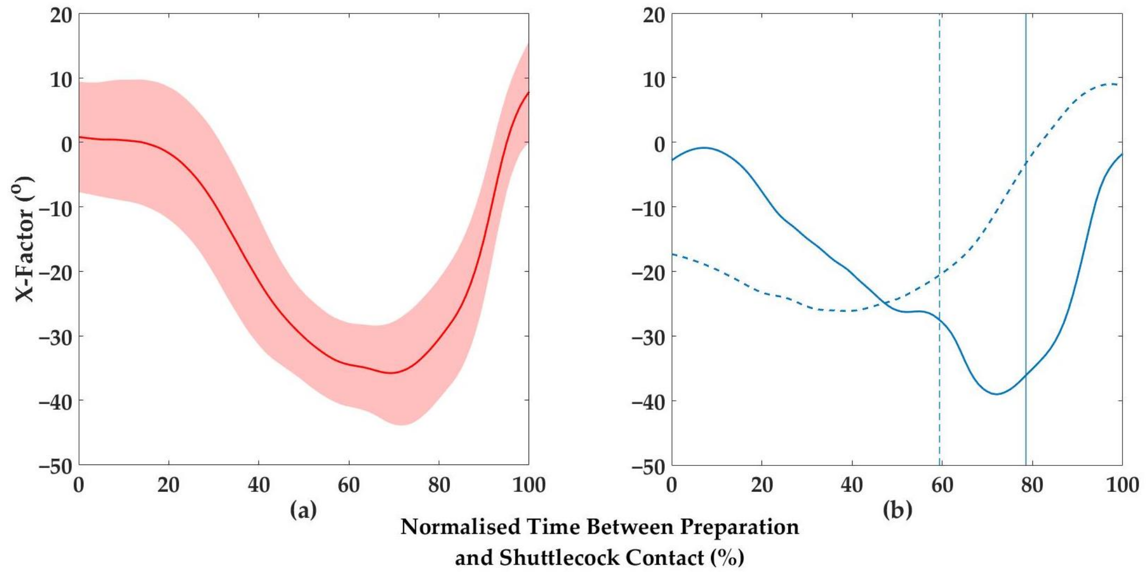

Figure 4. (**a**) Mean (solid line) ± SD (shaded area) for normalised X-factor between preparation and shuttlecock contact key instants for all participants; (**b**) Normalised X-factor between preparation and shuttlecock contact key instants for participants with the fastest (solid line) and slowest (dashed line) smash. The end of retraction (ER) key instant for each participant is represented by a vertical line. X-factor at ER was significantly correlated with shuttlecock speed.

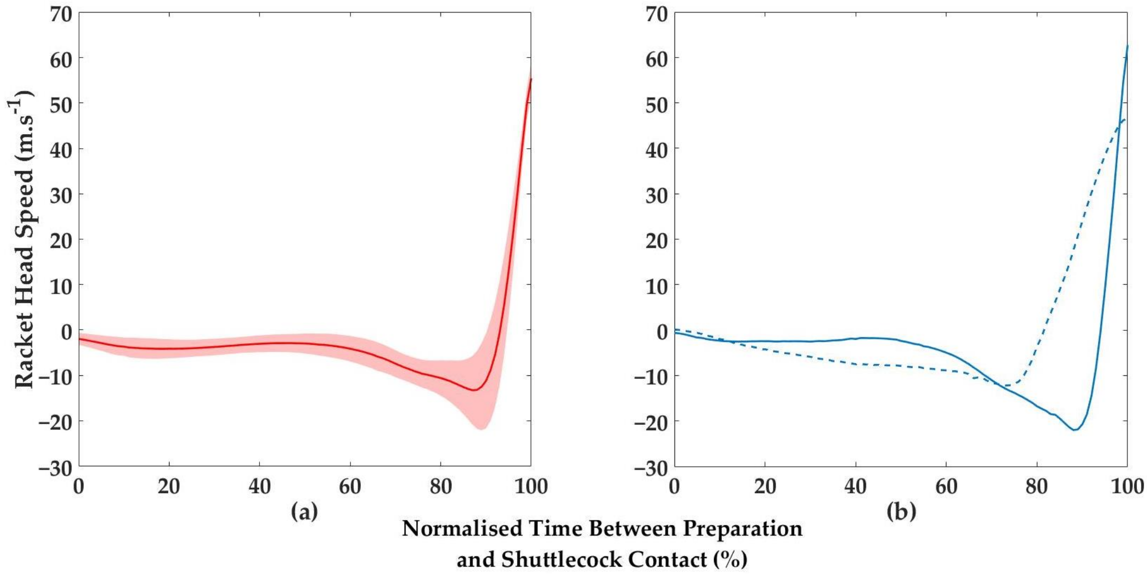

Figure 5. (**a**) Mean (solid line) ± SD (shaded area) for the normalised racket head speed between preparation and shuttlecock contact key instants for all participants; (**b**) Normalised racket head speed (normal to the stringbed plane) between preparation and shuttlecock contact key instants for participants with the fastest (solid line) and slowest (dashed line) smash. The acceleration phase begins at the point at which the racket head speed becomes positive, following the initial negative peak, and the duration between this turning point and shuttlecock contact was significantly negatively correlated with shuttlecock speed.

Multiple regression analysis revealed that the duration of AP alone explained 25.0% of the variation in shuttlecock speed, with a standard error of the estimate (SEE) of 4.4 $m{\cdot}s^{-1}$. The addition of X-factor at ER explained 43.7% of the variance in post-impact shuttlecock speed (SEE = 3.8 $m{\cdot}s^{-1}$), where a shorter acceleration phase and a more negative X-Factor at ER caused greater shuttlecock speeds (Table 5; Figure 6).

Table 5. Multiple regression equations explaining variance in shuttlecock speed.

Model	Kinematic Parameters	Coefficient	95% CI		Variable, p	Model		
			Lower Bound	Upper Bound		Percent Explained	p	SEE
a	(Constant)	110.1	93.2	127.0	<0.001	25.0	0.02	4.4
	AP Duration	−536.5	−976.8	−96.2	0.020			
b	(Constant)	95.8	76.7	114.9	<0.001	43.7	0.05	3.8
	AP Length	−514.0	−898.1	−129.9	0.012			
	X−Factor at ER	−0.4	−0.7	−0.1	0.024			

Abbreviations: CI: confidence intervals, SEE: standard error of the estimate, AP: acceleration phase, ER: end of retraction.

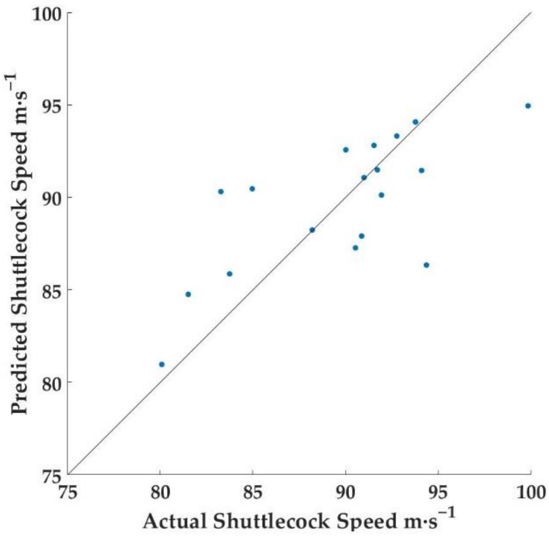

Figure 6. Predicted shuttlecock speed against actual shuttlecock speed for the two-parameter stepwise regression equation (Table 5; Model b). With a higher percentage of the variation in shuttlecock speed explained the closer the data points lie to the line y = x (predicted shuttlecock speed = actual shuttlecock speed).

4. Discussion

Racket head speeds and shuttlecock speeds achieved by the participants showed good agreement with previously reported values by elite players [2,27,28]. Shuttlecock speed was greatest in the international players (94.4 ± 3.2 $m{\cdot}s^{-1}$), followed by national players (91.2 ± 2.6 $m{\cdot}s^{-1}$) and then regional players (86.4 ± 4.6 $m{\cdot}s^{-1}$), suggesting that the ability to achieve greater post-impact shuttlecock speeds is a good indication of playing level [29]. A one-way ANOVA revealed a significant difference in shuttlecock speed between groups ($F_{(2,15)} = 7.29$, $p = 0.006$). Bonferroni post-hoc tests revealed the international group smashed significantly faster than the regional group (mean difference = 8.06 $m{\cdot}s^{-1}$, CI: 2.22, 13.90; $p = 0.006$). The national group were not significantly different to either the international or regional groups. Five kinematic variables correlated significantly with shuttlecock speed: racket head speed at impact, peak wrist joint centre linear velocity, length of the acceleration phase, shoulder internal rotation angle at SC and X-factor (transverse) at ER. These results are indicative of proximal joint motions (shoulder and trunk) causing greater linear velocities in the distal segments (wrist and racket).

Racket head speed at impact, normal to the stringbed plane, correlated very highly (r = 0.903; CI: 0.753, 0.964; $p < 0.001$) with instantaneous post-impact shuttlecock speed. This is a larger effect size than those previously reported [2,27], which may be due to the more accurate calculation of post-impact shuttlecock speed i.e., at a precise time of impact, and an appropriate racket head speed (normal to the stringbed plane) interpolated to the time of initial contact with the shuttlecock in the present study. The non-perfect relationship between racket head and shuttlecock speed may be due to differences in racket specifications used by each player, where impact efficiency (location and coefficient of restitution), as well as mass properties of the racket, will affect the amount of linear momentum transferred to the shuttlecock, for a given impact velocity. Longitudinal impact locations, calculated using the previously described methodology of Peploe et al. [16], ranged between −29.4 and 24.9 mm from the racket head centre, whereas medio-lateral impact locations ranged between −33.2 and 17.1 mm from the racket head centre (medial–negative, lateral–positive; relative to the player). Modelling the racket as two segments (handle and frame) and assuming a frame transverse angular velocity of 80 rad·s^{-1} at impact, consistent with experienced players [28], the difference in racket head speed at the most proximal and distal longitudinal impact locations would be 4.3 m·s^{-1}, suggesting that impact location can have a large effect on subsequent shuttlecock speed, even given identical input in terms of racket angular velocities.

As well as racket head speed, peak linear velocity of the wrist joint centre, was found to be a strong predictor of shuttlecock speed (r = 0.767; CI: 0.467, 0.908; $p < 0.001$), indicating that players should ultimately aim to achieve high linear velocities within distal components of the kinetic chain. This correlation was stronger than previous reported by Rambely et al. [4] in elite international players, who reported a low positive relationship (r = 0.454) despite mean values in the present study showing good agreement (14.2 vs. 11.7 m·s^{-1}) with differences attributable to the variety in player ability in the present study and differences in capture frequency (400 vs. 50 Hz), where 50 Hz may be inadequate for the badminton smash [28]. Greater shuttlecock speeds were also produced when AP was shorter in duration (r = -0.543; CI: -0.805, −0.101; $p = 0.020$), demonstrated in Figure 5b, where the racket head speed becomes positive much closer to impact, when comparing the “fastest” to the “slowest” participant.

Furthermore, two kinematic technique factors significantly correlated with shuttlecock speed. First, players who were in a position of greater shoulder internal rotation at impact produced greater shuttlecock speeds (r = 0.508, moderate; CI: 0.054, 0.788; $p = 0.031$), where a clear difference in position between the “fastest” and “slowest” player is shown in Figure 3b, despite very similar minimum positions. This suggests that greater shoulder internal rotation allows more work done by this joint rotation, which Liu et al. [6] found contributed 66% towards racket head velocity. However, correlational analysis revealed a non-significant relationship between shoulder internal rotation range of motion and shuttlecock speed (r = 0.403, low; CI: −0.079, 0.732; $p = 0.097$). When accounting for the time in which this range was completed, i.e., average angular velocity, the correlation came closer to significance (r = 0.444, low; CI: −0.029, 0.755; $p = 0.065$). Second, a low negative correlation was found between X-factor at ER and shuttlecock speed (r = 0.484; CI: −0.755, −0.022; $p = 0.042$), where players who produced a greater pelvis–thorax separation angle in the transverse plane at ER produced greater shuttlecock speeds. Again, a clear difference is seen between the “fastest” and “slowest” participants in Figure 4b. X-factor (maximum pelvis-thorax separation) has previously been found to be a strong correlate (r = 0.60, $p < 0.01$) with shuttlecock speed [12]. A greater rotational countermovement of the torso presumably allows greater trunk rotation contribution to racket head speed, which Teu et al. [9] found to contribute 57% to racket head speed.

It has been previously reported that both peak vertical ground reaction force and jump height significantly correlate with shuttlecock speed (r = 0.548 and 0.508, respectively) [2]. The present study found a non-significant correlation, with CI marginally crossing zero, between jump height and shuttlecock speed (r = 0.454; CI: −0.017, 0.760; p = 0.059); however, a similar effect size. Perhaps greater jump heights are a characteristic of more able players, who typically produce greater shuttlecock speeds [12,29], and serves as a tactical factor allowing players to produce steeper smash strokes as opposed to producing greater shuttlecock speeds. Note that jump height was significantly correlated with racket head speed in the present study (r = 0.494; CI: 0.035, 0.781; $p = 0.037$).

The fact that distal linear velocities (wrist and racket) best explain variation in shuttlecock speed, yet proximal angles of the trunk and shoulder best explain variation in shuttlecock speed, is suggestive of the kinetic link principle whereby movements of a proximal-to-distal nature generate and conserve angular momentum to produce high distal end-point velocities [5,30–32]. Important longitudinal axis rotations, typically difficult to measure and observe, may not always follow this strict sequence with regards to timing, however the proximal-to-distal nature of overhead strokes provides a good general understanding of how high distal end-point velocities can be generated [33,34]. A more negative X-factor at ER causing greater shuttlecock speed endorses the idea of the stretch–shortening cycle, whereby more elastic energy is stored and recovered to enhance the concentric phase when X-factor is more negative at ER. The stretch–shortening cycle has been linked to greater velocities in throwing actions due to enhancement of the concentric phase [35,36]. Finally, no ranges of motion were found to significantly correlate with shuttlecock speed. Lees et al. [32] previously suggested that increasing the range of motion can improve performance (racket head speed) by increasing the acceleration path of the racket, allowing more muscular force to be generated and applied to accelerate the racket.

A further relevant biomechanical principle, not explored in this study, is the velocity lever principle [32]. The angle between the forearm and racket longitudinal axes is of importance for generating racket head speed. For example, if the racket is held at 90° to the forearm, then the racket head will move through the greatest distance when the forearm pronates, increasing the racket head linear speed for any given angular velocity of pronation [31]. Likewise, if the elbow is flexed at 90°, the contribution from shoulder internal rotation is maximised [30]. This principle is difficult to analyse within a complex motion such as the badminton smash, as multiple segmental rotations are responsible for producing the racket motion, as well as ensuring racket head orientation is optimal at impact, which may make certain joint angles, such as a racket–forearm angle of 90°, undesirable. Tang et al. [37] reported that within their cohort of four elite players, the average racket–forearm angle was 147°, which may represent a suitable compromise between the height and the speed at contact in practical play.

The multiple linear regression analysis found that two predictor variables were able to explain 43.7% of the variance in shuttlecock speed (Table 5; Figure 6). Participants with the fastest smashes were found to have a shorter acceleration phase duration and more negative (greater separation) X-factor at ER. From a practical standpoint, this would suggest that players attempt to delay the onset of their forward swing (when the racket head velocity normal to the stringbed becomes positive) such that the forward swing can be completed in the shortest possible time. This would ultimately achieve a greater velocity of the racket, i.e., the same acceleration path of the racket for a given player but completed in a shorter time period [31]. Additionally, players should seek to utilise as much counter-rotation of the trunk as possible before reversing this rotation within the acceleration phase.

A potential limitation to the present study was use of each participant's own racket causing a lack of experimental control over the impact mechanics between racket and shuttlecock, including effective mass of the "racket particle" within the collision between racket and shuttlecock, and thus the momentum transferred [27]. The effect of racket properties on player kinematics is also a potential source of limitation, where Whiteside et al. [38] reported that increasing the "swingweight" of the racket caused a reduction in peak angular velocities of shoulder internal rotation and wrist flexion during the tennis serve, where both of these joint rotations have been reported to be the two greatest contributors to racket head speed at impact [39]. Conversely, players are accustomed to their own racket, and introducing a "control" racket may require a great amount of familiarization or cause suboptimal performances due to unfamiliarity with the racket. It must also be acknowledged that the present study relies on investigation of joint kinematics at discrete time points (i.e., key instants). Future studies may therefore extend the current work using methodologies to investigate the continuous time series of kinematic data, such as statistical parametric mapping [40], vector coding [41] or principal component analysis [42], as well as considering other biomechanical principles not explored within this study. Additionally, differences in anthropometric data were not accounted for, where the same angular velocities and joint angles may lead to different linear velocities. Retrospective power analysis revealed that for the lowest significant correlation coefficient (r = 0.484), with 80% power and a significance threshold (p = 0.05), a sample size of 31 would be required. The study was therefore underpowered; however, recruiting more participants meeting the minimum standard criteria was not achievable.

5. Conclusions

In conclusion, proximal kinematics explained the greatest proportion of variation in shuttlecock speed during the forehand jump smash stroke in a cohort of experienced male badminton players. From a practical standpoint, it is suggested that players and/or coaches attempt to produce high shuttlecock speeds by increasing racket and distal joint centre linear velocities. This should be achieved primarily by having a greater internal rotation angle at shuttlecock contact. Furthermore, greater pelvis–thorax separation during the backswing phase is likely to aid the concentric phase of the swing via the stretch–shortening cycle.

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