RELATIONSHIPS BETWEEN WHOLE-BODY KINEMATICS AND BADMINTON JUMP SMASH RACKET HEAD SPEED

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The purpose of this study was to identify kinematic determinants of shuttlecock speed in the badminton jump smash. Three-dimensional kinematic (400 Hz) data were collected for 18 experienced male badminton players using an 18 camera Vicon Motion Analysis System. Each participant performed 12 jump smashes. The trial with the fastest shuttlecock speed per participant was analysed using an 18-segment rigid body model. Parameters were calculated describing elements of the badminton jump smash technique. Four kinematic variables were significantly correlated with racket head speed. Greater peak wrist joint centre linear velocity, jump height, shorter acceleration phase, and greater shoulder internal rotation at shuttlecock / racket impact.

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

INTRODUCTION: The forehand smash is an effective attacking shot in badminton, accounting for 54% of ‘unconditional winner’ and ‘forced failure’ shots in international matches (Tong & Hong, 2000). A shuttlecock with a greater post-impact speed will give an opponent less time to return the shuttlecock. Few studies have investigated the kinematic determinants of shuttlecock speed in the badminton smash by elite players. Ramasamy et al. (2019) revealed three kinematic variables significantly associated with shuttlecock speed: maximal wrist angular velocity during the acceleration phase (*i.e.* start of the forward swing to contact); maximal racket head speed between backswing and contact; and jump height, defined as minimum to maximum centre of mass height. Ultimately, racket head speed is the most important variable for producing shuttlecock speed as shuttlecock speed is determined by the transfer of momentum during the collision between the racket stringbed and shuttlecock. 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. Rambely et al. (2005) found that the wrist was the predominant contributor (26.5%), whilst the elbow and shoulder joints contributed 9.4% and 7.4%, respectively, towards racket tip velocity. Additionally, use of low frame rates and unclear methodologies for defining both shuttlecock speed and racket head speed mean that it is difficult to compare results. This study aimed to identify full-body kinematic parameters that best explain the generation of post-impact racket head velocities in the badminton jump smash.

METHODS:

Participants

Eighteen male badminton players (24.3 ± 7.1 years; 1.84 ± 0.08 m; 79.6 ± 8.8 kg) of regional (n = 9), national (n = 4), and international (n = 5) standard participated in this study. Each performed twelve forehand jump smashes from a racket-fed lift via an international coach / player, representative of match conditions. Testing procedures were explained to each participant, and informed written consent was obtained in accordance with the institutional ethics committee.

Data Collection

Forty-seven 14 mm retro-reflective markers were attached to the participant (Figure 1). An 18 camera Vicon Motion Analysis System (400 Hz; OMG Plc, Oxford, UK) collected 3D kinematic data of the participant, racket and shuttlecock on a badminton court. Joint centres were calculated from a pair of markers placed across the joint so that their midpoint coincided with the joint centre (McErlain-Naylor et al., 2014). Hip, thorax, neck and head joint centres were calculated according to Worthington et al. (2013). 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 1). Participants used their own racket and new Yonex AS40 shuttlecocks throughout.

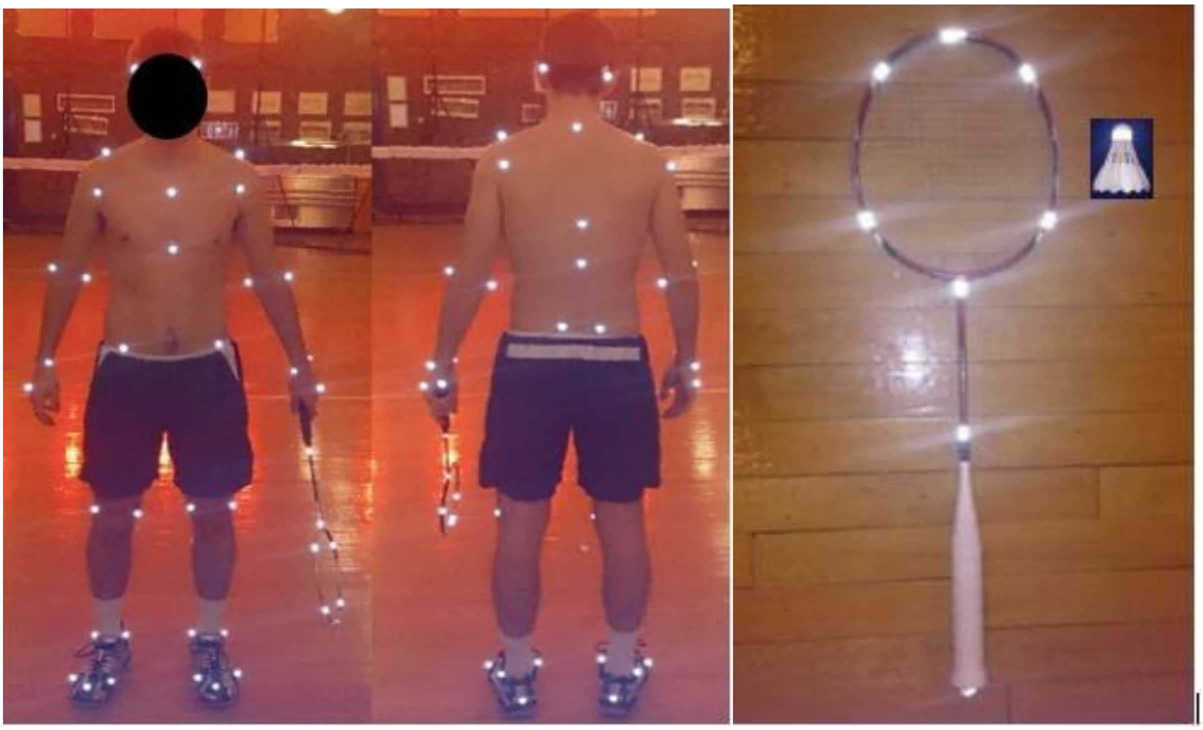

Figure 1. Marker locations for the participants; racket and shuttlecock marker locations.

Data Reduction

Position data were labelled within Vicon Nexus 1.7.1 and imported into Matlab v.2018b 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. Six angles were calculated for each trial: shoulder internal / external rotation; elbow flexion / extension; elbow pronation / supination; wrist palmar flexion / extension; wrist ulnar / radial deviation; and X-factor. Joint angles were calculated using three-dimensional rotation matrices, defining the rotation applied to the proximal segment coordinate system in order to bring it into coincidence with the coordinate system of the distal segment. 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 (Wu et al. 2005). Wrist angles were normalised based on the player adopting their normal grip within a static trial, which was considered the neutral position. 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 global transverse plane. Instantaneous post-impact shuttlecock speed and racket- shuttlecock contact timing were determined using a logarithmic curve-fitting methodology (Peploe et al., 2018) with minor adjustments for application to the badminton smash. Pre- impact racket head centre velocity was interpolated to the calculated time of initial shuttlecock contact. Due to the focus on investigating maximal performance each player’s trial with the greatest shuttlecock speed was used for further analysis.

The movement was defined around the backswing and acceleration phases, divided by five discrete instants: preparation was the point at which the centre of mass height was minimal; end of retraction was 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 was when the racket tip was at its lowest vertical point (Martin et al. 2012); turning point was the point, after minimum (most negative), at which the racket head velocity normal to stringbed became positive; and shuttlecock contact was the closest motion capture frame to the previously defined instant of racket-shuttlecock contact. The backswing phase was the time between preparation and turning point, whilst the acceleration phase was the time between turning point and shuttlecock contact. Joint angles were defined at each key instant and their maximum range of motion through to contact calculated. Furthermore, post-impact shuttlecock speed, racket head speed at impact, jump height and peak shoulder, elbow, wrist joint centre linear velocities were calculated for each trial. Duration of phases, as well as total swing time were also calculated for each trial.

Statistical Analysis
All statistical analyses were performed in Matlab v.2018b. Pearson product moment correlation analyses, including 90% confidence intervals (CI) were performed between each kinematic (independent) variable and racket head speed. An alpha of 0.1 determined significance.

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 were 56.3 ± 4.0 m·s^{-1} (range: 46.7 - 64.6 m·s^{-1}). Four kinematic variables were significantly correlated with racket head speed. Greater peak wrist joint centre linear velocity (r = 0.712; CI: 0.507, 0.917; p < 0.001), jump height (r = 0.494; CI: 0.035, 0.781; p = 0.037), shorter acceleration phase (r = -0.600; CI:-0.833, -0.184; p = 0.009) and greater shoulder internal rotation at shuttlecock contact (r = 0.563; CI: 0.131, 0.816; p = 0.015) were associated with greater shuttlecock speeds. It should be noted that the elbow pronation angle at preparation (r = 0.495; CI: 0.036, 0.781; p = 0.037) was found to be significantly correlated with racket head speed, however upon inspection of the data it was evident that this correlation was entirely due to one player. This player had a very large pronation angle at this key instant, which was coincidentally the player with both the slowest shuttlecock and racket head speed. This result was therefore discounted and ignored.

DISCUSSION: Racket head speeds achieved by the participants showed good agreement with previously reported values by elite players (Ramasamy et al., 2019; Kwan. M., 2010; Kwan et al., 2011). Racket head speed at impact, normal to the stringbed plane, correlated very highly with instantaneous post-impact shuttlecock speed (r = 0.903; CI: 0.753, 0.964; p < 0.001) justifying the use of racket head speed as a performance variable. Whilst jump height was significantly correlated with racket head speed and Ramasamy *et al.* (2019) also found that our thoughts are that jump height in the smash is a characteristic of more able players attempting to produce steeper smash strokes, rather than being a causal variable of faster racket head speeds and shuttle speeds.

Distal linear velocities (wrist) explained the variation in racket head speed, yet proximal angles of the trunk and shoulder also explained the variation in racket head speed. This 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. 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 (Marshall, 2000; Fleisig et al., 2003). A more negative X-factor at end of retraction causing greater racket head speed endorses the idea of the stretch–shortening cycle, whereby more elastic energy is stored and recovered to enhance the concentric phase. The stretch–shortening cycle has been linked to greater velocities in throwing actions due to enhancement of the concentric phase (Elliott, 2006; Elliot et al., 1999). Finally, no ranges of motion were found to significantly correlate with racket head speed although Lees et al. (2008) 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.

The velocity principle, not explored in this study, may also be critical to understanding the development of greater distal velocities in the badminton smash motion (Lees *et al.* 2008). This principle relates to how the angle between segments influences the effect of proximal rotations. For example, if the elbow angle is 90° the effect of shoulder internal rotation is maximised. Similarly, if the racket is held at 90° to the forearm segment, the contribution from radio-ulnar pronation is maximised. This is a difficult principle to observe, due to the complex nature of the badminton smash motion, where multiple joint rotations are responsible for generating racket head speed (Liu *et al.* 2002). Tang *et al.* (1995) reported that amongst four elite players, the forearm-racket angle was 147°, which suggests a compromise between the height and speed at contact between racket and shuttlecock.

Potential limitations existed during this study, including lack of experimental control over the racket and therefore the impact mechanics between the racket and shuttlecock, as well as the effect that the racket properties may cause to the technique and kinematics of the player (Whiteside *et al.,* 2014).

CONCLUSION: This study has shown that proximal kinematic joint angles caused greater linear velocities at distal joint centres and greater racket head speeds. Greater peak wrist joint centre linear velocity, jump height, shorter acceleration phase, and greater shoulder internal rotation at shuttlecock contact were all found to have a significant correlation to racket head speed. It is suggested that players and/or coaches should aim to decrease the length of the acceleration phase of the racket though technique/strength to increase racket head speed.

REFERENCES

Elliott, B. (2006). Biomechanics and tennis. Br. J. Sports Med. 2006, 40, 392–396.

Elliott, B.C.; Baxter, K.G.; Besier, T.F. (1999). Internal rotation of the upper-arm segment during a stretch-shorten cycle movement. J. Appl. Biomech. 1999, 15, 381–395.

Fleisig, G.; Nicholls, R.; Elliott, B.; Escamilla, R. (2003). Kinematics used by world class tennis players to produce high-velocity serves. Sports Biomech. 2, 51–64

Kwan, M. (2010). Designing the World's Best Badminton Racket. Ph.D. Thesis, Aalborg University, Aalborg, Denmark.

Kwan, M.; Andersen, M.S.; Cheng, C.-L.; Tang, W.-T.; Rasmussen, J. (2011). Investigation of high-speed badminton racket kinematics by motion capture. *Sports Eng, 13,* 57–63

Lees, A.; Cabello, D.; Torres, G. (2008). *Science and Racket Sports IV*; Routledge: London, UK.

Marshall, R.N.; Elliott, B.C. (2000). Long axis rotation: The missing link in proximal-to-distal sequencing. J. Sports Sci. 2000, 18, 247–254.

McErlain-Naylor, S., King, M. & Pain, M.T.G. (2014). Determinants of countermovement jump performance: a kinetic and kinematic analysis. *Journal of Sports Sciences, 32*, 1805-1812.

Peploe, C., McErlain-Naylor, S.A., Harland, A.R., Yeadon, M.R. & King, M.A. (2018). A curve fitting methodology to determine impact location, timing, and instantaneous post-impact ball velocity in cricket batting. *Journal of Sports Engineering and Technology, 232*, 185-196.

Ramasamy, Y., Osman, J., Sundar, V. & Joseph, S. (2019). Ground reaction force and kinematics of forehand jumping smash among elite Malaysian badminton players. Proceedings of the 37th International Society of Biomechanics in Sport Conference, Oxford, United States, July 21-25; Walsh, M., Stutz, M., Breen, S., Eds.

Rambely, A.S., Osman, N.A.A., Usman, J. & Abas, W.A.B.W. (2005) The contribution of upper limb joints in the development of racket velocity in the badminton smash. Proceedings of the 23rd International Symposium on Biomechanics in Sports, Beijing, China; Wang, Q., Eds.

Tong, Y.-M. & Hong, Y. (2000). The playing pattern of world's top single badminton players, Proceedings of the 18th International Symposium on Biomechanics in Sports, Hong Kong; Hong, Y., Eds. pp. 825-830.

Worthington, P. King, M. & Ranson, C. (2013). The influence of cricket fast bowlers' front leg technique on peak ground reaction forces. *Journal of Sports Sciences, 31*, 434-441.

Wu, G., van der Helm, F.C.T., Veeger, H.E.J., Makhsous, M., Van Roy, P., Anglin, C., Nagels, J., Karduna, A.R., McQuade, K., Wang, X., Werner, F.W. & Buchholz, B. (2005). ISM recommendation on definitions of joint coordinate systems of various joints for the reporting of human joint motion-Part II: shoulder, elbow, wrist and hand. *Journal of Biomechanics, 36,* 981-992.

Tang, H.P.; Abe, K.; Ae, M.; Katoh, L. 3-D cinematographic analysis of the badminton forehand smash: Movement of the forearm and hand. In Science & Racket Sports; Reilly, T., Hughes, M., Lees, A., Eds.; E & FN SPON: Cambridge, UK, 1995; pp. 113–118.

Whiteside, D.; Elliott, B.; Lay, B.; Reid, M. The effect of racquet swing weight on serve kinematics in elite adolescent female tennis players. J. Sci. Med. Sport 2014, 17, 124–128.