Analysis of the short serve in Badminton and investigation into training to improve the short serve

Researchers:
Dr Jodie Cochrane Wilkie (j.wilkie@ecu.edu.au)
Dr James Croft
Mr Shayne Vial
Prof Anthony Blazevich

School of Medical and Health Science
Centre of Exercise and Sport Science Research
Edith Cowan University
Joondalup
Western Australia

Introduction

Badminton has grown in popularity since it was included in the Barcelona Olympics in 1992, with approximately 200 million active players around the world (Chen et al., 2009; Ghosh et al., 1993; Faude et al., 2007). In 2005, the Badminton World Federation changed the required number of points needed to win a game from 15 to 21 (Phomsoupha & Laffaye, 2015); whilst the number of games per match remained at three. The new points system resulted in shorter match (Chen et al., 2009; Ooi et al., 2009; Faude et al., 2007) despite there being a greater number of rallies. This was partly due to there being shorter rallies and a higher-paced attacking style of badminton (Cabello Manrique, & Gonzalez-Badillo, 2003). Furthermore, the average play-to-rest ratio increased from 1:2.3 to 1:2 (Faccini & Dai Monte, 1996). The new system has therefore put more emphasis on the quality and consistency of the service in an attempt to win the rally in the fewest number of shots (Cabello Manrique & Gonzalez-Badillo, 2003; Faccini & Dai Monte, 1996). There are four main types of serves used in competitive play. All of the service types cause the shuttlecock to follow a parabolic trajectory with varying angles (Chen et al., 2009). The short serve appears to be employed more often than any of the other type of serve in badminton doubles; although this has yet to be explicitly verified. The short serve is a serve where the shuttlecock lands on or near the front line of the service square rather than deep in the square. In doubles matches the goal of the short serve is to force the opponent to hit the shuttlecock at a steep angle in order to clear the net, allowing an offensive player to hit the shuttlecock from a high point, from which it is easier to score a point (Edwards et al., 2005). This will potentially shorten the rally duration as well as the number of shots needed to win the point (Lees, 2003; Chow et al., 2014).

The short serve

Badminton differs from most racquet sports as a second serve is not allowed if a fault is committed on the first serve, e.g. a service error. Players therefore need to be consistently accurate for each serve. The short serve is considered the most common serve used in doubles, which can be executed using either the forehand or backhand stroke, though it is most commonly performed using the backhand (Phomsoupha & Laffaye, 2015; Edwards et al., 2005). A small movement (racquet swing) is needed to execute the short serve This motion may occur predominantly at the elbow or shoulder joint using a push-like movement pattern, or at the wrist joint with a flick-type movement (Cabello Manrique & Gonzalez-Badillo, 2003; Edwards et al., 2005). Many elite badminton players report aiming for the white tape along the top of the net as this guides the athlete to serve the shuttlecock as close to the net as possible. Top-tier coaches and elite players report that a low trajectory with the apex occurring before going over the net as well as a steep drop off constitutes a successful and highly accurate short serve. In addition it was described that the return shot often indicates whether the serve is successful, as the opponent may be forced to play a high shot when an accurate serve is achieved. This is the only serve that requires a high degree of accuracy and low racquet velocity (Gawin et al., 2013).

Importance of the short serve accuracy

In an elite badminton environment, the serve is thought to be the most important shot of a rally (Edwards et al., 2005; Renick, 1977) because an accurate serve can put the opponent in a defensive position (Cabello Manrique & Gonzalez-Badillo, 2003). Conversely, a poor serve can allow the opponent an offensive opportunity. Indeed, the serving side wins only 39% of rallies after an inaccurate serve in comparison to 69% after an accurate serve (Phomsoupha & Laffaye, 2015). This suggests that the serve accuracy has a significant impact on the outcome of the point, although participants in that study were semi-skilled and unskilled athletes in singles matches, and the researchers did not distinguish between service types. Anecdotal evidence suggests that an accurate short serve can be effective in affecting the outcome of a rally between elite badminton players with the optimal short serve trajectory often causing the opponent to play a high shot which is easier to score a point from for the serving team. This could be more evident in elite doubles play due to their

shorter rally durations, suggesting that the service component of a rally could significantly impact the outcome of the rally. However, there is very little published research examining the performance of, or outcome from, the short serve and none that investigates the factors associated with high accuracy. Furthermore, because the opponent generally always returns the serve, the shuttlecock rarely lands on the ground, it may be more appropriate to use the trajectory of the short serve to measure accuracy.

Technique associated with short serve accuracy

A paucity of research has been published that focuses on the short serve in badminton. A video analysis examined arm movement during the forehand long and the backhand short serves (Hussain et al., 2011). The elbow joint was found to significantly influence the velocity of the shuttlecock in both types of serves, but no significant differences were found between the forehand long and short serve wrist and shoulder angles. Shuttle height at contact and the maximum shuttle height during flight also differed. Though the study established that there are differences between each service type, the result that the elbow joint angle was associated with shuttle velocity was to be expected. The study highlights the need for further research to ascertain the specific movement patterns of the short serve that results in a successful (i.e. accurate) serve. Understanding how various segments are coordinated in order to achieve an accurate outcome is essential in the design and development of all aspects in training (i.e. technique, strength and conditioning etc). The relationship between movement patterns and performance accuracy has not been well documented. Two movement patterns that are frequently discussed when assessing technique are throw and push-like movement patterns (Schmidt, 2012; Schorer, Baker, Fath, & Jaitner, 2007). Although, it is commonly assumed that push-like movement patterns are used in accuracy oriented tasks, this has yet to be explicitly verified in the short serve. The server must organise specific joints and segments to move the racquet to contact the shuttlecock in a specific way to produce the desired trajectory. The intricacy is apparent when the a number of combinations an individual might use to perform the short serve is considered, for example, the shoulder joint has three degrees of freedom (DOF), the elbow two, the hand relative to the forearm has three (Dounskaia & Wang, 2014; Sidaway, Sekiya, & Fairweather, 1995). It is unknown if limiting or ‘freezing’ the DOF and simplifying the movement or freeing DOF (Bernstein, 1967) and allowing a more complex movement is most associated with accuracy. Therefore, research is required to determine the movement patterns that are most associated with accurate short serve

Movement variability

Expert performance in precise movements such as the short serve, require low variability of the end effector (e.g. hand and racquet), also known as trajectory (Button et al., 2003; Schöllhorn & Bauer, 1998). However, it may be argued that variability is necessary as performers adapt to multiple changing constraints allowing joint motion to co-vary to maintain the end effector. For example, if a particular joint deviates from its normal trajectory, other joints will show deviations from their normal trajectories to achieve the goal of the task, this is known as joint-space variability.

When accuracy is the most important goal athletes are more likely to suppress variability in order to maintain accuracy (Darling & Cooke, 1987). In precision throwing tasks, the variability of the release parameters (time, angle and velocity at release phase) does not change across trials. Instead, athletes compensate with an increase in movement variability in the acceleration phase through coadaptation of the speed and angle of the joints at the release phase to maintain accuracy (Dupuy et al., 2000; Wagner et al., 2012). This suggests that maintaining a degree of variability is a strategy used by more skilled athletes to adapt to subtle changes in the time, angle and velocity parameters of the joints and segments at the release phase (Dupuy et al., 2000; Kudo et al., 2000). Movement variability has not been reported in accuracy-based racquet sports such as the badminton short serve. Assessment of movement variability in the precision task of the badminton short serve

will increase our knowledge of the potential role of variability in elite sporting populations and may lead to better training methods for short serve accuracy.

Purpose

Coaches and players believe that the short serve is a major factor influencing the outcome of a rally. In this study, the biomechanical determinants of accuracy in the badminton short serve and the role of functional variability will be investigated. A training intervention program will then be developed and implemented to improve the short serve accuracy of players. The effectiveness of the short serve training intervention will be determined.

Methodology

Part 1 – Technique and role of movement variability in short serve accuracy

The first part of the research investigated the techniques associated with accuracy in performing a short serve and the role of movement variability in short serve accuracy.

Participants

Eight players (4 male, 4 female; mean age: 23.4 ± 5.1 y, body mass: 73.2 ± 11.1 kg, height: 175 ± 8.6 cm) volunteered from the Senior Australian National Doubles Badminton squad to participate in the study. Each player was free from injury or illness at the time of testing. Due to the sample group competing at an elite level a moderate effect size of 0.25 was chosen for the kinematic variables (full-body joint angles), a power level of 0.80, $\alpha = 0.05$ and a 20% attrition rate (Kuntze et al., 2010). Prior to testing commencement, informed consent from each participant and ethical approval from Edith Cowan Human Research Ethics Committee was obtained.

Experimental design and protocol

This study used a cross-sectional design with all testing being conducted at the biomechanics laboratory at the Australian Institute of Sport (AIS). Body mass, height, leg length and knee, wrist, elbow and shoulder joint widths were measured for each participant. A participant from each playing pair had the full-body marker set placed on them, defined by a previously validated model (Spratford & Hicks, 2014), as well as their racquet and the shuttlecock for three-dimensional motion analysis (Figure 1). A badminton court surface with markings was setup in the AIS biomechanics laboratory to recreate match conditions (Figure 2). Participants performed a general warm-up that they normally use before competition.

During the testing session the participants wore normal match attire and used their own racquets to ensure that technique and playing performance was not compromised during testing. Players performed 160 serves (80 from each side of the court to two targets) each with an opponent present to simulate match conditions. Serves from one side toward the centre line (40 serves) were analysed because the shuttlecock travels over the centre of the net regardless of which side the serve is performed, and because serving to the centre line is the most common direction to serve toward in competition.

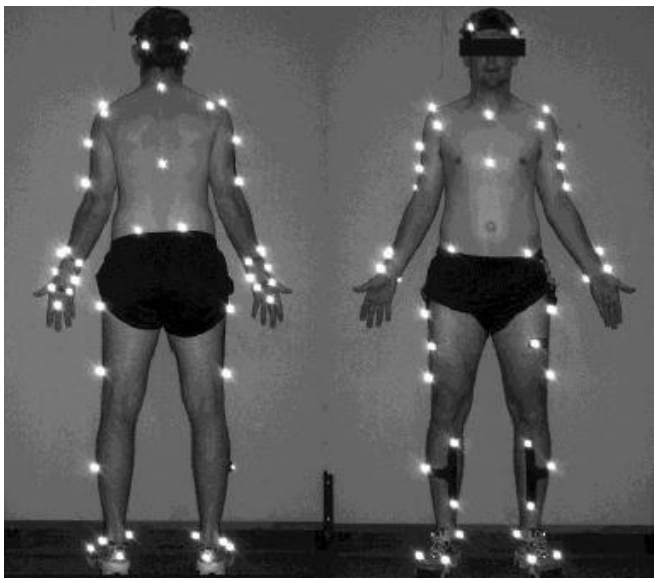

Figure 1. University of Western Australia full body marker set.

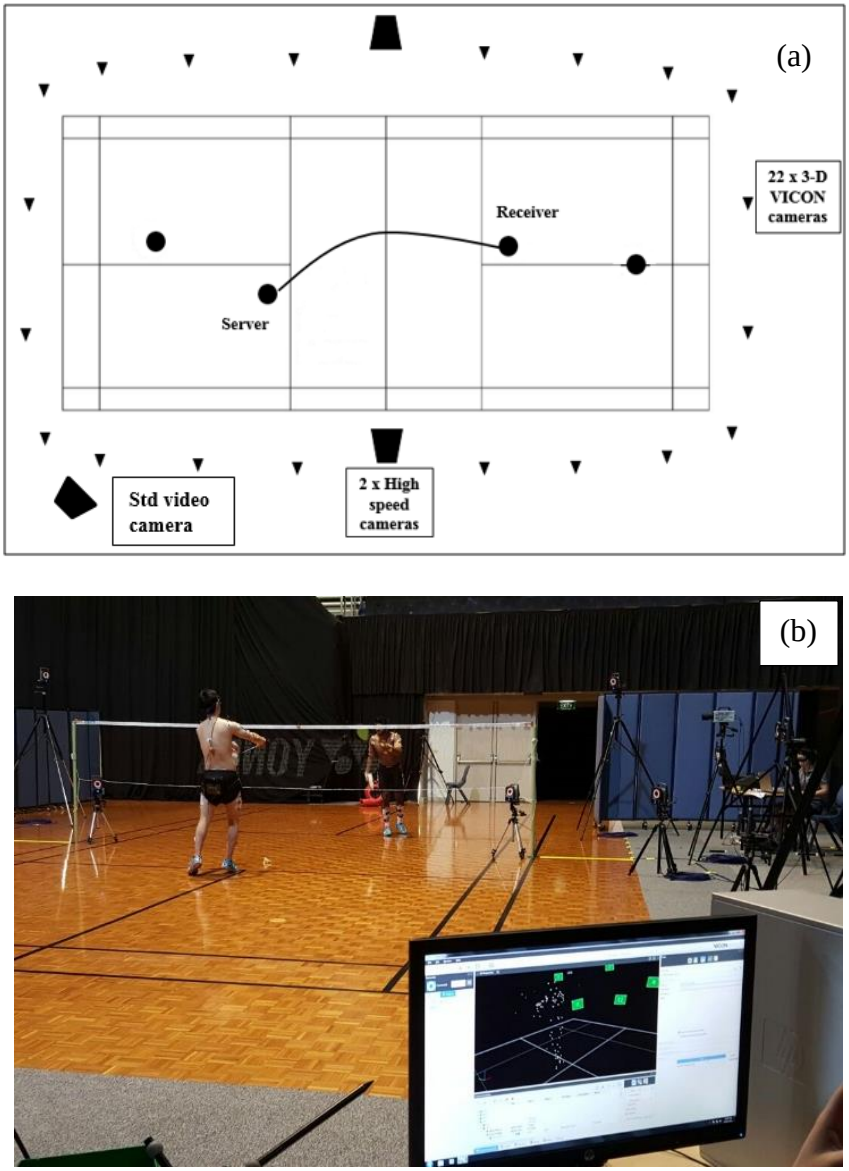

Figure 2. (a) Plan view of lab setup, (b) tester's view of lab setup.

The player's short serve technique was examined using three-dimensional motion analysis. Short serve accuracy was determined by assessing the shuttlecock trajectory, apex position, shuttlecock velocity and height over the net also using three-dimensional motion analysis. Twenty-two VICON motion analysis cameras (Oxford Metrics Ltd., Oxford, UK) set at a sampling rate of 250 Hz were positioned to create a capture volume around the entire badminton court with a height of 4 m. The cameras captured the retro-reflective markers on the racquet, shuttlecock and players, for analysis of full body kinematics shuttlecock velocity, trajectory and apex position and racquet head velocity and rotation.

Data analysis

Short serve performance was based on the trajectory of the shuttlecock during the short serve assessed by measurement of the apex location and height over the net. The apex location was determined by extracting the positional values when the shuttlecock reached its peak vertical point (vertical Z axis), then taking the position (anterior-posterior Y axis) at that point, showing the location of the apex relative to the net position. Next, the shuttlecock position as it passed over the net was subtracted from the net height, giving the exact height as it passed over the net. Since the trajectory of the short serve usually travels over the centre of the net, the side to side (medio-lateral X axis) was deemed negligible for performance accuracy. To categorise each serve, the individual and group median was determined. This was selected to provide specific accuracy results for a player, since the rules dictate that a serve must be contacted below the waist, which could have different heights for each player, and therefore an individual accuracy measure was needed. The group median was calculated as an overall accuracy measure to enable comparison between player accuracy levels. For each player, the apex location and median height above the net was calculated. For serves that fell below the median for apex location and height above the net were classified 'accurate' and if they were above the median they were classified as 'inaccurate'. For serves which were below the median for apex location but were above the median for height above the net were classified as 'apex good'. Similarly, the serves that were below the median for the height above the net requirement but above the median for apex location were classified as 'clearance good'.

The service action divided into three parts: the first backward movement of the racquet defined the start of serve, the final backward movement of the racquet defined the end of the backswing, and the start of the forward swing, and the start of the forward swing, and racquet-shuttlecock contact defined the end of the service action. The follow through was not analysed as it occurs after contact. The three-dimensional positions of the reflective markers were reconstructed using VICON Nexus software (Oxford Metrics Ltd., Oxford, UK). All data were filtered using a 6-Hz low-pass Butterworth filter, with the cut-off frequency determined from residual analysis (Yu, Gabriel, Noble, & An, 1999). The coordinates were imported into Visual 3D software (C-Motion, Inc., Germantown, MD, USA) and an upper-body model and racquet-hand model were created to calculate the short serve kinematics.

Technique analysis - principal component analysis

A principal component analysis (PCA) was performed on the joint angles of the dominant arm for each player to determine the relevant modes that describe the essential features of the serve (Daffertshofer, Lamoth, Meijer, & Beek, 2004; Federolf, Reid, Gilgien, Haugen, & Smith, 2014). The eigenvector with the largest variance in the data set was taken to represent the direction of the largest movement of the player. The second eigenvector then represented the direction of the second largest movement in the subspace perpendicular to the largest movement, and so on. Applying the PCA to individuals allowed quantification of player-specific movement patterns. Since each player could theoretically execute the short serve using a different movement pattern, a different set of principal components can be created, allowing the grouping of common movements from different

players. Measuring short serve accuracy in combination with the PCA allowed the identification of the movement patterns that resulted in more accurate serves.

Movement variability analysis

Normality of the kinematic data was verified using a Shapiro-Wilk test ($p > 0.05$). One-way ANOVA tests were used to compare differences in variability between joint angles in the sagittal and transverse planes at the start, backswing, and contact point.

Part 2 – Training to improve short serve accuracy

The research proposed to develop a short serve training intervention (based on results from Part 1) and implement and assess the effectiveness of the training intervention on short serve accuracy. Additional to this the study we also investigated the predicted landing position of the shuttlecock from the short serve in a match-like situation to determine if the traditional training for the short serve of aiming for a target on the ground e.g. a position near where the centre line bisects the service line, is actually most suitable and applicable for the developing the short serve accuracy in the game.

Participants

Nine female and male state and university level badminton players (age: 20.4 ± 6.4 years, body mass: 56.4 ± 5.8 kg, height: 167.5 ± 7.1 cm) volunteered for this study. Prior to testing commencement, informed consent from each participant and ethical approval from Edith Cowan Human Research Ethics Committee was obtained.

Experimental design and protocol

Players participated in two testing sessions, one prior to the short serve training intervention (pre-testing) and one following the completion of the training (post-testing). Both sessions undertook the same testing outlined below.

Testing sessions

All players were free from injury at the time of testing, wore their normal match attire and used their own racquets. A badminton court was marked out and a net was placed in accordance with the International Badminton Federation standards, in the Edith Cowan University Biomechanics Research Laboratory. Players performed badminton-specific play for warm-up and to familiarise themselves with the testing environment. Players performed 80 short serves (40 from each side of the court) targeting the ground where the centre line intersects the short service line. Serves from one side toward the centre line (20 serves) were analysed. The motion-capture system consisted of 8 cameras in session and collected with a sampling rate of 1000 Hz (VICON Oxford Metrics Ltd., Oxford, UK). Reflective tape was placed around the base of the head of the shuttlecock to track its trajectory. See Figure 3 for testing set-up.

Training intervention

A training program was developed based on the results of Part 1 with the aim of improving the players short serve accuracy. Players completed eight training sessions over 4 to 6 weeks. The training focused on improving the trajectory of the short serve. The optimum short serve trajectory was determined from the accurate serves in Part 1, with the shuttle height being around 152cm at a horizontal position of 30cm beyond the net, 143cm height at 60cm beyond the net and 125cm at 90cm beyond the net (i.e. on the opponent's side of the net). Based on these measures targets were developed with specified heights (approximately 10-15cm greater than the optimal heights to allow the full width of the shuttlecock to pass under the top bar of the target) and were to be positioned at 30cm, 60cm and 90cm beyond the net for the shuttlecock to pass through. The players were instructed to serve the shuttlecock through one of the three different targets. See figure 4 for an example of the targets and set-up at training. Players served 10 shuttlecocks consecutively from the

left or right side and then alternated service side, targeting the ground just over the service line where it intersects with the centre line. The order of the side serving from and the target height/position were randomised. The players did a total of 180 servers per session, 60 serves through each of the three targets. The targets forced the player to serve with a trajectory which had the apex before the net and the shuttle height above the net was low. This trajectory was proposed to be most accurate in Part 1 and difficult for the opponent to return effectively. See figure 5 for diagram of an accurate short serve trajectory. Over the eight training sessions the difficulty increased with targets being lowered and the gap for the shuttlecock to pass through being reduced. In the last four sessions the targets were placed at both 30cm and 90cm beyond the net for some trials to train the optimal trajectory for the short serve. Players were provided score cards with the trial and target order and players recorded how many serves out of each group of 10 serves through the target and achieved landing over the service line, close to the correct side of the centre line. Following completion of the training players did the post-testing session which replicated the pre-testing session described earlier.

Figure 3. Short serve testing undertaken using 3-dimensional motion analysis systems

Figure 4. Short serve training intervention, with a range of targets (which players were instructed to serve through) being used to optimise the trajectory of the short serve.

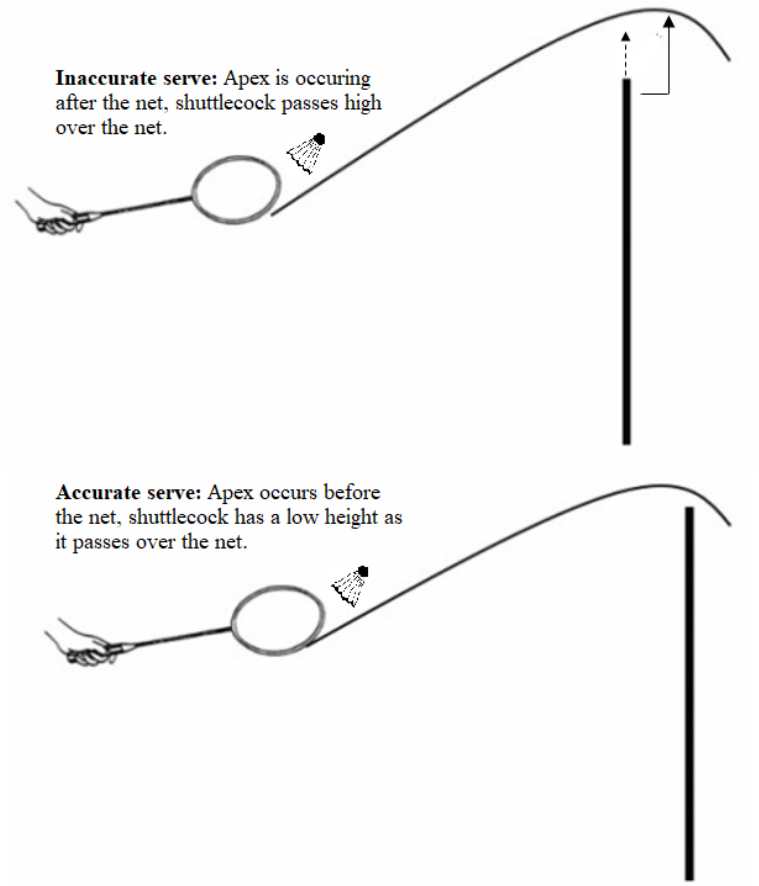

Figure 5. Trajectory of an inaccurate and accurate short serve. Solid arrow represents apex location, dotted arrow represents height over net.

Data analysis

Short serve performance for the pre-testing and post-testing sessions was undertaken similar to that in Part 1. The trajectory of the shuttlecock was tracked and processed using VICON Nexus software (VICON Oxford Metrics Ltd., Oxford, UK). Shuttlecock position at apex and height over the net was calculated using custom written code in Matlab (v 9.2, The Mathworks Inc, Chatswood, NSW, AU). Apex location was determined by finding the position (anterior-posterior Y axis) of the shuttlecock at its highest point (vertical Z axis). The shuttlecock height as it passed over the net was subtracted from the net height to calculate net clearance. Median apex location and median net clearance for each player and the group was calculated. An accurate serve had apex location closer to the server than the median and net clearance below the median. Serves where both apex location were further than the median and net clearance was greater than the median were classified as 'inaccurate' serves. Serves that met only one of the criteria were classified as 'apex good' or 'clearance good' as appropriate.

Predicted landing position accuracy in game-situation.

Additional analysis was undertaken to examine whether there was a difference between the landing location of the shuttlecock between training conditions (no opponent present- data from Part 2) and match conditions (opponent present – data from Part 1). The full shuttle trajectory data from Part 2 was used to create a model to predict the landing position from the initial part of the trajectory (which is necessary for Part 1 data - when an opponent is present they typically return the shuttlecock so the landing position can't be measured). Once the model had been validated the predicted landing position of the shuttlecock in Part 1 when players served with an opponent present, similar to match conditions, was determined. Using the error distribution quantified by the Bland-Altman plots, the predicted landing position was determined relative to the service line if the distance between the prediction and the serving line was greater than the 95% limit of agreement.

However, if the distance was less than the limits of agreement, than the serve was considered to fall *on* the serving line. The proportion of serves falling before, on, or over the line were determined for each player as well as an average over all players.

Results

Part 1 – Technique and role of movement variability in short serve accuracy

Technique - principal component analysis

Following assessment and interpretation of the principal component analysis players were grouped qualitatively according to their eigenvalues, group A (players 1, 6, & 7), group B (players 2 & 5), group C (players 3 & 8); player 4 did not share similar eigenvalues with any players so will be reported separately. The explained variance (%) in the data for the first two principal components for each group was; A = 92%, B = 92.3%, C = 97.2%, player 4 = 95.6%, with ~5% of variance in the data accounted for in the remaining four principal components. Therefore, only the first two principal components are reported for each group.

Results from the PCA suggest that group A restricted movement of the shoulder joint throughout the entire serving motion, which was confirmed with the range of motion (ROM) exhibited in the shoulder joint in the elevation (4°±3°) plane, and internal/external rotation (5°±4°) plane (Table 1). The highest loading was the elbow joint (PC1) in both the flexion/extension and pronation/supination planes, with the remaining movement amplitude originating from the wrist joint (PC2) in the abduction/adduction plane. The serve motion began by a small flexion and pronation of the elbow during the backswing, then extension and supination in the forward swing through to contact. Group A synchronised elbow extension and supination while the wrist joint began the movement in abduction or near the neutral position, the elbow extended and the wrist adducted through to contact. The wrist continued to flex until the end of the backswing was reached, then began extending through to racquet-shuttlecock contact. This movement pattern used elbow extension and supination with wrist adduction and flexion, with both the elbow and wrist joints tightly coupled throughout the movement.

Table 1. Range of motion (ROM) of each joint in the sagittal and transverse plane. Players are grouped together according to the PCA results.

		Shoulder ROM (°)		**Elbow ROM (°)**		**Wrist ROM (°)**	
Group	**Player**	**Flex/Ext**	**Rot**	**Flex/Ext**	**Sup/Pro**	**Flex/Ext**	**Abd/Add**
A	**1**	7.13	1.78	15.25	3.47	15.55	34.86
	6	3.56	4.92	12.50	5.92	18.73	17.10
	7	2.06	9.85	7.78	6.30	10.88	13.32
B	**2**	1.62	5.11	4.86	1.76	11.96	18.09
	5	3.63	5.44	11.66	6.68	9.21	26.96
C	**8**	21.83	8.02	20.25	9.18	16.73	35.74
	3	32.18	21.11	14.50	8.41	69.11	29.51
	4	7.25	10.49	16.76	11.16	23.71	41.29
M		10.29	8.03	12.40	5.96	21.74	25.08
SD		11.94	6.30	5.05	2.61	21.16	8.97

Players in group B used a similar strategy of restricting the shoulder joint. However, motion was also restricted at the elbow joint in the pronation/supination plane. Almost all of the movement

occurred through elbow extension, specifically for player 2 who had an eigenvalue ~ 1. PCA 2 identified the remainder of the movement at the wrist joint in the abduction/adduction plane. One similarity between group A and B was the slight flexing of the elbow during the backswing followed by extension through to contact. However, elbow flexion was minimal and most of the movement at the elbow occurred in extension, which was tightly coupled with the wrist adducting throughout the movement until contact. One major difference between these groups however, was pronation/supination of the elbow for group A, while elbow extension and wrist adduction, were the dominant in group B. Nonetheless, both groups utilised a push-like movement pattern.

In contrast to groups A and B, players in group C used a combination of shoulder, elbow, and wrist movement in varying planes. Most of the movement occurred in elbow pronation/supination, with wrist flexion/extension and abduction/adduction contributing. The eigenvalues identified that the shoulder joint (eigenvalue = 0.27) played a smaller role in comparison to the weightings of the elbow (0.39), and wrist (0.42) joints, with both players elevating the shoulder whilst pronating the elbow, and continued shoulder elevation as the elbow began to supinate. However, there was a small difference between players, with the predominant wrist motion for player 3 being adduction (with some flexion), and the predominant wrist motion for player 8 being wrist flexion (with some adduction). Though some restriction was evident, the main feature of this group was the use of all three joints in the hitting arm, presenting a slightly more complex push-like movement pattern than exhibited in groups A and B.

The primary contributors for player 4 were elbow pronation/supination followed by internal/external rotation of the shoulder (PC1), with wrist flexion/extension and abduction/adduction accounting for the remaining portion of the serve movement (PC2). Internal rotation and elbow pronation occurred at the same time. As the shoulder began to externally rotate the elbow moved into supination, the wrist extended and adducted throughout the movement, revealing a rolling type of movement pattern. However, the movement exhibited during the backswing was minimal in comparison to the forward swing.

Accuracy results

Table 2 shows the percentage of serves classified as, accurate, inaccurate, apex good, and clearance good, as well as the first two principal components for each player. The overall average accuracy results for each group were: group A (27%), group B (50%), group C (16.5%), and player 4 (0%). Group B were the most accurate group, and also produced the least number of inaccurate serves. Although some of the players had a low number of accurate serves, they often satisfied one of the accuracy criteria. For example, players 3 and 4 scored 0% in overall serve accuracy, but 57% and 55% had net clearance below the group median (apex good). Similarly, for player 8, 62% of serves were under the median apex location but all of the net clearances were higher than the median (clearance good).

Table 2 also shows the dominant movement pattern for each player and their serve. Elbow pronation/supination was one of the primary contributors for group A, which was the only difference observed between groups A and B, yet the accuracy scores were considerably different. Although group C and player 4 had different techniques, these players included the shoulder joint in the serve motion. Player 8 (group C) had similar accuracy scores to players in group A, while players 3 (group C) and 4 scored 0% overall accuracy, ~40% of the serves performed were classified as inaccurate. A common feature observed across all players was a lack of movement occurring during the backswing, suggesting that most of the players incorporate simultaneous joint rotations, with slightly different methods of executing it. Moreover, the PCA and angle-angle plots suggest that better accuracy was achieved by restricting the number of degrees of freedom used.

Table 2. First two principal components for each player for each group. Percentage (%) of 'accurate', 'inaccurate', 'apex good', and 'clearance good' of all serves for all players (group median).

		Principal Components and Accuracy Scores (%)					
Group	**Player**	**PC1**	**PC2**	**% Accurate**	**% Inaccurate**	**% ApexGood**	**%ClearanceGood**
A	1	Elbow Pro/Sup & Flex/Ext	Wrist Adduction	34	25	16	19
	6	Elbow Pro/Sup & Flex/Ext	Wrist Adduction	36	25	29	25
	7	Elbow Pro/Sup & Flex/Ext	Wrist Adduction	11	63	32	21
B	2	Elbow Flex/Ext	Wrist Adduction	40	13	30	23
	5	Elbow Flex/Ext	Wrist Adduction	60	10	35	35
C	3	Elbow Pro/Sup & Wrist Add	Elbow Flex/Ext	0	37	27	27
	8	Elbow Pro/Sup & Wrist Flex	Elbow Pro/Sup	33	5	38	33
Player 4	4	Elbow Pro/Sup & Shldr Rot	Wrist Adduction	0	40	30	30
M				27	27	30	27
SD				21	19	7	6

Movement variability analysis

Biological movement variability was calculated by using the individual means ($\bar{X}$), standard deviations (SD), standard error of the mean (SEM% = [(SD / $\sqrt{n}$ / $\bar{X}$] × 100, where n is the number of trials), and coefficients of variation (CV% = SD / $\bar{X}$ × 100). Biological coefficients of variation (BCV% = CV% - SEM%) were calculated for the kinematics of each individual (Bradshaw et al., 2007). Players were grouped according to the results derived from the principal component analysis in Study One. Table 3 shows the CV (%) and BCV (%) of the shoulder, elbow, and the wrist joint angles in the sagittal plane at the start, end of the backswing, and contact point. Table 4 shows the CV (%) and BCV (%) of shoulder, elbow, and wrist joint angles in the transverse plane at the start, end of the backswing, and contact point.

Lower variability in the joint's sagittal plane was found when compared to the transverse plane ($p < .001$) for the shoulder, elbow, and wrist joints for all players (Table 4). The higher variability displayed in the transverse plane occurred predominantly at the start and end of the backswing, however some players also exhibited high variability in this plane at contact. Players 1 (51.4%) and 6 (16.4%) showed highest variability at the start and end of the backswing in the wrist joint in the transverse plane, whilst players 7 (9%) and 2 (13%) exhibit similar variability in all three phases for the elbow in the transverse plane (Table 4). Player 5 showed very little variability in all joints and planes, while player 4 (67.9%) and 8 (59.2%) had highest variability in the wrist joint in the transverse plane, and low variability in all remaining joints. Player 3 showed higher variability in the transverse plane for the shoulder joint (26.5%) at the start of the swing, and in the wrist joint (29%) at the end of the backswing and contact point. Players either had a larger 'spike' in variability in a particular plane with lower variability in the remaining phases, or displayed similar levels of variability across all three phases with no significant spike in any specific phase.

Group B was identified as the most accurate servers and Table 5 indicates that this group displayed lowest joint angle variability with an overall mean of 2.5% in the sagittal plane, and 5.9% in the transverse plane. Variability in the other groups in the sagittal plane were 2.9% for group A; 3.6% for group C, and 3.9% player 4.Variability in the transverse plane for group A was 8.7%, 12.8% for group C, and 10.5% for player 4. No significant difference was found when comparing variability of joint angles between accurate and inaccurate serves individually and as a group ($p > 0.05$). Analysing of the intertrial variability of timing of the backswing and timing at contact (BCV%) revealed that all players displayed greater variability during the backswing phase when compared at contact point ($p < 0.001$), however no difference was found in the variability of timing between accurate and inaccurate serves ($p > 0.05$).

Table 3. Shoulder, elbow, and wrist angular position (°) – sagittal plane

	Coefficient of variation (%)									Biological coefficient of variation (%)								
Player	**Shoulder angle (°)**			**Elbow angle (°)**			**Wrist angle (°)**			**Shoulder angle (°)**			**Elbow angle (°)**			**Wrist angle (°)**		
	Start	**BS**	**Contact**	**Start**	**BS**	**Contact**	**Start**	**BS**	**Contact**	**Start**	**BS**	**Contact**	**Start**	**BS**	**Contact**	**Start**	**BS**	**Contact**
1	2.8	2.7	2.9	3.0	3.1	3.3	1.9	1.6	3.8	2.3	2.2	2.4	2.5	2.6	2.7	1.5	1.3	3.1
6	3.6	2.8	3.1	2.9	3.0	3.9	3.7	2.4	4.3	2.9	2.2	2.5	2.3	2.4	3.2	3.0	2.0	3.5
7	1.8	1.8	2.0	1.9	3.4	2.7	1.9	1.4	2.8	1.4	1.4	1.5	2.9	2.6	2.1	1.5	1.1	2.2
2	2.2	2.4	2.6	2.0	2.0	1.5	1.5	1.8	2.8	1.7	2.0	2.0	1.5	1.6	1.6	1.5	1.5	2.3
5	3.3	2.7	3.2	2.2	2.8	2.7	2.2	2.0	2.3	2.6	2.1	2.5	1.7	2.2	2.9	1.7	1.6	1.8
3	8.0	3.1	2.8	5.0	2.7	2.7	17.8	1.8	2.2	6.6	2.6	2.3	4.1	2.2	2.2	14.5	1.4	1.8
8	2.2	1.6	1.8	2.2	2.5	3.7	1.8	1.5	2.2	1.7	1.2	1.4	1.6	1.9	2.8	1.4	1.2	1.7
4	3.8	3.1	3.7	3.3	3.9	3.8	2.7	4.1	6.4	2.9	2.4	2.9	2.6	3.0	3.0	2.1	3.2	4.9
MEAN	3.5	2.5	2.8	2.8	2.9	3.0	4.2	2.1	3.4	2.8	2.0	2.2	2.4	2.3	2.6	3.4	1.7	2.7
SD	2.0	0.6	0.6	1.0	0.6	0.8	5.5	0.9	1.5	1.7	0.5	0.5	0.9	0.4	0.5	4.5	0.7	1.1

Start = first backward movement of the racquet; BS = the end of the backswing; Contact = racquet-shuttlecock contact point.

Table 4. Shoulder, elbow, and wrist angular position (°) – transverse plane

	Coefficient of variation (%)									Biological coefficient of variation (%)								
Player	**Shoulder angle (°)**			**Elbow angle (°)**			**Wrist angle (°)**			**Shoulder angle (°)**			**Elbow angle (°)**			**Wrist angle (°)**		
	Start	**BS**	**Contact**	**Start**	**BS**	**Contact**	**Start**	**BS**	**Contact**	**Start**	**BS**	**Contact**	**Start**	**BS**	**Contact**	**Start**	**BS**	**Contact**
1	7.0	5.4	5.9	8.7	5.1	5.6	13.4	52.4	21.7	5.7	4.4	4.8	7.1	4.2	4.6	11.0	42.9	17.8
6	3.6	2.8	3.1	5.6	5.7	6.1	16.4	11.8	9.7	2.9	2.2	2.5	4.5	4.6	4.9	13.2	9.5	7.8
7	2.6	3.4	4.3	10.6	8.2	9.0	4.8	2.3	2.4	2.1	2.8	3.4	8.5	6.6	7.2	3.9	1.9	1.9
2	2.2	2.0	2.6	13.7	11.5	12.8	5.3	5.1	3.5	1.8	1.6	2.1	11.0	9.3	10.4	4.3	4.1	2.9
5	6.5	3.8	4.9	4.0	4.2	4.3	5.4	5.0	5.7	5.0	3.0	3.8	3.0	3.2	3.3	4.2	3.9	4.4
3	26.6	5.1	6.6	5.4	4.7	6.1	6.6	30.3	27.6	21.3	4.1	5.3	4.4	3.8	4.9	5.3	24.3	22.2
8	8.9	4.9	3.7	5.3	5.3	7.6	59.4	9.1	7.8	6.9	3.8	2.9	4.1	4.1	5.9	45.8	7.0	6.0
4	3.9	3.0	3.7	4.6	2.6	3.7	68.0	3.1	2.4	3.0	2.3	2.8	3.5	2.0	2.8	52.4	2.4	1.9
MEAN	7.7	3.8	4.4	7.2	5.9	6.9	22.4	14.9	10.1	6.1	3.0	3.5	5.8	4.7	5.5	17.5	12.0	8.1
SD	8.0	1.2	1.4	3.4	2.7	2.9	25.9	17.6	9.5	6.4	1.0	1.1	2.8	2.3	2.4	19.9	14.4	7.7

Start = first backward movement of the racquet; BS = the end of the backswing; Contact = racquet-shuttlecock contact point.

Table 5. Variability in the timing of the backswing and time to contact separated into groups from Study Two (Biological Coefficient of variation, %)

Group	Player	BS acc	BS inacc	FS acc	FS inacc
A	1	12.1	8.7	10.1	7.4
	6	9.0	6.5	6.4	7.0
	7	7.5	5.2	7.5	5.0
B	2	8.2	11.9	5.8	10.8
	5	9.4	7.5	5.9	5.0
C	3	13.3	12.1	11.0	9.6
	8	4.1	12.9	4.0	9.1
*	4	7.5	13.7	5.6	9.8
Mean		8.9	9.8	7.0	8.0
SD		2.9	3.2	2.4	2.2

BS = backswing; FS = forward swing; acc = accurate; inacc = inaccurate.

Part 2– Training to improve short serve accuracy

Results of the short serve accuracy in the pre-testing and post testing sessions are shown in Figure 6, displaying the two components of trajectory accuracy. The vertical dashed line indicates the group median for apex location, while the horizontal dashed line indicates the group median for height above the net. Zero on both axes indicates the position of the net. Serves that fell below the median for apex location and height above the net are located in the bottom left quadrant, and were classified as 'accurate' serves (green), while the red trials did not meet either of the criteria and were classified as 'inaccurate'. Serves in the top left quadrant (black) had good apex location, but were higher over the net than the median. Similarly, serves in the bottom right quadrant had low net clearance but the apex was closer to the server than the median. These serves were classified as either 'apex good', or 'clearance good', respectively. Figure 6a shows the trajectory accuracy of the players' short serves in the pre-testing session (pre) and the figure 6b shows the trajectory accuracy of the players' serves following the training intervention (post). A notable improvement in the accuracy following the training intervention is clearly displayed by the lower group median for apex location (apex was closer to the server), and a lower group median for height above the net (shuttle closer to net). The group median for shuttlecock apex location and height above the net was 179mm and 231mm, respectively in the pre-testing session and following the training the group median improved to 65mm for the shuttlecock apex location and 191mm for net clearance (height above the net). There were also a much greater amount of serves in the post-testing session that were below the pre-testing session medians and classified as accurate.

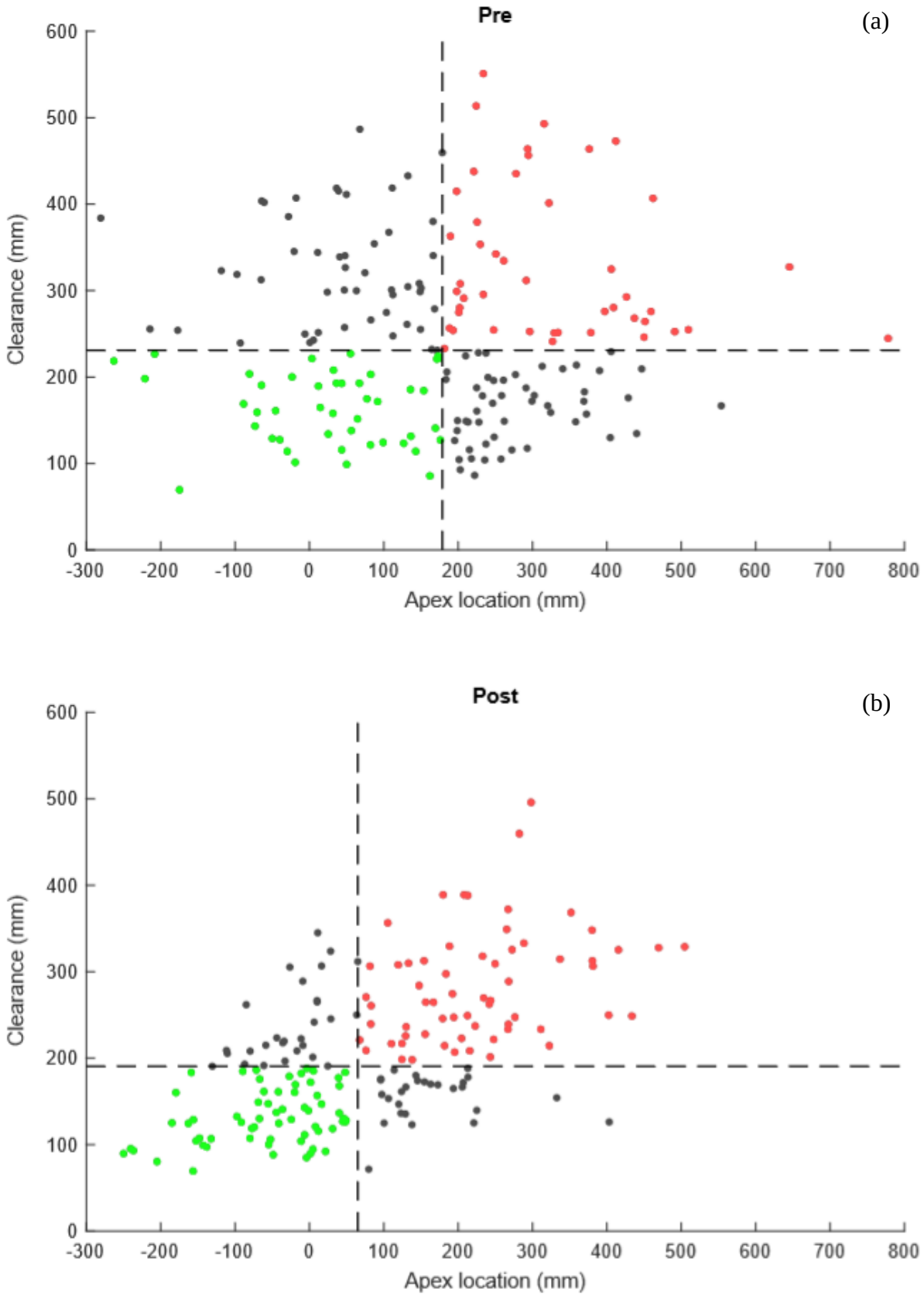

Figure 6. Dash line represents median apex (horizontal) and height (vertical) location of shuttle across all players. Green indicates good apex and height location, while red represents bad apex and height location, black represents serves that did not have either good or bad apex and height locations. (a) Trajectory accuracy of the players' short serves in the pre-testing session, (b) trajectory accuracy of the players' serves in the post-testing session.

Predicted landing position accuracy in game-situation

There was no significant bias between the actual landing position and predicted landing position. The mean horizontal error (anterior-posterior) was 6 cm ± 14.5 cm, and the vertical error (up-down) was 9.1 cm ± 16.3 cm. The prediction error was slightly higher than expected, perhaps due to the nature of the shuttlecock flight that turns in the air shortly after contact. The prediction model was applied to the shuttlecock trajectory when an opponent was present (Part 1 data). The predicted landing location for all serves for each player is shown in Figure 7. Overall the distribution around the service line appears normal ($p > 0.56$).

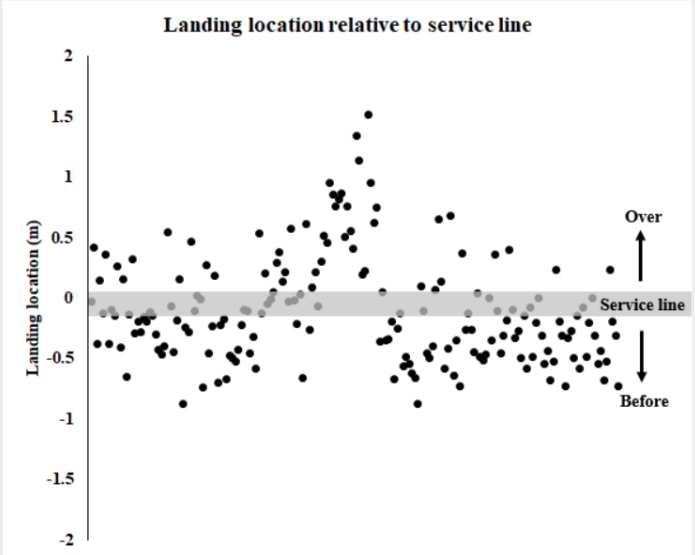

Figure 7. Landing prediction for all serves for all players. The zero point represents the service line, positive reflects that the serve went over the service line, zero indicated the serve landed on the line, negative landed before the service line.

Table 6 shows the individual player landing predictions for before, on the line, or over the line. The addition of 'on the line' was added because a large proportion of serves were predicted to land on some part of the service line (40 mm wide). It was apparent that some players tended to have higher proportion of serves land in certain areas, players 5 and 8 had no serves (predicted) that landed over the line, while players 1, 2, 3, and 6 had the majority of their predicted landings occur on or before the line. While players 4 and 7 were heavily bias toward the shuttlecock landing over the line.

Table 6. Shows the individual predicted landing location for before, on, or over the service line for each player.

	Landing Location (%)		
Player	**% Before**	**% On the line**	**% Over**
1	29	55	16
2	40	50	10
3	2	65	33
4	0	20	80
5	70	30	0
6	50	35	25
7	0	10	90
8	69	31	0
M	33	37	32
SD	30	18	35

Discussion

Technique

Our analysis confirmed that a push-like movement pattern was used for the short serve, using simultaneous joint rotations, offering players more control over the serve motion (Kerr & Ness, 2006). The push-like pattern causes the distal segment, in this case the racquet, to move in a flat arc or near-straight line, resulting in increased accuracy of the serve. In other sports that utilise a push-like movement pattern using the upper-arm have reported that all joints are used. However, the most accurate servers fixed the shoulder joint throughout the whole movement. Because the shoulder remains fixed, the pushing movement originates at the elbow, suggesting that the shoulder may act to stabilise the serve motion. This could be due to the low mass of the shuttlecock or because of the short distance the shuttlecock travels for the short serve.

We found that movement of the elbow in the sagittal plane was the task-relevant degree of freedom for the most accurate players. The accuracy of the short serve was directly influenced by the task-relevant degrees of freedom (i.e. elbow extension), and those which are surplus to task performance (i.e. shoulder joint) are either redundant, can negatively impact accuracy, or act as a stabiliser for the serve (Davids et al., 2003). The accurate servers used a strategy of restricting specific degrees of freedom, and by limiting the shoulder joint throughout the movement, perhaps allowed more control over the elbow joint (i.e. task relevant degree of freedom).

All players displayed some sort of push-like movement pattern when performing the short serve with varying levels of complexity and accuracy. The most accurate servers restricted the serve motion more than the least accurate servers; simplifying the movement to a single joint in a single plane was a common feature displayed amongst the more accurate players. Although it appeared that using a simplified push-like movement pattern is better for accuracy, in a match situation it may be beneficial to use a more complex movement pattern to disguise the serve motion. We chose to use a match-like environment to ensure a representative design (Cabello Manrique & Gonzalez-Badillo, 2003; Faccini & Dai Monte, 1996; Glazier, 2010; Phomsoupha & Laffaye, 2015a). However, because we required cameras and reflective markers and didn't play complete points the differences may have changed their serving behaviour. In an actual match the server may adapt their serve in an attempt to deceive the opponent. It would be useful in future studies to assess the role of the receiver on the complexity of the serve action.

Movement variability

Almost all of the joint angle variability at each phase occurred in the transverse plane. Thus, introducing variability in the transverse plane, which plays a smaller role in the performance of the task, was associated with reduced variability in the task-dependent sagittal plane. Sagittal plane movement was a defining feature of the serve motion, and the key parameters in performing an accurate serve, such as the position of the shuttlecock at its apex and height above the net also occur in this plane. This key characteristic was exhibited across all players, perhaps because the racquet swing movement itself is of small amplitude, range of motion of specific joints is restricted, and in turn restricts variability in the task-dependent plane (sagittal), from where the majority of the movement originates. Varying joint angles in the transverse plane demonstrates a compensatory mechanism used to minimise variability of the task-dependent parameters, resulting in players exploiting the available variability in the redundant plane to satisfy the constraints of the task (i.e. reducing sagittal plane variability).

By separating technological noise and biological variability, we were able to pinpoint specific joints and planes that players incorporated variability into their movement. Players incorporated specific movement strategies to ensure accuracy of the racquet trajectory at contact. Joint angles in the transverse plane were most variable. The timing of the swing was also variable, with the

backswing showing more variability than the forward swing. This suggests that the players incorporate variability in one dimension to compensate for the anterior-posterior and vertical dimensions which directly impact accuracy of the serve. Varying the timing of the backswing to reduce the variability at the contact point was a common feature displayed across all of our players, irrespective of serve accuracy. Expert badminton players seem to use variability as function to ensure stable performance. Thus, skill acquisition of the short serve may be accompanied with the server demonstrating more constraint in particular planes within the arm joints.

Training to improve short serve accuracy

The research demonstrated that the training intervention was effective. Therefore training focusing on optimising the shuttle trajectory in the short serve results in an improvement in accuracy of the short serves, so focusing on extrinsic factors such as the shuttle path may be more beneficial than focus on intrinsic factors such as the arm movements. This training involved providing knowledge of performance on the shuttlecock's trajectory traveling through the target (or missing) and knowledge of results on if shuttlecock successfully landed over the service line and close to the centre line. It supports other research which shows an improvement in learning and performance when participants are provided knowledge of performance, i.e. giving information about the characteristics (of the shuttle) that led to the performance outcome (Magill, 2007; Magill, 2001). Furthermore, using targets in training also provides a type of feedback to the player associated with increasing motivation. It demonstrates that this type of training with the players focusing on the shuttle trajectory improved their performance by intuitively making the players adjust their technique to achieve an optimal trajectory and more accurate serve.

Predicted landing position accuracy in game-situation.

Elite coaches and players report that when performing the short serve in competition, their aim is influenced predominantly by the opponent. The short serve is almost always returned, so it's unknown how many serves would land in the service box. If many of the serves in matches would land before the line then it may be inappropriate to serve to ground-based targets in practice.
The prediction model allowed us to compare landing locations in training and simulated match conditions. Despite the error in predicting the landing locations results showed that the majority of serves would have landed on or before the line. The disparity in landing location between training and match-like conditions suggests that training should be altered to better reflect match conditions.

Instead of relying on landing location (which rarely occurs in a match and is likely short of the line in many instances) we suggest that services are evaluated using apex location and height above the net. This method is more representative of match conditions, and training to achieve these criteria more accurately reflects a match environment. We found that players with better trajectory accuracy in match-like conditions tended to serve either on or short of the service line. If these players practice using targets on the ground without attention to the trajectory their training programs wouldn't reflect match-play. These findings suggest that coaches and players should consider using a training partner or targets that constrain the trajectory of the shuttlecock to develop an accurate trajectory.

Conclusion

There are several conclusions and practical implications of this research. *Technique:* Training a push-like movement pattern allows the endpoints of the chain (i.e. racquet) to follow a linear or flat arc path, leading to greater accuracy. Segmental rotations occur simultaneously which would be a key coaching point, allowing more control over the racquet, ensuring better consistency at the racquet-shuttlecock contact point. Since the elbow extension and wrist adduction were the prime movers of the serve motion in the most accurate servers, it may be suggested that these factors garner more attention in a training program. *Varying Movement:* Evidence against the idea of a

common optimal technique has been thoroughly researched. Using a representative trial is therefore not appropriate, however invariant features that emerge from particular movement patterns can provide key performance indicators for instructors and coaches. Because there are differences in movements between players, this has important implications for their physical training. The exercises performed in training by each player should be done in a way that replicates their individual movement pattern, this ensures movement specificity. *Training:* Undertaking a training intervention which focused on the optimal trajectory for a short serve by using targets to serve through was found to be successful and is recommended. Coaches and players competing at a high level should consider a mixed (training partner and targets) approach when training for short serve accuracy. Using a training partner is suggested, with short rally drills to replicate a match environment. Using short rally drills is useful because it provides consequence, the training partner can punish a poor serve two or three shots after the serve is performed, which more accurately reflects how a rally will be played out in such an instance. Using a training partner prepares the server for gameplay conditions, however the server should also focus on improving trajectory accuracy, and targets that limit the area the shuttlecock can travel through can be used and are effective.

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