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Accuracy in the badminton short serve: A methodological and kinematic study

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A methodological and kinematic study

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DECLARATION

I certify that this thesis does not, to the best of my knowledge and belief:

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USE OF THESIS

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ABSTRACT

In sports, accuracy is an essential component of actions such passing, shooting, and aiming. Executing a movement or action that requires a high degree of accuracy is a critical determinant of success in many individual and team sports. Each sport has different methods for evaluating accuracy, however an overarching goal is to determine whether an object hits its target, or assess the distance by which it misses. However, in some sports accuracy is not readily measureable because an object might not reach a target, i.e. the object is intercepted, or it collides with another object or a person, or an endpoint might not be visible. One example of this is the badminton serve, where the shuttlecock is normally hit by a receiving player before it reaches the ground, its intended endpoint. The goal of one common serve type, the short serve, is to force the opponent into hitting the shuttlecock upward at a steep angle in order to clear the net, allowing a serving player to hit the shuttlecock from a point high above the net from which it is easier to score. The optimal trajectory of the short serve, therefore, is one in which the apex occurs before the shuttlecock crosses the net and results in a steep downward trajectory. To accomplish this, the swing trajectory of the racquet must be accurate itself, which is usually accomplished by use of a short period of swing (i.e. swing length). In practice the analysis of both swing technique and shuttlecock trajectory is usually done subjectively (by the coach), however objective quantification is necessary in order to determine the shuttlecock trajectories and racquet swing techniques that provide the best serve result to allow correct representation of serve accuracy. The main issue is that an objective measurement is needed, and since the shuttlecock doesn't land on the ground, it makes it difficult to determine serve accuracy with the existing protocols. The broad aims of this Master's thesis were to (i) develop a new method of measuring accuracy of the short serve; (ii) compare and contrast the technique/s of elite badminton players using principal component analysis; and, (iii) determine the magnitude of variability in the movement patterns of elite players performing the short serve.

In the first study (Study I), a specific definition of accuracy was presented that allowed assessment when the endpoint is not reached (i.e. when the shuttlecock does not land on the court). The accuracy of an object's trajectory is typically evaluated by determining whether it hits a target, or measuring the

distance by which it misses. For the badminton short serve, the rules dictate that the shuttlecock must land on or beyond the service line (1.98 m from the net) after traversing the net. However these constraints are insufficient to distinguish poor from good serves; a serve where the shuttlecock clears the net by a small margin but continues and does not reach its apex until after it passes the net might be considered poorer in accuracy (easier for receiver to return) than one in which the shuttlecock reaches its apex before the net even if its height over the net is greater. In this study, short serve trajectories were recorded with and without a receiver present. Two separate data collection sessions and 13 players were tested across both sessions (Session A and B) (age: 23.4 ± 5.1 years, body mass: 73.2 ± 11.1 kg, height: 175 ± 8.6 cm). Data from trials with full trajectory (without an opponent) were used to create a model enabling the prediction of shuttlecock landing. This model was then used to predict the shuttlecock landing point in trials with a receiver, with an important finding being that 69% of serves would have landed on or short of the service line. Thus, receivers might benefit from leaving a majority of serves in competition in order to win the point; servers make the assumption that receivers will return most serves and therefore choose to serve short. Using the new accuracy method, serve accuracy was categorised as accurate, inaccurate, apex good, and clearance good. This provided individual and group accuracy ratings.

In Study II a three-dimensional model was developed to examine the upper body kinematics during the badminton short serve. Textbook definitions hold that push-like movement patterns produce trajectories of the highest accuracy, however reducing complexity (i.e. degrees of freedom) is also stated as essential. Nonetheless, these patterns may be mutually exclusive, since push-like patterns may exhibit considerable complexity. The purpose of Study II was to describe the short serve movement patterns used by elite badminton players to determine whether push-like or low-complexity (or both) patterns predominate. Eight participants were recruited from the Senior Australian National Doubles Badminton squad (mean age: 23.4 ± 5.1 years, body mass: 73.2 ± 11.1 kg, height: 175 ± 8.6 cm). Three-dimensional kinematics were measured with an opponent present and analysed using principal component analysis to determine what movement patterns were used in this accuracy-based skill. Results showed that all players adopted a push-like movement pattern, but the most accurate servers also constrained the number of degrees of freedom by allowing movements of the elbow and wrist joints only in a single plane.

The main objective of Study III was to understand the role that movement variability plays in a precision-based movement. Little research has been published examining movement variability in sports, specifically in skills that require accuracy. The badminton short serve provided a unique opportunity to examine how elite athletes vary their movement patterns, since it requires precise multi-joint coordination to achieve an accurate serve. Recent research has shown that a rigid or inflexible system may not be good for performance and that it is more appropriate to understand the adaptability of a movement in an ever-changing environment. A three-dimensional motion analysis of eight elite badminton players performing 30 short serves with an opponent present to replicate match conditions was conducted. The results identified that players incorporate variability in specific phases of their movements reduce variability at racquet-shuttlecock contact. Higher medio-lateral (transverse plane) variability was displayed in most joint angles across all players. This strategy incorporated variability in the task-redundant dimension (transverse) to reduce variability in the task-relevant dimension (sagittal), which directly impact accuracy of the serve. Variability was also present in the timing of the swing itself, varying the timing of the backswing to reduce the variability at the contact point was a common feature displayed across all subjects, irrespective of whether the serve was accurate or not. Findings suggest elite badminton players use joint and timing variability in a functional capacity.

In conclusion, the methods developed to analyse the accuracy and kinematics of an accuracy-based task such as the badminton short serve revealed a greater insight into what defines an accurate serve, and how elite players coordinate and vary their movement to achieve accuracy. The results from Study I suggest that training either with an opponent present or serving on or slightly short of the service line may lead to better serve performance. The results from Study II provide the coach or player with information on the ideal movement patterns for short serve accuracy i.e. reducing the number of degrees of freedom involved (i.e. reduce movement complexity), using a push-like movement, and paying close attention to the movement from the elbow and wrist joints. The final study (Study III) revealed that elite badminton players vary their movement in a plane (transverse) that has less impact on the outcome of the task, thus reducing the variability in the plane (sagittal) that has the larger impact on the serve movement.

PUBLICATIONS RELATED TO THESIS

Conference publications

Vial, S., Cochrane, J., Blazevich, A and Croft, J. (2016). Examining racquet variability in the doubles badminton short serve. Physical Education and Sports Science Skill Acquisition Symposium (ASARG) 2016 conference, Singapore.
Awarded best presenter (2016) Physical Education and Sports Science Skill Acquisition Symposium conference.

Vial, S., Cochrane, J., Blazevich, A and Croft, J. (2017). A new method of measuring accuracy of the badminton short serve. Australian Skill Acquisition Network (2017) conference, Brisbane, Australia.

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CHAPTER 1 – INTRODUCTION

1.1 OVERVIEW

Accuracy is often an important component of sport performance and scoring. However, accuracy can be defined in different ways because the requirements differ from sport to sport. For example, in archery, the closer the arrow lands toward the centre of the target the more points are scored (Laborde, Dosseville, Leconte, & Margas, 2009). In basketball, accuracy is defined by whether the ball passes through the hoop (Khlifa et al., 2013; Schmidt, 2012). In team-based sports, accuracy can be defined as successful passes to a teammate, or shots on target (i.e. hoop or through goal posts) (Button, MacLeod, Sanders, & Coleman, 2003; Finnoff, Newcomer, & Laskowski, 2002; Katis et al., 2013; van den Tillaar & Ulvik, 2014). Accuracy is commonly evaluated as either hitting the target, or by how far the object finishes from the target (van der Kamp, 2006). Yet, there are many sports that do not have an endpoint from which to measure accuracy (Duncan, Chan, Clarke, Cox, & Smith, 2017; Edwards, Lindsay, & Waterhouse, 2005). For a sport like badminton and in particular the short serve, accuracy requires a more appropriate definition because the short serve is almost always returned, unless an obviously poor serve is performed (Duncan et al., 2017; Edwards et al., 2005). The non-parabolic nature of the trajectory can make it difficult to judge if the shuttlecock is landing in or out of the service square, so most opponents tend to hit the shuttlecock rather than leave it to avoid this predicament.

The validity of end-point accuracy (i.e. the finishing point from the target) for skills like the short serve is drawn into question as it fails to account for the trajectory of the shuttlecock. However, there are a small number of testing protocols available to evaluate the performance of the badminton short serve, one of the more popular tests is called the French short serve test (French & Stalter, 1949). This protocol uses small circles placed in the opposition's service square with a tightrope placed 20cm above the net. Players are scored based on where the shuttlecock lands, and if it travelled underneath the tightrope (i.e. between the net and tightrope), the coach also subjectively evaluates the serve trajectory (French & Stalter, 1949). More recently, Edwards et al., (2005) developed a protocol which requires the player to serve into a 1m² grid near the front middle of the service square. Players were instructed to aim for the grid on the floor, and accuracy was calculated using the average radial error from the front centre corner of the grid. This protocol was developed by observing how players train for the short serve, usually performing hundreds of serves aiming at a marked target near the front middle section of the service square (Edwards et al., 2005).

The aforementioned tests have been used to determine serve or shot accuracy in multiple studies (Bottoms, Sinclair, Taylor, Polman, & Fewtrell, 2012; Duncan et al., 2017; Teo, Newton, & McGuigan, 2011); however, the protocols assume that the server would normally aim for a specific location on the court. According to elite badminton players and coaches this is not the case, the server often uses the white tape across the top of a net as a guide to place the serve. Moreover, the players aim may be influenced by the presence of an opponent. One reason for this is that the opponent will often ‘attack’ or move toward the net as soon as the server has made contact (Phomsoupha & Laffaye, 2015a). This allows the opponent to contact the shuttlecock from a higher point, permitting a more offensive shot to be played at a downward angle, which can lead to a significant advantage in the rally (Duncan et al., 2017; Phomsoupha & Laffaye, 2015a). Because the opponent generally always returns the serve, the shuttlecock rarely lands on the ground, therefore it may be more appropriate to use the trajectory of the short serve to measure accuracy.

Projecting an object such as a shuttlecock to a specific target or place on a court with a high degree of accuracy is important for success in many sports (Duncan, Chan, Clarke, Cox, & Smith, 2016; Edwards, Waterhouse, Atkinson, & Reilly, 2007; Phomsoupha & Laffaye, 2015a). 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 relation 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). A throw-like movement pattern is where successive body segments or joints move sequentially, generally the object being thrown lags behind the elbow and/shoulder joint, this is because producing high velocity is usually the main goal of this movement pattern (Schmidt, 2012; Wagner, Pfusterschmied, Klous, von Duvillard, & Muller, 2012). Push-like movement patterns are often used to produce large forces or when the task requires accuracy, in which segmental rotations occur simultaneously (Kerr & Ness, 2006). It is commonly assumed that push-like movement patterns are used in accuracy oriented tasks, however this has yet to be explicitly verified.

The short serve has a small racquet swing compared to other strokes, and is a stroke which requires precision in order to be successful. 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 number of degrees of freedom an individual might use to perform the short serve is considered. For example, the shoulder joint has three degrees of freedom, the elbow two, the hand relative to the forearm has three (Dounskaia & Wang, 2014; Sidaway, Sekiya, & Fairweather, 1995). Traditionally, novices tend to initially freeze degrees of freedom, and as they gain expertise in the task they then begin to free degrees of freedom, generally showing increased ranges of motion (Button et al., 2003; Scholz & Schoner, 1999). Recent research has shown that coordination changes are specific to the task and the learner, for example, may constrain some degrees of freedom , then free them, and then constrain again (Glazier, 2010). Identifying variables that define stable and reproducible relationships amongst degrees of freedom can provide valuable information to coaches and players when training accuracy for the short serve. Since the service initiates every point in badminton, understanding what movement pattern and specific degrees of freedom are used to perform an accurate short serve is a critical component in gaining a competitive advantage in each rally (Duncan et al., 2017; Phomsoupha & Laffaye, 2015b).

Skilled performers are capable of restricting degrees of freedom which are not vital to performance, and incorporating degrees of freedom which directly influence performance (Vereijken, Vanemmerik, Whiting, & Newell, 1992). For a complex task, which requires a high degree of accuracy, the performer may restrict irrelevant degrees of freedom to reduce complexity (Seifert, Button, & Davids, 2013). By simplifying the movement the performer reduces the risk of introducing error into the movement (Pekny, Izawa, & Shadmehr, 2015). Better players could adjust their movement pattern by simplifying the movement in order to achieve an accuracy.

Expert performance in many sports is traditionally characterised by coordinated sequencing of segments of the body in a particular movement pattern in a consistent manner (Horan, Evans, & Kavanagh, 2011). Primarily, performance is affected by how the human system interacts with the environment and perturbations associated with the task and environment (Trommershauser, Gepshtein, Maloney, Landy, & Banks, 2005). Instead of assuming that in most sporting tasks each movement has a universally optimal technique, it is more appropriate to understand the adaptability of the movement to a changing environment (Bartlett, Bussey, & Flyger, 2006; Bradshaw, Maulder, & Keogh, 2007). Consideration of how experts vary their movement pattern to achieve the goal of the task is essential to improve performance. Understanding the functional role that movement variability plays is important to reveal whether the task requires stability, or the ability to adapt to certain irregularities that occur during a particular movement pattern (Antunez, Hernandez, Garcia, Vaillo, & Arroyo, 2012; Harbourne & Stergiou, 2009; Murnaghan, Carpenter, Chua, & Inglis, 2017). Experts produce movement patterns that show underlying similarities, yet there are subtle differences between each movement (Lockhart & Stergiou, 2013).

Several studies have investigated movement variability at different skill levels and found increases in variability with skill level (Button et al., 2003; Davids, Shuttleworth, Button, Renshaw, & Glazier, 2004; Seifert et al., 2013). Suggesting that more skilled performers utilise a level of functional variability to achieve the goal of the task. This supports the dynamical systems perspective. Variability in a movement can be seen as necessary variations that occur to allow adjustments in a continuously changing environment (Bergin, Tucker, Vicenzino, van den Hoorn, & Hodges, 2014; Davids, Glazier, Araujo, & Bartlett, 2003a). Skilful performance in precision-based movements such as the short serve in badminton require low variability of the end effector (e.g. hand and racquet), also known as trajectory variability (Newell, 2000; Todorov, Li, & Pan, 2005). However, low variability of the end effector can be achieved through greater joint angle variability as performers adapt to task constraints (Todorov & Jordan, 2002).This proposes that maintaining a degree of variability is a strategy used by more skilled players to adapt to subtle changes in the movement (Kudo, Tsutsui, Ishikura, Ito, & Yamamoto, 2000).

Accuracy is a critical component for success in many sports. Therefore, it is important to understand how to appropriately measure accuracy in specific contexts, rather than adapting existing protocols to suit the researcher, instead, develop the most suitable methodology for the task. Once the accuracy measures are established, identifying how individuals coordinate their movement to achieve accuracy is essential in the design and development of any training program. Previous research has shown that optimal movement patterns cannot be applied universally. As a result, extracting invariant features of expert players can often reveal better modes for training specific components, such as accuracy of the short serve.

1.1.1 Aims of Thesis

The first objective of this thesis is to use the short serve in badminton to introduce a new perspective on performance accuracy, and to add to the existing knowledge base of accuracy in sport through expanding accuracy definitions and developing new methodologies for measuring additional parameters. The second aim was to address a wide-spread assumption about how athletes coordinate their movement for accuracy, as there is currently no research which has set out to explicitly answer such a question. There has been a relatively recent shift in the biomechanical and motor control literature arguing that biomechanists should consider movement variability as a function of movement rather than error alone (Bartlett, Wheat, & Robins, 2007). Therefore, the final aim of this thesis was to examine movement variability of the short serve. Since this is a discrete multi-joint movement with a small range of motion, it might reveal how experts use or suppress variability as a function of performance accuracy.

1.2 REVIEW OF THE LITERATURE

1.2.1 Chapter Overview

This chapter contains a review of the literature addressing accuracy and movements associated with accuracy in sport. The review focusses on the badminton short serve, a skill that requires a high degrees of accuracy to be successful (Duncan et al., 2016; Edwards et al., 2005). The literature will be reviewed under four broad sections (Sections 1.2 to 1.5), i) an overview of badminton and the short serve, ii) accuracy in sport, iii) movement patterns associated with accuracy, iv) varying movements in an accuracy-based skill.

The opening section introduces the game of badminton and the short serve itself. The next section describes the current protocols designed to measure accuracy in a variety of sports, with most protocols using the landing or endpoint to classify how accurately the task was performed. The shortfalls of this method for specific sports such as the badminton short serve, and that using endpoint accuracy is not the most appropriate way of evaluating short serve accuracy, are discussed. Section 1.4 then addresses the lack of existing evidence on what type of movement patterns are associated with accuracy; much of the research that has explored movement patterns in sport have focused on gross motor skills, or skills which require high velocity. The degrees of freedom problem (Bernstein, 1969) is discussed and how the principle of abundance could influence movement complexity, and therefore what type of movement pattern used for accuracy. This leads to section 1.5, which begins by defining movement variability and how task constraints, such as accuracy, influence how individual joints may vary. Also, when movement variability is present, how it might fluctuate at different phases of a movement and the implications of this is examined. Lastly, this section discusses the interaction between movement variability and accuracy-based skills.

1.3 OVERVIEW OF BADMINTON

Badminton has grown in popularity since it was included in the Barcelona Olympics in 1992. There are now around 200 million active players around the world (Cabello Manrique & Gonzalez-Badillo, 2003). Badminton is also the fastest racquet sport in the world. Shuttlecock velocities reach up to 103 $m \cdot s^{-1}$ (metres per second), and an average velocity during a rally are in the range of 52 – 75 $m \cdot s^{-}$

[1]. The game itself has sporadic bursts of high intensity movements with short periods of rest (Zhu, 2013). A typical rally lasts seven seconds with 16-20 s of rest with an effective playing time of 31% (Chin et al., 1995; Ooi et al., 2009). A national level match usually lasts 30-35 min, with an average of 12 min playing time. This means that to play professionally, badminton players must be able to produce large forces to perform powerful smash shots and, in contrast, fine motor skills to execute precision shots repeatedly (Faccini & Dai Monte, 1996). In 2005, the Badminton World Federation changed the required number of points needed to win a game from 15 to 21; while the number of games per match remained at three (Phomsoupha & Laffaye, 2015a). The new points system resulted in shorter match durations despite a greater number of rallies. This was partly due to shorter rallies and a higher-paced attacking style of badminton. 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 impact of the quality and consistency of the service in order to win the rally in the fewest number of shots (Phomsoupha & Laffaye, 2015a).

Once the opponent signals that they are ready to receive the service, the first forward movement of the server's racquet will initiate the serve. The server and receiver are positioned diagonally in the service areas on each side of the court. Players either serving or receiving are permitted to lean forwards or sideways outside of the service area, as it is common for the receiver to "attack" the shuttlecock long before it is near the ground (Phomsoupha & Laffaye, 2015a). The server is required to initially contact the base of the shuttlecock with the racquet head. This rule seems incongruous, however it was instated after some players first contacted the shuttlecock transversely on the feathers which inverted the shuttlecock and created an unfair advantage for the server (Macquet & Fleurance, 2007). Badminton official rules (Badminton World Federation, 2005) state that the shuttlecock cannot be struck from a position where its vertical height is above the waist when serving, which would constitute a service fault. The waist is defined as the imaginary line around the body at the point of the lowest part of the server's last rib. This rule was installed to prevent a "smash" (overhead shot) shot being used as a serve. In March 2018, the Badminton World Federation (BWF) will implement an experimental law which has stated that the whole of the shuttlecock must be below 1.15 metres from the court upon contact with the racquet.

1.4 ACCURACY

1.4.1 Defining Accuracy

In many ball sports (including shuttlecocks and other projectiles) the accuracy of projecting the object to a specific place on a field or a court is important for success (Duncan et al., 2017; Freeston & Rooney, 2014). How accurately the task is performed will subsequently impact game-play, and could ultimately influence the result of the match. In golf, the line and distance from the hole are key indicators of accuracy (Hume, Keogh, & Reid, 2005; Libkuman, Otani, & Steger, 2002; Sim & Kim, 2010; Sommer & Ronnqvist, 2009); shooting accuracy in soccer has a variety of definitions, for example, the number of shots vs goals scored, or the number of shots that hit the target (Finnoff et al., 2002; Katis et al., 2013; van der Kamp, 2006). In the Olympics, archery involves attempting to hit a target from a fixed distance of 78 metres, the bullseye is 6 cm in diameter (Laborde et al., 2009). The aforementioned sports all have varying definitions of accuracy, however most sports that require accuracy have a target or an endpoint with which to measure accuracy, and with how well a player can accurately execute a task has a significant effect on win or loss.

1.4.2 Short Serve Accuracy

As with most racquet sports, the serve is critical in how the rally plays out (Edwards et al., 2005). However, badminton does differ in that a second serve is not permissible if a fault is committed on the first serve, for example, a service error (Bottoms et al., 2012). Players therefore need to be consistently accurate for each serve. There are four different types of serves used, with each the shuttlecock follows a non-parabolic trajectory with varying angles (Chen, Pan, & Chen, 2009). 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. This suggests that the serve accuracy has a significant effect on the outcome of the point, but this has yet to be verified. The current study focuses on the most commonly used serve in badminton doubles, the backhand short serve (Duncan et al., 2017).

The purpose of the serve is different for doubles and singles, partly due to different court dimensions (see Figure 1.1) and the addition of a team mate on each side in doubles (Duncan et al., 2017). 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 (Ikram Hussain et al., 2011). The return shot can indicate whether the serve is successful, as the opponent can be forced to play a high angled shot toward the back of the court, allowing an offensive shot to be played (Phomsoupha & Laffaye, 2015a). Top-tier coaches and elite players have stated that during training players tend to aim to for the shuttlecock to land on or near the front line of the service square. An accurate short serve can be defined as one that has a low trajectory with the apex occurring before going over the net as well as a steep drop-off. This is the only serve that requires a high degree of accuracy and low racquet velocity (Duncan et al., 2017; Edwards et al., 2005).

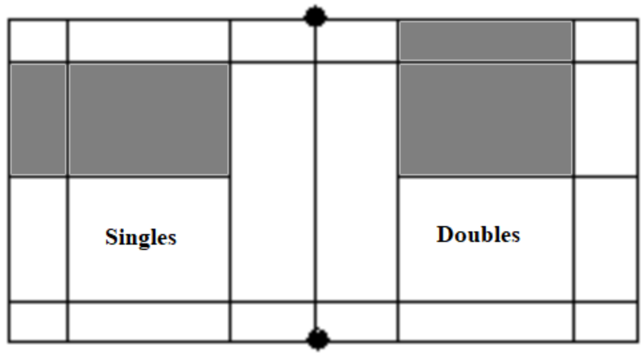

Figure 1.1 Landing areas for singles and doubles.

1.4.3 Measuring & Evaluating Accuracy

In sports that require some form of accuracy the outcome is often assessed on the basis of whether the object hits the target or not, or by how far the object finishes from the target. This is known as end-point accuracy, and is one method of measuring accuracy (Antunez et al., 2012; Bottoms et al., 2012). However, in some sports there are circumstances where the ‘end-point’ cannot be measured or observed to determine whether the attempt can be deemed accurate or inaccurate. For example, in badminton the short serve is rarely left, as the the server and opponent are positioned relatively close to each other and the serve is hit with a low force, meaning it is easier to make contact with the shuttlecock when compared to returning a shot such as the jump smash (Duncan et al., 2017; Edwards et al., 2005). Another reason the short serve is always returned is because it is difficult to judge the trajectory as to whether the serve is landing in or out of the service square, resulting in most opponents returning the serve to avoid this problem. Because of these factors, the shuttlecock tends to never land in the opponent's service square, unless it is left by the returning player, which only occurs when an obviously poor serve is performed (Duncan et al., 2017). Since the shuttlecock tends not to land in match situations, it is not known whether the shuttlecock would actually reach the service square of the opponent during a match. Therefore, end-point accuracy for the short serve as it fails to account for the trajectory of the shuttlecock.

The most commonly used protocol to evaluate short serve accuracy was developed by Edwards et al., (2005). The protocol required players to serve into a $1m^2$ grid near the front middle of the service square on the opposite side of the court (Edwards et al., 2005), a method which was developed by observing how players train for the short serve. Accuracy scores were calculated using the average radial error based on where the shuttlecock landed in the grid, if the shuttlecock landed outside the grid then that trial was disregarded. Also, the tests assume that the badminton player would normally aim for a specific location on the court. According to elite badminton players and coaches (see appendix 4) this is not the case, instead, their aim is effected by a combination of factors including the characteristics (i.e. strengths and weaknesses of that individual), and the position of the opponent. If the server is influenced by environmental factors such as game situation (i.e. even game/pressure point etc), strengths or weaknesses of the opponent, or perhaps using the net as a visual guide, then the trajectory of the serve may be altered (Cabello Manrique & Gonzalez-Badillo, 2003).

A more complete definition of accuracy is needed, specifically for task where the endpoint is not measurable or observable, such as the short serve. Measuring trajectory to determine accuracy is not only important to accurately reflect match situations, but it can also identify a disparity between actual performance and perceived performance. For example, players may train to a target on the ground, but in match situations, the trajectory of the serve may change because an opponent is present.

This could be due to the opponent ‘attacking’ or moving toward the net as soon as the server has made contact, thus reducing the distance the shuttlecock may travel and potentially changing serve trajectory. This is important information to improve training for actual performance in game.

1.4.4 Representative Learning Design

Athletes adjust their movement pattern based on information from other athletes or objects used in their respective sport (Pinder, Davids, Renshaw, & Araujo, 2011). Therefore, it is important that a training environment represents situations are similar to those faced during a match. Representative Learning Design (RLD) is a framework for assessing key areas when are simulated in training and how accurately they reflect match situations (i.e. competition). The primary goal of RLD is to ensure that practice replicates the performance environment faced by the athlete (Pinder et al., 2011).

1.5 MOVEMENT PATTERNS ASSOCIATED WITH ACCURACY

1.5.1 Performance Accuracy

Being able to perform tasks accurately is important in daily living, such as reaching for a glass of water, or inserting a bank card into a payment machine (Smeets, Frens, & Brenner, 2002). In sport, performing skills that require accuracy can affect whether the task is deemed a success or failure. For example, in baseball the fielder must throw the ball to the base defender accurately in order to stop the opposing team from scoring points (Escamilla, Speer, Fleisig, Barrentine, & Andrews, 2000; Fleisig, Chu, Weber, & Andrews, 2009). In golf putting, the goal is to get the ball in the hole in the fewest number of shots possible (Neumann & Thomas, 2008). Each sport has differing requirements for achieving accuracy, and it is important to understand what movement patterns are used when accuracy is the primary goal of the task. Analysing movement patterns is used to understand how movements are performed, and through this, develop new training programs and interventions to improve performance (Dounskaia & Wang, 2014).

1.5.2 Throw and Push-like Movement Patterns

Most of the research examining movement patterns focuses on throw-like patterns. This is reasonable, since throw-like movements are used in many sports such as baseball, cricket, American football, and so on (Escamilla et al., 2000; Fleisig et al., 2009). For this movement pattern, successive body segments move in sequence, usually the object being thrown lags behind the elbow and/or shoulder joint (Schmidt, 2012). This is because producing high velocity is usually the key objective in using a throw-like movement pattern (Schmidt, 2012; Wagner et al., 2012). That is not to state that accuracy does not feature in throw-like movement patterns, but when the main goal is achieving high speed, or the furthest distance, this is a common technique to use (van den Tillaar & Ettema, 2007).

Anecdotal evidence suggests that when precision or accuracy is key to task performance, a push-like movement pattern is used (Blazevich, 2012; Portus & Farrow, 2011). However, little research has examined which movement pattern is best for accuracy, with a small number of published books and research articles reporting that push-like movement patterns are best for accuracy-based tasks (Blazevich, 2012; Portus & Farrow, 2011; Tant, 1993). To date, no research has been published explicitly verifying what movement pattern is used when the goal is accuracy. Understanding what type of movement pattern is used for accuracy is a fundamental question in movement science.

Some studies have performed kinematic analyses of movements in specific sports, and as a result, identified movement patterns that could be associated with accuracy (Kerr & Ness, 2006; Portus & Farrow, 2011; Tant, 1993). One such study analysed the volleyball jump set shot, which found that the height and position of the ball, in relation to the player performing the jump shot, are required for an accurate set shot (Tant, 1993). A pushing pattern was found to occur when players aligned their arms behind the ball, creating a longer contact time and allowing more control over the ball, which created a more vertical arc, leading to greater accuracy (Tant, 1993). Portus and Farrow (2001) found that cricket batters used a push-like movement pattern when facing fast-paced bowlers, opting for more control, instead of using a large ‘wind-up’ for the backswing. This push-like movement pattern was used by batters to place the ball into the gaps in the field, resulting in greater accuracy than a stroke which produces a large force.

Such skills are reactive in nature, the performer is required to react to the actions of either an opponent or teammate (Portus & Farrow, 2011; Tant, 1993). This means that the performer could adapt the movement pattern depending on the situation (Martin, Greger, Norris, & Thach, 2001; Tottenham & Saucier, 2004; Trommershauser et al., 2005). For example, their positioning may have been sub-optimal to receive the ball, or to play the shot. Alternatively, it may be that the player misjudged the timing or position of the ball, therefore altering the movement, perhaps adapting to the situation using a combination of movement patterns to find the most suitable solution (Simbana-Escobar, Hellard, Pyne, & Seifert, 2017). In the badminton short serve, the defining features of an accurate serve - the location of the apex and height above the net - determine accuracy. This is not a reactive task, it is discrete, as it has a clear beginning and end (Golenia, Schoemaker, Mouton, & Bongers, 2014). It is not yet known how an individual coordinates their movement in a discrete skill to achieve a high degree of accuracy. Understanding what type of movement pattern leads to better accuracy is important for a wide variety of sports, which may assist in improving strength and conditioning programs, skill development, and, specific training interventions.

1.5.3 Principle of Abundance

There are a number of ways for an individual to coordinate their joints in order to achieve a goal. The number of these varying configurations that determine movement of a segment or number of segments is defined as the degrees of freedom (Bartlett et al., 2007; Dounskaia & Wang, 2014). For example, the shoulder joint has three degrees of freedom, the elbow two, the hand relative to the forearm has three, all of which can combine in many different ways (Diedrichsen, Shadmehr, & Ivry, 2010; Latash, Scholz, & Schoner, 2002). Traditionally, novices tend to initially freeze the degrees of freedom, and as they gain expertise in the task they begin to free the degrees of freedom (Fleisig et al., 2009; Ko, Han, & Newell, 2017). More recent research has shown that coordination changes are specific to the task and the learner, for example, some degrees of freedom are constrained, then released, and then constrained again (Glazier, 2011). Some researchers have found that experts free the degrees of freedom in certain accuracy-based skills such as the basketball free throw (Button et al., 2003), while other studies disagree, stating that when the goal is accuracy, supressing the degrees of freedom is better for performance (Schutz & Schack, 2013).

The short serve appears quite simple, perhaps because the movement of the racquet swing is relatively small. However, the intricacy becomes apparent because of the number of possible positions and orientations that each limb segment could follow. Furthermore, to achieve an accurate serve the performer must coordinate their swing using the racquet to contact the shuttlecock in such a way so as to achieve the desired trajectory. Researchers have identified that there are many more degrees of freedom available than is strictly needed to perform a task, this is known as the *principle of abundance* (Chow, Seifert, Herault, Chia, & Lee, 2014; Davids, Glazier, Araujo, & Bartlett, 2003b). Studying such pattern formations allows the identification of degrees of freedom that define stable performance, providing valuable information to coaches and players on how to train for specific skills, such as accuracy in the short serve. It is not yet known which type of movement pattern/s are best for accuracy. Understanding how experts coordinate task-dependent and task-redundant degrees of freedom, in this case the badminton short serve, can reveal common features exhibited, allowing improved training programs leading to better performance.

1.5.4 Movement Complexity

Few published research articles have specifically analysed movements patterns associated with accuracy skills. It is currently unknown if push-like movement patterns are optimal for accuracy, and whether reducing complexity (i.e. degrees of freedom) is related to accuracy. Perhaps push-like patterns have been associated with accuracy skills because in these tasks the movement itself may be less complex. However, it could be that a different movement pattern (i.e. throw-like) may better for accuracy if the complexity were reduced e.g. less degrees of freedom involved. Although, using this type of movement pattern usually involves an increased number of degrees of freedom to perform the task, leading to a more complex movement pattern (Wagner et al., 2012). Some researchers have found that experts are more capable of constraining task-redundant degrees of freedom, and use task-relevant degrees of freedom to their advantage (Button et al., 2003; Davids et al., 2003b). For a complex task which requires a high degree of accuracy, it could be assumed that the performer would restrict task-redundant degrees of freedom to reduce complexity (Seifert et al., 2013). By restricting specific joints which may not be task-relevant, the performer reduces the risk of introducing error into the movement itself (Pekny et al., 2015). Perhaps the better performers modify movement patterns because of the task constraints, using a combination of movement patterns to achieve better accuracy. Further research needs to be undertaken to determine movement patterns and coordination strategies used in skills associated with accuracy.

1.5.5 Analysing Movement Patterns

Coaches and players are constantly striving to improve the performance of their strokes in badminton from a technical point of view, to give themselves an edge over their opponent. There is often a gap in communication between researchers, coaches and players, and this is partly due to the differences in quantifying and analysing player performance. For instance, researchers tend to record preselected variables and then perform various analyses to be able to provide a meaningful interpretation of the results. Whereas a coach usually observes the whole task being performed, breaking down the movement into specific components and provides feedback in a descriptive manner that the player can easily absorb. For example in the badminton short serve, a coach will often a define player's technique by describing specific movement patterns that they employ, such as "soft hands," "flick," "push," "rolling" (Phomsoupha & Laffaye, 2015a).

Quantitative and qualitative approaches play vital roles in sports science, with researchers using a more analytical method, while coaches use a more observational method. Individually both have limitations, for example, specifying variables prior to data collection may lead to researchers missing crucial data, or even reporting their findings incorrectly because of missing information (Federolf, Reid, Gilgien, Haugen, & Smith, 2014). In contrast, coaches often provide feedback based on their own observations and understanding of the player's technique or performance, often proving very advantageous for the player. However, one particular drawback of this method is that it is often subjective and may not always be the most appropriate feedback for that individual to improve technique or performance. Using pattern recognition methods to quantify technique and extract features from large data sets to classify individual and group differences is becoming more prevalent in applied sports biomechanics, one such method is called a principal component analysis (PCA). Moore et al., (2011) used this method to classify principal movement direction in cyclists to identify main features of individuals to allow classification into groups. To quantify alpine skier's technique, Federolf et al., (2012) used the same analysis to identify the main movement components, this approach provided a quantitative method of analysing technique in a manner that a coach or player would use to describe a movement.

1.6 MOVEMENT VARIABILITY

1.6.1 Defining Movement Variability

Movement variability is defined as the variations that occur in motor performance across several repetitions of a task over time. For example, variability is an intrinsic characteristic of human performance (Scholz & Schoner, 1999). Traditionally, movement variability has been associated with poor performance, however recent research has shown that variability is an essential component of human movement. Studies have shown that variability may offer flexibility to adjust to an ever-changing environment; an important component of skilful movement (Bartlett et al., 2007; Chow et al., 2014). Moving proficiently is not exclusively due to the coordination between different segments of the body (Schorer et al., 2007; Wagner et al., 2012). Meaning that efficient movement is due to how well the system or organism interacts with the environment, particularly in response to unexpected changes (Davids et al., 2003b; Simbana-Escobar et al., 2017).

1.6.2 Bernstein – Degrees of Freedom Problem

Movement of a task such as the short serve involves a number of possible positions and orientations that each limb segment could follow to achieve an accurate serve. The number of these varying configurations that determine the movement of a segment or number of segments is defined as the degrees of freedom (Bartlett et al., 2007). Bernstein (Bernstein, 1967) claimed that one of the foremost difficulties in achieving efficient movement is the ability to overcome degrees of freedom that are not necessary for that particular movement (Button et al., 2003; Dupuy, Motte, & Ripoll, 2000). Bernstein (1930) conducted some of the first studies to understand why movement varies in different phases, joints, and planes. One of his most famous studies examined expert blacksmiths striking a chisel with a hammer (Latash, 2012). The blacksmiths varied their joint angles, and as a result this reduced variability of the hammer, ensuring accuracy when striking the chisel. He suggested that when learning a new skill some movements are limited with less range of motion, this is known as the degrees of freedom being “frozen”. As skill level increases, movement of each segment in varying orientations and positions increases, therefore there is a release or “freeing” of the degrees of freedom (Davids et al., 2003b; Newell, 1986).

1.6.3 Task Constraints

Newell (1986) expanded this by suggesting that this “freezing” or “freeing” is due to specific task constraints and cannot be expressed across different tasks (Newell, 1986). Expert performance in precision-based movements have been reported to require low variability of the end effector (e.g. hammer) (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. When accuracy is the most important goal, it is not yet known if experts more likely to suppress variability in order to maintain accuracy, or increase variability in task-redundant degrees of freedom (Darling & Cooke, 1987). In precision throwing tasks, researchers found that the variability of the release parameters (angle at release phase) does not change across trials. Instead, players compensate with an increase in movement variability in the acceleration 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 skilful players to adapt to subtle changes in joints and segments at the release phase (Button et al., 2003; Dupuy et al., 2000; Kudo et al., 2000).

Task constraints are related to the goal of the task and therefore what is required to achieve the goal i.e. angles of each joint for successful performance and consequently, specific body movements to produce these outcomes (Newell, 1986). Each task constraint requires differing levels of movement variability (Davids et al., 2003b; Newell, 1986). The task constraints of the badminton short serve are determined by the range of paths that the shuttlecock can follow and the movement patterns that can produce these paths. Variability is common when movements are repeated (Button et al., 2003; Langdown, Bridge, & Li, 2012), however movement variability generally increases as an individual becomes more proficient in a task (Button et al., 2003). Nonetheless, movement variability has been commonly regarded as a phenomenon that should be minimised for improved performance, with researchers often characterising elite performers with a lack of variability (Button et al., 2003; Wagner et al., 2012).

1.6.4 Variability in Accuracy Tasks

Movement variability has not been reported in accuracy-based racquet sports such as the badminton short serve, but similar arm movements occur in the Frisbee throw. In one study, novice throwers showed greater consistency in the proximal joint rotations which reduced hand trajectory variability, while the elbow-wrist relationship (distal joints) remained more variable across practice (Davids et al., 2003b; Wagner et al., 2012). Thus determining the optimal level of movement variability needed for successful performance. In other sporting tasks that require accuracy such as the basketball free throw, Button et al (Button et al., 2003) reported higher inter-trial movement consistency by the more skilled players, specifically at the elbow and wrist joints (Button et al., 2003; Muller & Sternad, 2004). More accurate players displayed a greater range of motion of the wrist than novices while range of motion at the elbow was similar across skill levels, supporting the hypothesis that degrees of freedom are released in a proximal to distal sequence (Button et al., 2003; Dupuy et al., 2000). Trajectory variability of the elbow joint was maintained across skill levels, while joint-space variability, or co-variation of joint motion appears to affect the elbow and wrist toward the end of the throwing action, implying that functional features of a precision throwing task are compensated by key release parameters (joint angle) to maintain accuracy (Kudo et al., 2000). Hence, there is higher trajectory variability observed in the middle of the movement, and lower variability at the beginning and end of the movement (Kudo et al., 2000). Therefore, functional variability appears to be a factor used by higher skilled players to ensure task success.

Importantly, individualised movement patterns have been observed, with researchers suggesting individual analysis of participant’s movement variability. Schőllhorn & Bauer (1998) supports this notion; they identified individual movement patterns during throwing tasks, affirming that players acquire a technique that is optimised to their individual boundary conditions (i.e. constraints). Consequently, no optimal movement technique can be distinguished due to individual specificity (Button et al., 2003; Kudo et al., 2000; Yang & Scholz, 2005). Though, successful performance has been observed when co-variation of joint motion is present, also known as a synergy (Bartlett et al., 2007; Button et al., 2003; Davids, Renshaw, & Glazier, 2005; Yang & Scholz, 2005). These findings led Yang & Scholtz (Yang & Scholz, 2005) to suggest that Bernstein's hypothesis of overcoming the redundant degrees of freedom may require re-evaluation. In its' place, they described it as an issue of how the available degrees of freedom of different joints are synchronised to stabilise the performance variables for optimal movement.

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. Furthermore, understanding how elite players incorporate movement variability in game situations will add to the growing knowledge base in this field.

1.6.5 Analysing Movement Variability

Biological noise is inherent in most movements, in some instances it can be detrimental to performance, however it can also have a functional capacity, leading to stable performance (Rein, Bril, & Nonaka, 2013). For example, variability of endpoint accuracy (i.e. performance consistency), and movement coordination, which may introduce variability to achieve an accurate outcome (Bradshaw et al., 2009; Bradshaw et al., 2007). Traditionally, the coefficient of variation (CV%) is used as a measure of variation for discrete analyses. This measure alone may include technological error (i.e. video set-up, environmental changes) and biological movement variability. Bradshaw et al., (2007) created a method that estimates biological (intraindividual) variability using the standard error of the mean (SEM%) as an estimation of the technological error, biological variability (BCV%) is then simply calculated by deducting SEM% from the CV% (Bradshaw et al., 2007).

Movement variability has not been reported in accuracy-based racquet sports such as the badminton short serve. It is unclear whether elite players would suppress variability to ensure accuracy, or incorporate variability as a function for performance (Darling & Cooke, 1987). However, players may vary specific joints at specific phases as a compensatory mechanism, which has been found to minimise variability of the task-dependent degrees of freedom (Bartlett et al., 2007; Glazier, 2011).

1.7 PURPOSE

Due to the interrelated gaps in information, the overall goal of this thesis was to add to the existing definition of accuracy; develop a method for measuring these additional accuracy parameters; understand how experts coordinate their movement to ensure an accurate performance; and, examine how movement varies in an accuracy-based skill. Therefore, the present research aimed to fill the gaps identified above. Three studies are presented, in Study I the shuttlecock trajectory data was collected from racquet contact to landing on the ground with no opponent present (Session A), and a separate session with an opponent present (Session B). These data were collected to validate our prediction model of the shuttlecock trajectory and landing location; the prediction model was applied to session B to predict where the shuttlecock lands when an opponent is present. In Study II, the kinematic data was collected on eight elite badminton players performing the short serve, a principal component analysis was performed to determine what movement pattern/s is used in a precision-based task. In Study III, the biological movement variability was calculated to determine if elite badminton players minimised variability of the task-dependent degrees of freedom, and understand how variability relates to short serve accuracy. Therefore, the purposes of this thesis were:

I. To predict where the shuttlecock lands when an opponent is present. Define a new measure of accuracy for the short serve; determine a new method of measuring accuracy of the badminton short serve.
II. To investigate the specific movement patterns associated with an accuracy-based task.
III. Examine biological variability in an accuracy-based task.

1.8 RESEARCH QUESTIONS

Study I: The Importance of Flight Trajectory in Measures of Performance Accuracy in Racquet Sports

1. Is there a difference between landing location of the shuttlecock between training conditions (no opponent) and match conditions (opponent present)?
2. If there is a difference between conditions, a more appropriate definition of accuracy and methodology to measure accuracy will be developed.

Study II: A Simplified Movement Pattern Results in Greater Performance Accuracy in a Precision-Based Sporting Skill

1. Which movement patterns are associated with accuracy in the badminton short serve?
2. Are the more accurate players using a more or less complex movement pattern?

Study III: The Role of Movement Variability in an Accuracy-Based Skill

1. Do players vary angles of specific joints at precise time points?
2. Is variability present in the timing of the racquet, and is it different at specific phases of the swing?

1.9 HYPOTHESES

Study I: The Importance of Flight Trajectory in Measures of Performance Accuracy in Racquet Sports

1. With an opponent is present, some of the short serves will fall short of the service line.
2. The new methodology for measuring short serve accuracy will be a more appropriate determination of serve accuracy.

Study II: A Simplified Movement Pattern Results in Greater Performance Accuracy in a Precision-Based Sporting Skill

1. The use of a push-like movement pattern from the shoulder to the elbow and wrist joints will lead to a more accurate short serve. The racquet head will follow a linear path.
2. The more accurate players will simplify the pushing movement pattern more than the less accurate players.

Study III: The Role of Movement Variability in an Accuracy-Based Skill

1. Players will incorporate variability in the task-redundant joints and planes to reduce variability of the task-relevant joints and planes.
2. Timing of the backswing will vary to reduce variability at racquet-shuttlecock contact.

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CHAPTER 2 - STUDY I

THE IMPORTANCE OF FLIGHT TRAJECTORY IN MEASURES OF PERFORMANCE ACCURACY IN RACQUET SPORTS

This chapter is being submitted to the *Journal of Behavoral Research Methods*

Vial, S., Croft, J., Blazevich, A., Schroeder, R & Cochrane, J (2018). The Importance of Trajectory for Performance Accuracy in Racquet Sports. *Behavioural Research Methods*.

2.1 ABSTRACT

In many sports, accuracy is an essential component of actions such as passing, shooting, and aiming. Accuracy is often evaluated by either hitting a target, or how far the object finishes from it, for example, free throw percentage. For the badminton short serve, the rules dictate that the shuttlecock must clear the net and land on or beyond the service line. However these constraints are insufficient to distinguish poor and good serves: a serve that just clears the net but continues to rise is easier to return than one with the apex before the net. Rating serves solely on end-point accuracy (i.e. the finishing point from the target) fails to account for the shuttlecock's trajectory. This is particularly important because practice drills often involve serving to targets placed along the service line but in games the serve rarely lands because the opponent returns it. In this study, short serve trajectory was collected without and with an opponent. The full trajectory (without an opponent) was used to create a model to predict the landing location from the flight path. The validated prediction model was applied to trajectory data with an opponent present to predict landing location. Based on predictions from this model 69% of serves to an opponent would have landed on or short of the service line. The results demonstrated the need to measure trajectory of the shuttlecock to classify serve accuracy more appropriately. This study also showed that practicing serving to floor targets may not replicate serves that occur in a match against an opponent, and that the method of measuring the trajectory of the shuttlecock should be adopted when measuring short serve accuracy as it more accurately reflects accuracy performance during a match-like situation.

2.2 INTRODUCTION

In many ball sports (including shuttlecocks and other projectiles) the accuracy of projecting the object to a specific place on a field or a court is important for success (Duncan et al., 2017; Freeston & Rooney, 2014). Performance is often evaluated based on endpoint accuracy, i.e. either hitting the target, or by how far the object finishes from the target (Escamilla et al., 2000). For example, in throwing darts, points are scored depending on where the dart lands on the board (Edwards et al., 2007), and in goal-based sports such as soccer and hockey the ball must land within the net (Finnoff et al., 2002; Kerr & Ness, 2006). How accurately the task is performed will subsequently influence game-play, and could influence whether the match is won or lost (Maquirriain, Baglione, & Cardey, 2016).

Quantifying accuracy is specific to the sport. For example, the free throw in competitive basketball games is analysed by counting the success rate of all throws, providing an evaluation of accuracy as a completion percentage (Rojas, Cepero, Ona, & Gutierrez, 2000; Schmidt, 2012). In baseball pitching the functional throwing-performance index measures accuracy by the number of throws landing within a target square (Escamilla et al., 2000; Huang, Pietrosimone, Ingersoll, Weltman, & Saliba, 2011; Lust, Sandrey, Bulger, & Wilder, 2009). The accuracy of tennis groundstrokes is measured by using target areas in the opposition's court, lower scores for strokes that are short and down the middle of the court, and higher accuracy scores when the ball lands toward the side and top areas of the court (Lyons, Al-Nakeeb, Hankey, & Nevill, 2013). Badminton uses similar protocols to measure short serve accuracy: one of the first tests developed (the French short serve test, French & Statler, 1949) uses small targets in the opposition's service square with a tight rope placed 20 cm above the net. Players are scored based on where the shuttlecock lands and whether it travelled underneath the rope (i.e. between the net and rope). A more recent protocol uses a smaller target area (a 1 m^2 grid near the front middle of the service square) but removes the net height constraint (Edwards et al., 2005). Accuracy is calculated using the average radial error measured from the front corner that intersects the service squares (see Figure 2.1).

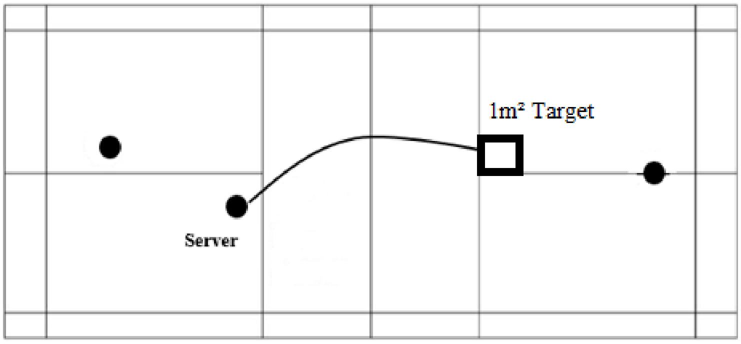

Figure 2.1 Example schematic for measuring short serve accuracy (Edwards et al., 2005).

One problem with these tests is that accuracy is measured solely by the landing location. In training, players often perform hundreds of serves per session to a target in the opposition's service square without a receiver. Accuracy of each serve is based on the landing location but a projectile can land in the same location with varying trajectories, meaning that two projectiles following distinctly different pathways could have the same "accuracy" (Chen et al., 2009; Martin et al., 2001).

According to elite players, when performing the short serve in competition, their aim is influenced by the opponent and their positioning (see appendix 4). In soccer, if the goalkeeper stands slightly off-centre, the penalty taker is more inclined to direct the shot to the larger space to the side of the goalkeeper (Masters, van der Kamp, & Jackson, 2007). Similar to taking a penalty in soccer, in a badminton match, the receiver is not able to actively defend the serve because of their position on the opposite side of the court. Furthermore, in badminton, the shuttlecock doesn't usually land because the opponent will generally return the shuttlecock (unless an error occurs). The opponent facing the short serve will move toward the net or 'attack' as soon as the server has made contact with the shuttlecock, thus reducing the distance the shuttlecock may travel (Duncan et al., 2017).

Since the landing location is not known in a match, knowledge of results is no longer available to the player, therefore removing the measure of accuracy the server would normally use in training. If the landing location is influenced with an opponent present, this could mean that the trajectory is also affected, suggesting that training the short serve in this way may not be representative of match conditions. This leads to the question, in a professional match, what best describes an accurate short serve?

2.2.1 PURPOSE

This research article is presented in two sections with the methodology and results presented together. The first part of the present research (Study 1) examined whether there was a difference between the landing location of the shuttlecock between training conditions (no opponent present) and match conditions (opponent present). In the event of the serves landing short of the service line, the second part (Study 2) aimed to provide a more complete definition of accuracy for the short serve; and, develop a simple and effective methodology for measuring these additional accuracy parameters.

2.3 STUDY 1

Since the landing location of the short serve in a training situation is known, the first aim of this research was to identify if there was a difference between the landing location of the shuttlecock in training and the predicted landing location when an opponent was present. We hypothesised that when an opponent was present, the shuttlecock would sometimes fall short of the opponent's service line because the trajectory is more important for accuracy when an opponent was present rather than the landing location.

2.3.1 METHODS

Two separate data collection sessions and 13 players were tested across both sessions (Session A and B) (age: 23.4 ± 5.1 years, body mass: 73.2 ± 11.1 kg, height: 175 ± 8.6 cm). In session A, 5 players performed 30 short serves each without an opponent so that the trajectory of the shuttlecock from racquet contact to landing could be collected. The full shuttlecock trajectory data was used to create a model to predict the landing position from the initial part of the trajectory (which is necessary for session B - when an opponent is present they typically return the shuttlecock so the landing position can't be measured). This full trajectory data was also used to validate the model by comparing the predicted landing position to the actual landing position. In session B, 8 players performed 30 short serves with an opponent present. The prediction model was applied to these serves to identify landing location with an opponent present. In both sessions, the short serves were targeted toward the midline of the opposition's service square (i.e. the most common area).

2.3.1.1 Testing Protocol

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. Players performed badminton-specific play for warm-up and to familiarise themselves with the testing environment. The order of serves were randomised for both sessions with players serving to the most common area during a competitive match - the edge of the opponents' service square near the line that bisects the service squares. The motion-capture system consisted of 8 cameras in session A and 22 cameras in session B and collected with a sampling rate of 250 Hz (VICON Oxford Metrics Ltd., Oxford, UK). Reflective tape was placed around the base of the head of the shuttlecock to track its trajectory. Shuttlecock positions were filtered using a 6 Hz low-pass Butterworth filter, which was determined using residual analyses (Yu, Gabriel, Noble, & An, 1999). The study was approved by Edith Cowan University Human Ethics Committee and players gave informed consent prior to testing.

2.3.1.2 Predicting Shuttlecock Landing

The aim of this section of the study was to investigate if the landing location of the shuttlecock was affected by the presence of an opponent. Using the full trajectory data from session A, players performed 150 short serves (30 serves per player), curve fitting models were applied and compared to actual trajectory data to determine the most suitable prediction model. A 4th order polynomial was used to characterise the trajectory (height and forward position) from the serve to apex and a 3rd order polynomial was used (height and time) to extrapolate until the shuttlecock was predicted to hit the ground. We used a least squares regression to fit a nonlinear model relating vertical position to horizontal position. Specifically, a third order polynomial ($z = c_3 y^3 + c_2 y^2 + c_1 y + c_o$) was chosen over a second order polynomial (appropriate for simple ballistics) since damping effects have a sizable influence on the trajectory of the shuttlecock (Chen et al., 2009). Although the third order polynomial does not specifically describe the effects of damping in a physical sense, this model was chosen to add a higher degree of freedom allowing for trajectory slopes not fully explained by simple ballistics.

Since the regression models were limited in their capacity to accurately extrapolate the shuttlecock's trajectory, the error was quantified by comparing predictions via the approach detailed above with the measured trajectories of serves allowed to fully reach the ground. The 150 short serves performed were characterized as described earlier and the predicted landing position was compared to measured values. Bland-Altman plots were used to assess error (difference between model prediction and measured values) as a function of the mean between the two values for each sample. Additionally, this analysis was used to assess agreement between the curve-fitting model and optical tracking to compare error (between model predictions and measurement) against mean value (horizontal landing position).

2.3.1.3 Probability Mapping

The prediction model was applied to the shuttlecock trajectory when an opponent was present (session B). A second nonlinear least square regression was used to characterize the horizontal position of the shuttlecock as a function of time, for the same segment of data. In simple ballistics, horizontal position increases linearly, at a constant velocity, since there are no horizontal forces acting on the mass. However, in actuality, the horizontal velocity of the shuttlecock decreases over time, due to viscous damping effects removing kinetic energy from the system. As such, a power fit with offset ($y = at^b + c, where\ y\ is\ ***, ...$) was used to allow for a decreasing slope ($b < 1$) over time. In order to extrapolate the shuttlecock's trajectory utilising both regression models, horizontal position was first predicted for an arbitrary but sufficient length of time (since predicted time of contact with the ground was not yet known). Next, the vertical position was extrapolated as a function of predicted horizontal position. Finally, the time of predicted ground contact was determined as predicted vertical position changing from positive to negative (i.e. falling below the ground), and the final horizontal position of the shuttlecock was recorded at this time. This value was then compared to the location of the serving line.

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.

2.3.2 RESULTS

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 (session B). The predicted landing location for all serves for each player is shown in Figure 2.2. Overall the distribution around the service line appears normal ($p > 0.56$).

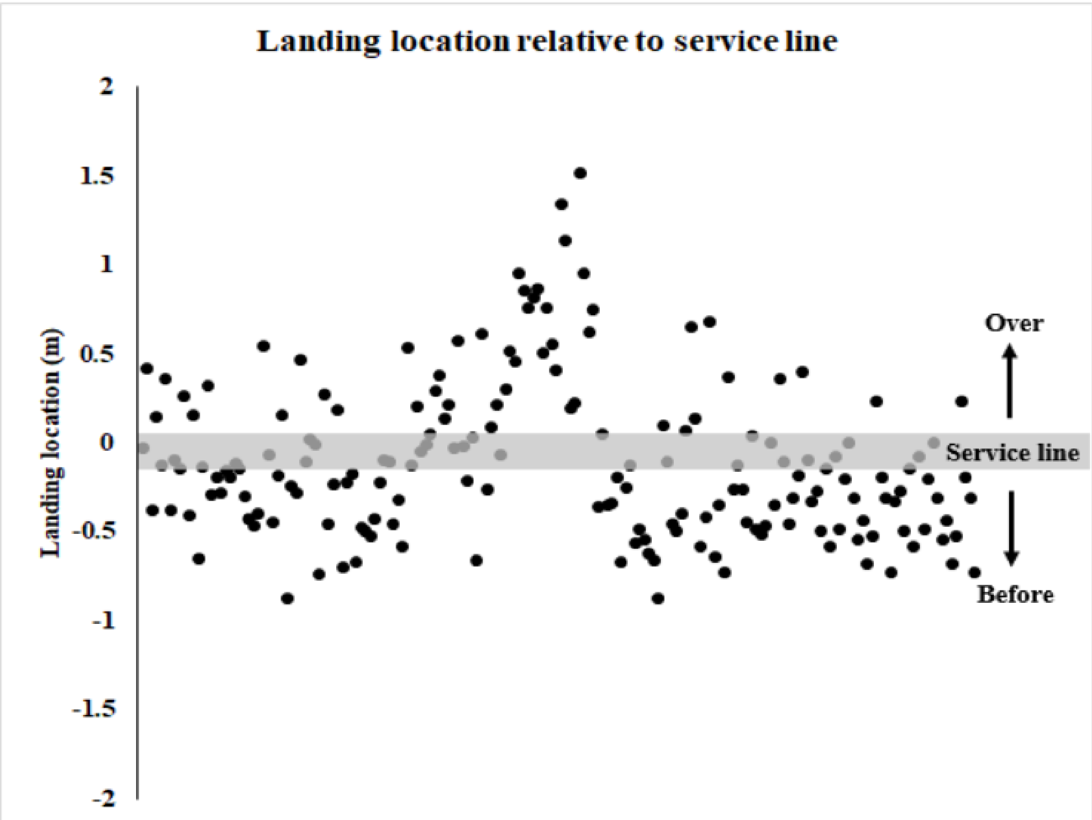

Figure 2.2 Landing prediction for all serves for all players in session B. Zero represents the service line, positive reflects serves that landed over the line, and negative reflects serves that landed before the line.

Table 2.1 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 biased toward the shuttlecock landing over the line.

Table 2.1 Individual predicted landing location before, on, or over the service line for all players (in session B).

	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

2.4 STUDY 2

A large proportion of serves landed short of the service line. Therefore, it was necessary to create a more appropriate definition for short serve accuracy using the trajectory of the shuttlecock. Since trajectory accuracy is not measured in badminton, a new step by step methodology to capture, analyse, and report trajectory accuracy results will be presented.

The results from Study 1 indicate that there was a discrepancy between the landing locations in training and match conditions, with the majority of short serves landing on or before the service line in a game-like situation. Additionally, because the shuttlecock is rarely allowed to land following a short serve, which suggests that using the trajectory as a measure for determining accuracy is more appropriate. Top-tier coaches and players defined the trajectory of an accurate short serve in match conditions (see appendix 4 for details), and based on these features we propose a new definition of accuracy for the short serve: a serve with a small movement that produces a flat trajectory with the apex occurring before the net (i.e. the shuttlecock has a downward trajectory once it has passed over the net) and a low height above the net. Therefore, the two variables used to measure accuracy of a short serve are apex location, and height above the net (see Figure 2.3). The procedures used to measure trajectory accuracy are outlined below.

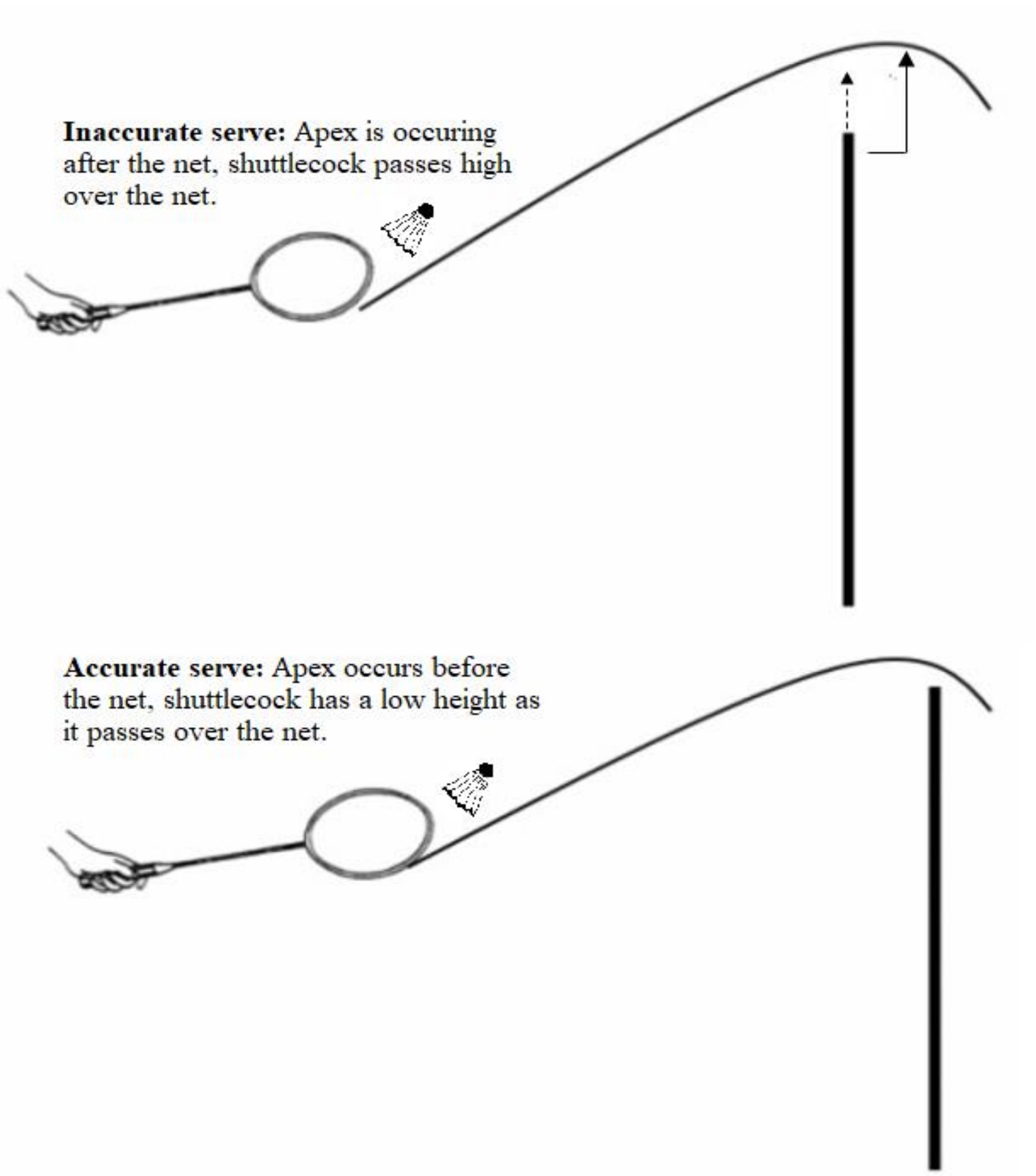

Figure 2.3 Side view indicating the trajectory of an inaccurate and accurate short serve. Solid arrow represents apex location, dotted arrow represents height above net.

2.4.1 METHODS

Eight players performed 30 short serves toward the midline of the opponents' service square with an opponent present. The trajectory accuracy of these short serves was determined. Shuttlecock apex and height over the net were captured using the 3D motion capture system (VICON, Oxford Metrics Ltd., Oxford, UK) as it was being used for another study on movement kinematics. A high-speed video camera could be used to capture the trajectory of the shuttlecock.

2.4.1.1 ANALYSIS

The shuttlecock trajectory was tracked and processed using VICON Nexus software (VICON Oxford Metrics Ltd., Oxford, UK). If using a 2-D video a range of free and licensed tracking and digitising software is available (e.g. Kinovea, SIMI Motion, etc). 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. Since the short serve usually travels over the centre of the net and the service position is close to the centre line, the side to side (medio-lateral X axis) was ignored. Median apex location and median net clearance for each player 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.

2.4.2 RESULTS

The two components of trajectory accuracy are shown in Figure 2.5. 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 (Figure 2.5), 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. The horizontal and vertical dotted lines represent the individual median for apex location and height above the net. Table 2.2 shows the percentage of accurate, inaccurate, clearance, and apex location of serves.

According to this new trajectory accuracy method, the most accurate server of the group was player 5, followed by player 2, and the least accurate players were 3, 4, and 7. Players 1, 6, and 8 had slightly more accurate than inaccurate serves. The most accurate servers 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 criteria. For example, players 3 and 4 didn't meet both criteria in any serves, however 57% and 55% of their serves respectively net clearance was below the group median. Similarly, for player 8, 62% of serves were under the median apex location although all of the net clearances were higher than the median.

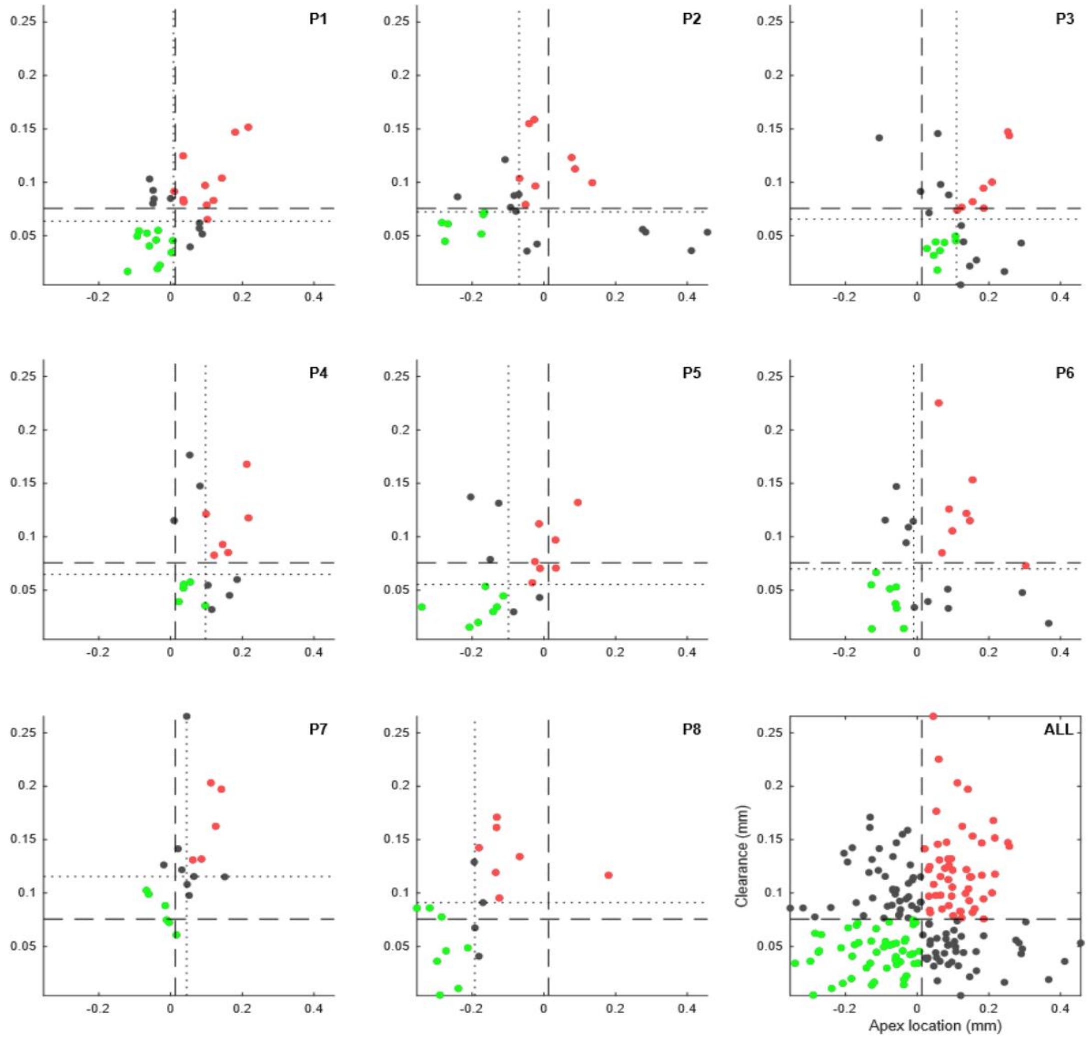

Figure 2.4 P1-P8 represents participant 1 to 8. Dashed line represents median apex (horizontal) and height (vertical) location of the shuttlecock across all players (bottom right). Dotted line represents median apex and height location of the shuttlecock. Green indicates serves that were classified as accurate, red indicates serves classified as inaccurate.

Table 2.2 Percentage of accurate and inaccurate serves for all players (based on being above or below group median as shown in figure 2.5).

	Overall			
Player	**% Accurate**	**% Inaccurate**	**% ApexGood**	**%ClearanceGood**
1	34	25	16	19
2	40	13	33	13
3	0	37	7	57
4	0	40	5	55
5	60	10	25	5
6	36	25	18	21
7	11	63	21	5
8	33	5	62	0

A qualitative comparison of trajectory accuracy against predicted landing accuracy position showed (from study 1) that the most accurate (trajectory accuracy) servers tended to serve so that the shuttlecock landed on or before the line of the service square when an opponent was present.

2.5 DISCUSSION

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. Rojas et al. (2000) reported similar results when analysing the basketball jump shot; players altered the trajectory when a defender was present to reduce the chance of the defender intercepting the shot. In the badminton short-serve the opponent may move toward the net to 'attack' the serve in an attempt to hit the shuttlecock from as high a point as possible. In order to reduce the receiver's advantage, the server may choose to serve the shuttlecock with a different trajectory in a way that would cause it to land on or before the service line.

Players adjust their movements based on information from the opposing player (Pinder et al., 2011). Thus, it is imperative that short serve training programs include a setting that represents those being faced in a match. The main goal is to ensure that practice replicates the performance environment faced by the athlete as closely as possible (Pinder et al., 2011).

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.

2.6 PRACTICAL APPLICATION

From a practical approach for coaches and athletes a single camera may be used. The camera should be aligned perpendicular to the net at an appropriate distance (see Figure 2.4) with a sampling rate of 200 Hz and a shutter speed of 1/500 s (Dingenen, Malfait, Vanrenterghem, Verschueren, & Staes, 2014). The camera should be calibrated using an object of known size so that the digitised image can be converted into metric units (Norris & Olson, 2011).

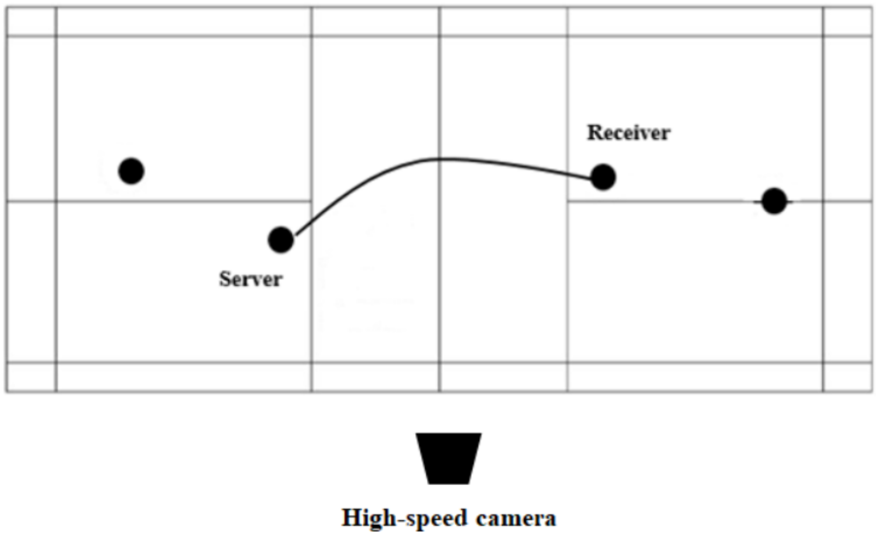

Figure 2.5 Schematic of the setup for apparatus used to capture serve trajectory.

2.7 CONCLUSION

When an opponent was present the landing location was affected suggesting that training for the short serve should be more match specific. This study has provided a more complete description of short serve accuracy, and a simple method for measuring the accuracy. This methodology could also be used for skills where the endpoint of the projectile is not known, or if endpoint accuracy is not the only criteria of success.

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CHAPTER 3 - STUDY II

A SIMPLIFIED MOVEMENT PATTERN RESULTS IN GREATER PERFORMANCE ACCURACY IN A PRECISION-BASED SPORTING SKILL

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Vial, S., Croft, J., Blazevich, A & Cochrane, J (2018). A Simplified Movement Pattern Results in Greater Performance Accuracy in a Precision-Based Sporting Skill.

3.1 ABSTRACT

In badminton doubles matches, the goal of the short serve is to achieve a low trajectory over the net, forcing the opponent to return the shuttlecock high at a steep angle in order to the clear the net, allowing an offensive player to hit the shuttlecock from a high point, from which it is easier to a score a point. The purpose of this study was to determine which movement pattern/s are associated with greater accuracy. Three-dimensional kinematics were obtained for eight members of the Senior Australian National Doubles Badminton squad as they performed 30 serves each. Rather than defining accuracy by the landing point of the shuttlecock (which rarely occurs in match situations), a combination of apex location relative to the net and height above the net from the shuttlecock trajectory were used. A principal component analysis revealed that the most accurate servers - 50% of serves classified as accurate - used a push-like movement pattern with elbow extension as the primary contributor, and wrist adduction as the second largest contributor. Furthermore, the most accurate servers restricted the shoulder joint in all planes, and the elbow joint in the pronation/supination plane. These findings suggest that a simplified push-like movement pattern may be best for accuracy in the badminton short serve.

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3.2 INTRODUCTION

Accuracy of a projectile landing on or near a target – also known as endpoint accuracy - can determine success in many sports (Jardine & Martin, 1983; Steele, 1990). For example, in darts, the impact location of the dart on the target determines the points that are scored (Smeets et al., 2002), in hoop-based sports such as netball and basketball, the ball must fall through the hoop (Khlifa et al., 2013; Steele, 1990), and in goal-based sports such as soccer and hockey the ball must land in the net (Finnoff et al., 2002; Kerr & Ness, 2006). There is some evidence that accuracy of the outcome in such sports may be related to the movement patterns that project the object (Etnyre, 1998; Tant, 1993) and the variability of the movement (Button et al., 2003).

If we consider throwing tasks, there are a variety of possible movement patterns because of the large number of degrees of freedom available at the shoulder, elbow, and wrist joints. (Diedrichsen et al., 2010; Perl, 2004). However, rather than being redundant, the large number of degrees of freedom create motor abundance, which may be a necessary component for coordinating movements (Latash, 2012). Bernstein (1967) suggested that novices tend to restrict or "freeze" degrees of freedom initially, and then "free" the degrees of freedom as they gain expertise in the task (Scholz & Schoner, 1999; Sidaway et al., 1995). More recent research has shown that coordination changes are specific to the task and the individual, as some degrees of freedom are restricted, then released, and then restricted again (Glazier, 2010). Freezing and freeing certain degrees of freedom at various phases of a movement has been shown to ensure stable performance (Etnyre, 1998; Martin et al., 2001; van den Tillaar & Ettema, 2006). Some researchers have found that experts free the degrees of freedom in certain accuracy-based skills, such as the basketball free throw (Button et al., 2003), while other researchers found that during a virtual pointing task, accuracy was improved by restricting the degrees of freedom (Schutz & Schack, 2013). The task itself appears to influence the incorporation or restriction of the degrees of freedom at either specific points of the task, or the entire movement. While novices tend to freeze degrees of freedom to simplify motor control, experts are capable of restricting those degrees of freedom that are not related to performance – task-redundant degrees of freedom (Vereijken et al., 1992) to reduce complexity (Seifert et al., 2013). By restricting specific joints that may not be task-relevant, the performer reduces the risk of introducing error into the movement (Pekny et al., 2015).

Due to the large number of degrees of freedom, there are many ways to move the arm relative to the trunk. They have typically been divided into throw-like movement patterns, where joints extend sequentially to produce high hand velocity; and push-like movement patterns, where multiple joints rotate simultaneously, which are often thought to be better suited for accuracy-based tasks (Blazevich, 2012). Few studies have investigated which type of pattern is used in accuracy tasks. Analysis of the volleyball set shot found a pushing pattern, with players aligning their arms behind the ball to “push” in the direction of the ball trajectory, causing the ball to follow a more vertical arc, which was associated with greater accuracy (Tant, 1993). Similarly, cricket batsmen tended to use a push-like movement pattern with a restricted backswing when facing fast-paced bowlers (Portus & Farrow, 2011), which allowed batters to guide the ball between fielders with greater accuracy. Push-like patterns have been associated with accuracy skills because they are assumed to be less complex but a push-like pattern may have similar complexity to a throw-like pattern, as it could utilise the same number of joints and segments. Therefore, it may be more appropriate to define an action by the level of complexity, rather than the movement pattern. Although push-like patterns are considered best for accuracy, it could be that a simplified or less complex version of either a push or throw-like movement pattern (i.e. number degrees of freedom involved) may be better for accuracy (Schutz & Schack, 2013).

The movement pattern and complexity may change depending on the type of task. In open-skilled tasks such as the volleyball set-shot and batting in cricket, the performers’ choices are determined, at least in part, on either a teammate or an opponent’s actions (Portus & Farrow, 2011; Tant, 1993). In closed-skilled tasks, such as the service in sports like tennis, table-tennis, and badminton however, is not dependent on the action of others (Antunez et al., 2012). Because the environmental constraints are different between open and closed-skilled tasks, it could be expected that the movement patterns are different, even though the goal (i.e. accuracy) is the same. Serving in these sports requires accuracy in order to gain an advantage in the rally, or to directly win the point (Phomsoupha & Laffaye, 2015a). In the sport of badminton, the goal of an accurate short serve is to achieve a low trajectory, with the apex occurring before the net and a steep downward angle once passing over the net (Duncan et al., 2017). This trajectory forces the opponent to hit the shuttlecock with a steep upward angle in order to the clear the net, allowing the server to hit the shuttlecock from a high point at a downward angle, from which it is easier to a score a point (Edwards et al., 2005). The server must coordinate specific segments of the body to move the racquet to contact the shuttlecock in particular way to produce an accurate serve. The backhand short serve has a small racquet swing compared to other strokes, although the range of motion may be small, it is a movement which requires precision in order to be successful (Duncan et al., 2017; Hussain et al., 2011).

Very little research has investigated types of movement patterns used in accuracy-based tasks (Blazevich, 2012; Portus & Farrow, 2011; Tant, 1993), and none in closed tasks, such as the short serve. Furthermore, it is unclear if individuals simplify the movement pattern in order to achieve accuracy. The aim of the present study was to identify which movement patterns were used in an accuracy-based task, and, if reducing complexity of the movement resulted in greater accuracy. We hypothesised that a push-like movement pattern using the shoulder, elbow, and wrist would be used by all players; and that more accurate players would restrict the task-redundant degrees of freedom (i.e. reduce complexity) to ensure stable performance.

3.3 METHODS

3.3.1 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 Australian National Doubles Badminton squad to participate in the study. All players were free from injury at the time of testing, and all players wore their normal match attire and used their own racquets during the testing. The study was approved by Edith Cowan University Human Ethics Committee and players gave written informed consent prior to testing.

3.3.2 Experimental Design and Protocol

A badminton court was marked out at the Australian Institute of Sport with a net setup in accordance with the Badminton World Federation standards. Twenty-two VICON infrared motion analysis cameras (Oxford Metrics Ltd., Oxford, UK) set at a sampling rate of 250 Hz were positioned around one half of the badminton court. Prior to data collection, the capture volume was calibrated using standard VICON processes (Figure 3.1). Eighty 14 mm reflective markers were placed on specific anatomical landmarks on each participant (see Appendix 6), with an additional three reflective markers placed on the racquet head to determine racquet position, three markers placed along the net, and reflective tape placed on the shuttlecock around the base of the head. Static calibration was performed with the participants standing in the anatomical position. Players completed their standard match-day warm-up and then performed badminton-specific play to familiarise themselves with the court whilst wearing the reflective markers. During testing, the participants were instructed to attempt to serve the shuttlecock as close to the front edge of the opponent's service square as possible, and the order was randomised and allocated as either (1) a wide serve toward the edge of the opponent's service square or (2) near the line that bisects the service squares. These are the most common service locations during competition. Players performed 160 serves (80 from each side of the court to two targets) with an opponent present to simulate match conditions. Serves from one side toward the centre line (30 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 in competition.

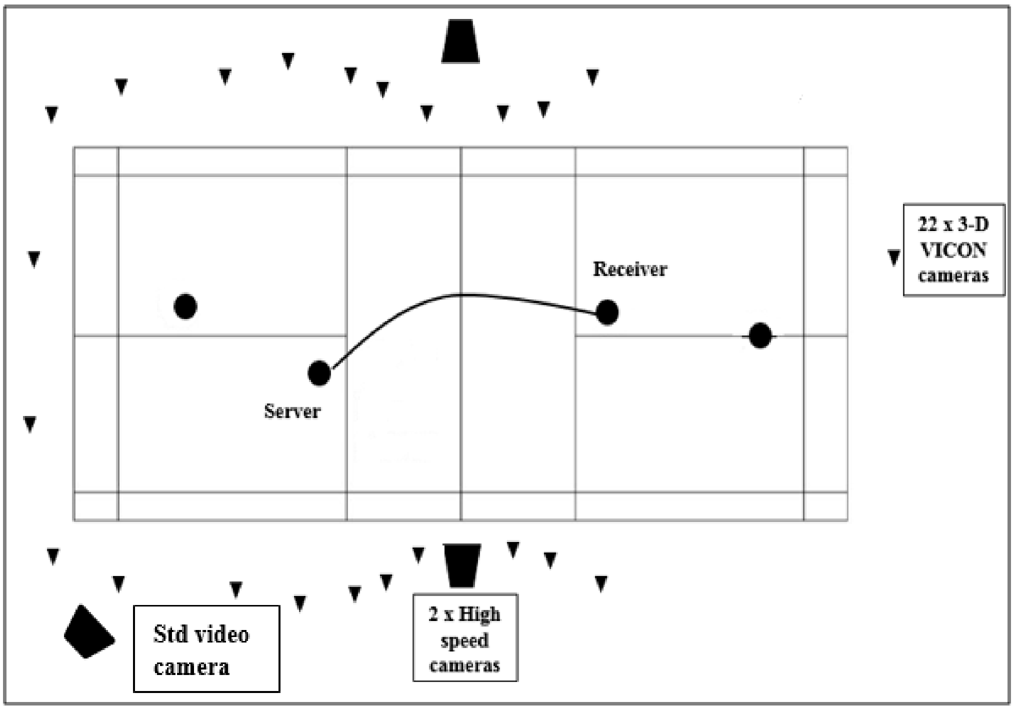

Figure 3.1 Experimental setup – badminton court with infrared cameras positioned around one half to capture the serving player.

3.3.3 Data analysis

The service action was 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 et al., 1999). The coordinates were imported into Visual 3D software (C-Motion, Inc., Germantown, MD, USA) and an upper-body model was created to calculate the short serve kinematics. A segment coordinate system for the racquet-hand system was created with the long axis originating from the midpoint of the markers placed on each side of the racquet head to the midpoint of the two wrist markers. Flexion-extension was determined as the vector cross-product between the long axis and the anterior-posterior axis (perpendicular to the long axis). The remaining segment coordinate systems (forearm, upper-arm, and trunk) were created according to Wu et al. (2005). For the wrist and elbow joint angles, a Cardan rotation sequence of X-Y-Z was used, but for the shoulder a Cardan rotation sequence of Z-Y-Z was used in order to determine shoulder elevation and external/internal rotation (Wu et al., 2005) because the arm is abducted between 40-140° during the short serve motion.

3.3.3.1 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 et al., 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.

3.3.3.2 Determining Serve Accuracy

Short serve performance was based on 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'.

3.3 RESULTS

3.3.1 Principal Component Analysis

Figures 3.2-3.5 show the explained variance in the data (a), the first principal component (PC1) (b), and second principal component (PC2) (c). The final three subplots (d-f) contain the angle-angle plots based on the principal component results, which were calculated relative to the start of the swing motion to allow comparison between individual trials and players. The angle-angle plots provide insight into intersegmental coordination. Horizontal and vertically aligned segments indicate a decoupled coordination, if the line is straight and diagonally oriented then two angles are changing at a constant ratio. One important feature is the turning point synchronisation, where two joint angles reverse direction concurrently as both joints reach their maxima they then switch at the same time. 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.

Table 3.1 Range of motion (ROM) of each joint in the sagittal and transverse plane. Players are grouped 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**	7.1	1.8	15.2	3.5	15.5	34.9
	6	3.6	4.9	12.5	5.9	18.7	17.1
	7	2.1	9.9	7.8	6.3	10.9	13.3
B	**2**	1.6	5.1	4.9	1.8	12.0	18.1
	5	3.6	5.4	11.7	6.7	9.2	27.0
C	**8**	21.8	8.0	20.3	9.2	16.7	35.7
	3	32.2	21.1	14.5	8.4	69.1	29.5
	4	7.2	10.5	16.8	11.2	23.7	41.3
M		10.3	8.0	12.4	6.0	21.7	25.1
SD		11.9	6.3	5.0	2.6	21.2	9.0

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 3.1). 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. The angle-angle plots (figure 3.2) showed that the players from 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 (Figure 3.2).

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 (Figure 3.3). 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 (Figure 3.4).

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 (Figure 3.5).

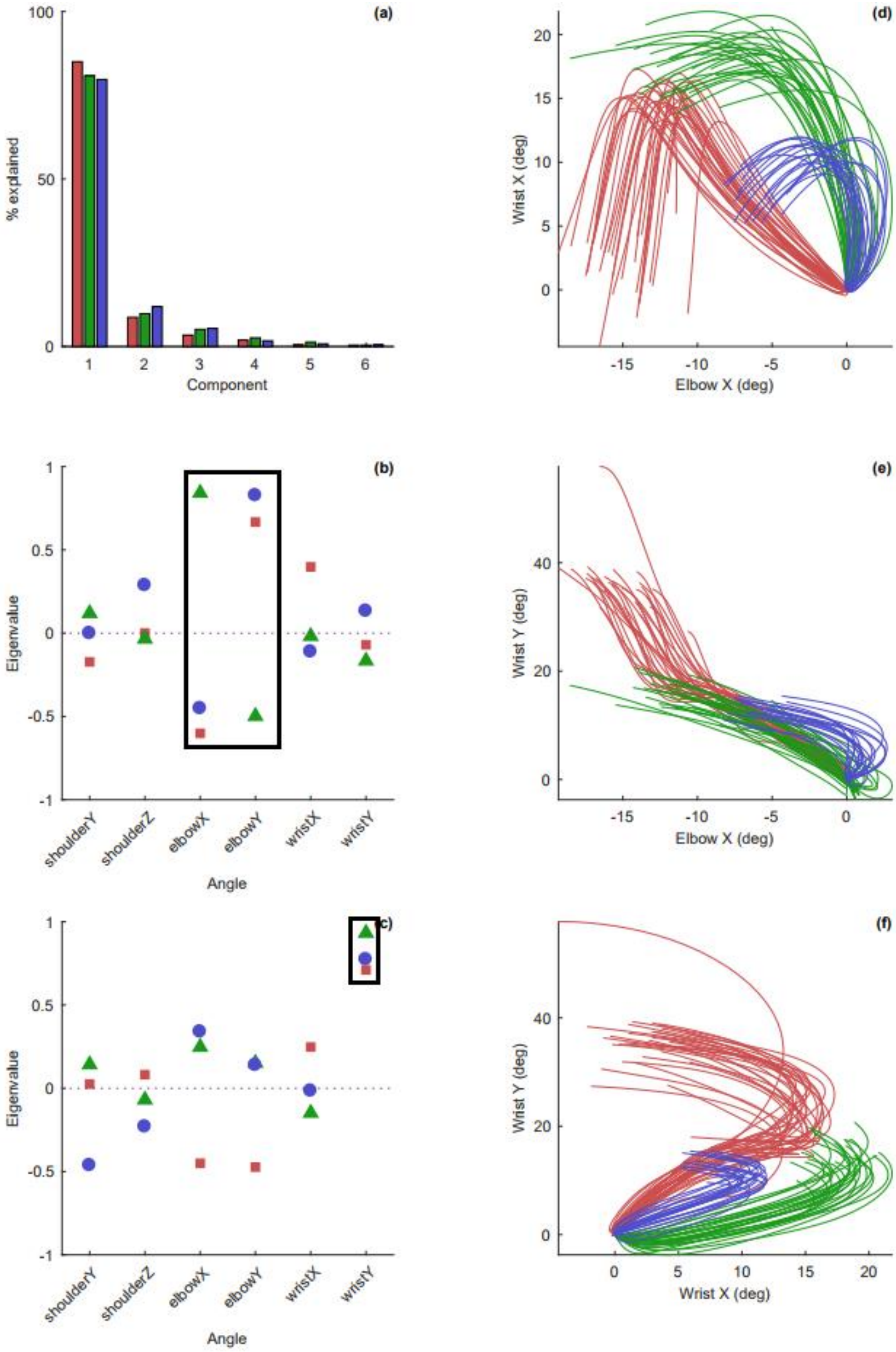

Figure 3.2 Group A – players 1 (red square), 6 (green triangle), & 7 (blue circle), (a) explained variability, (b) 1st principal component, (c) 2nd principal component, (d) elbow flex/ext (X axis) – wrist flex/ext (Y axis), (e) elbow flex/ext (X axis) – wrist abd/add (Y axis), (f) wrist flex/ext (X axis) – wrist abd/add (Y axis). Box in figure (b) and (c) indicate major loadings on principal components for each player.

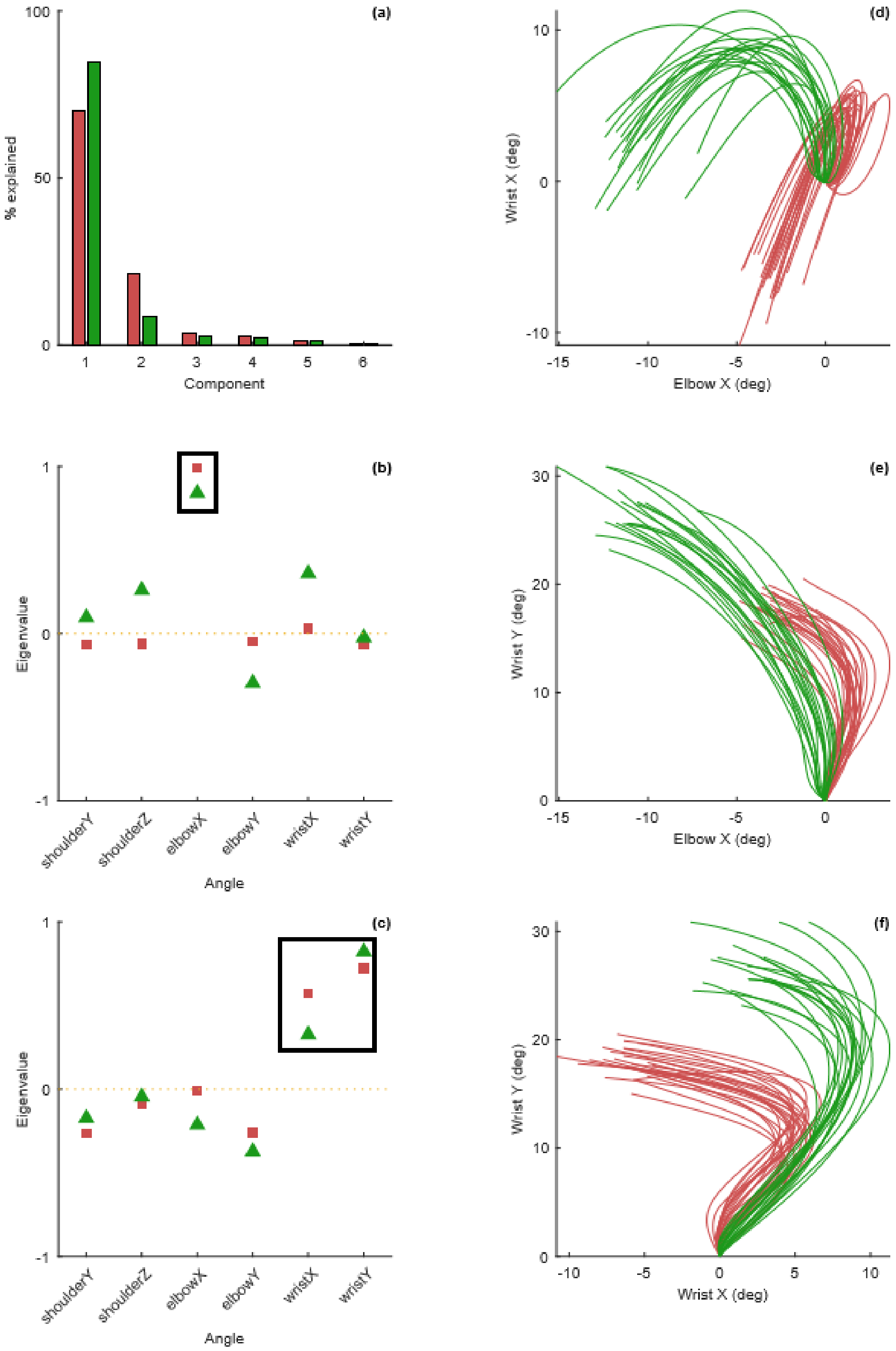

Figure 3.3 Group B – player 2 (red square) & 5 (green triangle), (a) explained variability, (b) 1st principal component, (c) 2nd principal component, (d) elbow flex/ext (X axis) – wrist flex/ext (Y axis), (e) elbow flex/ext (X axis) – wrist abd/add (Y axis), (f) wrist flex/ext (X axis) – wrist abd/add (Y axis). Box in figure (b) and (c) indicate major loadings on principal components for each player.

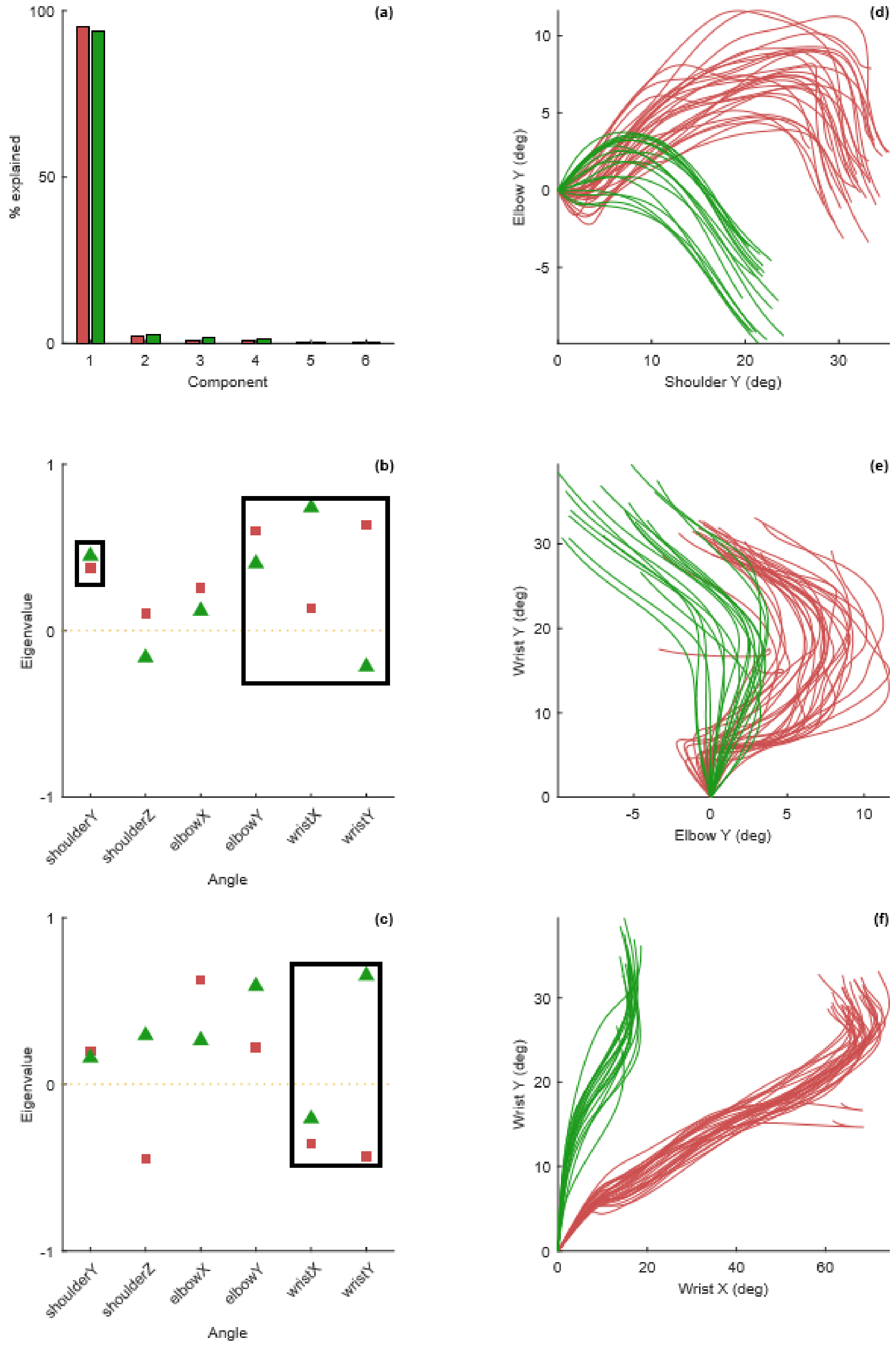

Figure 3.4 Group C – player 3 (red square) & 8 (green triangle), (a) explained variability, (b) 1st principal component, (c) 2nd principal component, (d) elbow pro/sup (X axis) – shoulder elevation (Y axis), (e) elbow pro/sup (X axis) – wrist abd/add (Y axis), (f) wrist flex/ext (X axis) – wrist abd/add (Y axis). Box in figure (b) and (c) indicate major loadings on principal components for each player.

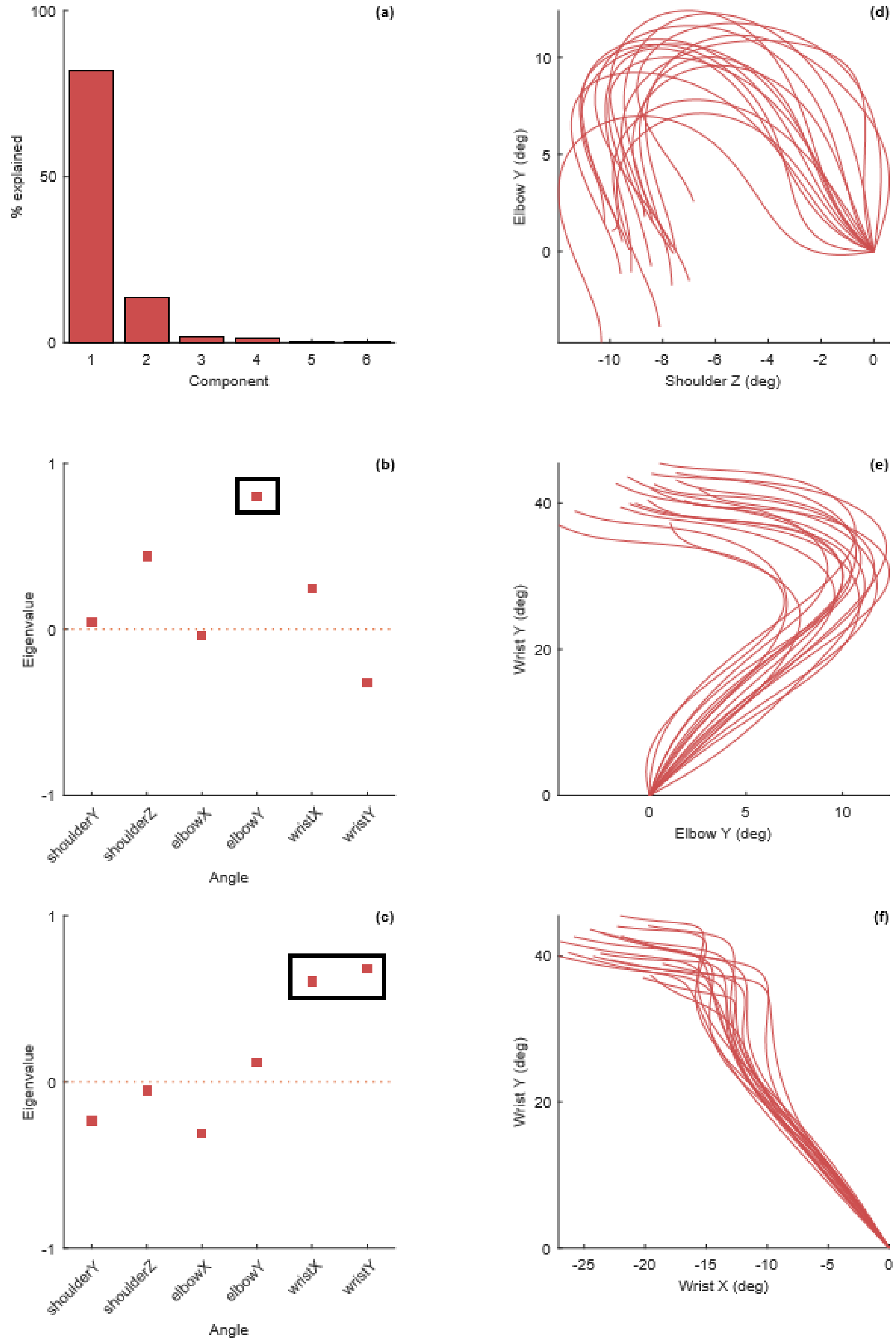

Figure 3.5 Player 4 (red square), (a) explained variability, (b) 1st principal component, (c) 2nd principal component, (d) elbow pro/sup (X axis) – shoulder rotation (Y axis), (e) elbow pro/sup (X axis) – wrist abd/add (Y axis), (f) wrist flex/ext (X axis) – wrist abd/add (Y axis). Box in figure (b) and (c) indicate major loadings on principal components for each player.

3.3.2 Accuracy Results

Table 3.2 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 3.2 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 3.2 First two principal components for each player in their respective groups. 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

3.4 DISCUSSION

The purpose of this study was to determine if a specific movement pattern was related to accuracy in a serving task. We found that all players used 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.

3.4.1 Restricting Degrees of Freedom

Depending on the task, skilled performers may release or restrict degrees of freedom (Schutz & Schack, 2013), depending on which are relevant to the task. We found that more accurate players move the elbow in the sagittal plane, restrict movement at the shoulder joint in all planes, and at the elbow in the transverse plane. The accuracy of the short serve was directly influenced by the task-relevant degree of freedom (i.e. elbow extension), and those which were superfluous to task performance (i.e. shoulder joint) were either redundant, or could negatively impact accuracy. The shoulder was not the primary contributor for any player, although it did have a small contribution for some players (player 3, 4, and 8). Throughout the serve motion the shoulder joint was relatively fixed, particularly in the more accurate servers (player 2 and 5). Because the shoulder remains somewhat fixed, the elbow and wrist act in a push-like manner, 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 (Davids et al., 2003b). Freezing or restricting specific degrees of freedom allows the server to control a few necessary degrees of freedom (Dounskaia & Wang, 2014; Scholz & Schoner, 1999). The accurate servers used a strategy of restricting specific degrees of freedom by limiting the shoulder joint throughout the movement, perhaps providing a stabilising function for the movement of the distal joints, allowing more control over the elbow joint (i.e. task relevant degree of freedom). However, restriction of degrees of freedom does not mean that they are 'removed' from the task altogether. The system may still use the 'irrelevant' degrees of freedom to ensure stable performance (Button et al., 2003; Davids et al., 2003b).

3.4.2 Push-like Movement Pattern

Our analysis confirmed that a push-like movement pattern was used for the short serve, using simultaneous joint rotations of the elbow and wrist, offering players more control over the serve motion (Kerr & Ness, 2006). The PCA revealed that the elbow and wrist were the prime contributors in specific planes for the serve motion. The angle-angle plots showed that the timing of movements (i.e. joints) occurred at the same time, indicating the use of a push-like movement pattern. The push-like pattern caused the distal segment, the racquet, to move in a flat arc or near-straight line. This results in greater accuracy because the contact point has less effect on shuttlecock direction if the path of the racquet is a line rather than an arc. Interestingly, the shoulder played a significantly smaller role in the pushing movement of the short serve than seen in most other push-like movement patterns (Martin et al., 2001; Smeets et al., 2002). For example, the netball chest pass, dart throwing, and the volleyball set shot are characterised by simultaneous extension of the shoulder and elbow (Edwards et al., 2007; Smeets et al., 2002). The most accurate servers (group A and B) utilised an elbow dominant serve, which produced the most accurate serves and the fewest inaccurate serves.

3.4.3 Reducing Task Complexity

Bernstein (1930) conducted some of the first studies investigating the challenge of organising the available degrees of freedom into a well-coordinated movement, and the multiple ways a movement may be executed in order to achieve a particular goal. He studied experienced blacksmiths striking a chisel with a hammer. The blacksmiths varied the trajectory of their individual joints.

In the current study, our results indicated that the solution to produce an accurate serve was to reduce the number of degrees of freedom involved. Thus, reducing the complexity of coordinating multiple joints in several planes to just one joint in a single plane, which was a feature exhibited by the more accurate players (Bartlett et al., 2007; Button et al., 2003). This approach may be used to decrease the risk of introducing error into the movement (Latash et al., 2002). For example, if a single component introduces error, other components contributing to the movement could exacerbate this error. A recent study by Dounskaia & Wang (2014) found that in a drawing task, the directional preferences of the movement were caused by a propensity to use a simplified movement pattern of the shoulder and elbow.

This preference refers to the joint control pattern, whereby either the shoulder or elbow is actively rotated while the other is passively rotated (Dounskaia & Wang, 2014). This might explain the passive involvement of the shoulder, while the elbow is an active rotator and the prime mover in the serve motion. Thus, restricting the shoulder, and therefore, the number of degrees of freedom involved simplifies the movement leading to a more accurate short serve.

Although it appears 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; Phomsoupha & Laffaye, 2015a; Pinder et al., 2011). However, because we required cameras and reflective markers and didn't play complete points the environment 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.

3.5 IMPLICATIONS

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 should garner more attention in a training program.

Although our results showed that simplifying the movement to a single joint in a single plane was a common feature amongst the more accurate players, it might be that in a real match the server may adjust their serve in an effort 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.

3.6 CONCLUSION

The purpose of this study was to investigate the type of movement pattern used for a task that requires a high degree of accuracy. Our hypothesis was proven mostly correct as all players displayed push-like movement patterns with varying levels of complexity and accuracy. However, the most accurate players used a combination of the elbow and wrist joints to generate the push-like movement pattern, while the shoulder remained fixed. Restricting task-redundant degrees of freedom resulted in a simplified push-like movement pattern, which reduced the complexity of the task, and was associated with greater accuracy.

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CHAPTER 4 - STUDY III

THE ROLE OF MOVEMENT VARIABILITY IN AN ACCURACY-BASED TASK

This chapter is being submitted to the *Journal of Motor Control*

Vial, S., Cochrane, J., Blazevich, A & Croft, J. (2018). The Role of Movement Variability in an Accuracy-Based Task. *Journal of Motor Control*.

4.1 ABSTRACT

Skilled performance in precision-based sports requires the coordinated sequencing of specific body segments in a particular movement pattern (Chow et al., 2014). A rigid or inflexible system may not be optimum in such circumstances, however skilled performers appear to be able to adapt their movements in rapidly changing environments (Latash et al., 2002; Simbana-Escobar et al., 2017). Nonetheless, the role of movement variability in sports that require fine motor skills with the goal of accuracy is still unclear. The aim of this study was to examine movement variability in the badminton backhand short serve, which is an action that requires precise multi-joint coordination to produce an accurate outcome. Three-dimensional kinematics were recorded from eight elite badminton players while they performed 30 short serves in simulated match conditions. Movement variability was analysed using the biological coefficient of variation for the upper-body kinematics, and timing of the swing for each player. Results showed that whilst players incorporated specific movement strategies to ensure accuracy of the racquet trajectory at contact, joint angles in the medio-lateral (transverse plane) were highly variable. The timing of the swing also varied, with the backswing showing more variability than the forward swing. Varying the timing of the backswing to reduce the variability at the contact point was a common feature displayed across all the players, irrespective of serve accuracy. Thus, players allowed variability in dimensions that did not impact performance, but minimised variability in essential planes of motion.

4.2 INTRODUCTION

Movement variability is an inherent feature of human performance and these variations occur in both space and time (Scholz & Schoner, 1999). Indeed, during repetitive actions, even elite athletes do not reproduce movement patterns identically (Hamill, van Emmerik, Heiderscheit, & Li, 1999; Langdown et al., 2012). While movement variability may have traditionally been considered a hallmark of performance decrements, recent research has shown that variability is a necessary feature of human movement (Button et al., 2003; Churchland, Afshar, & Shenoy, 2006; Latash et al., 2002). Variability may offer the flexibility to adapt to perturbations; an essential element of skilled movement (Bartlett et al., 2007; Chow et al., 2014). Nonetheless, moving efficiently (for humans) does not solely result from the coordinated interaction between different body segments (Schorer et al., 2007; Wagner et al., 2012), but is influenced by how well the system or organism interacts with its environment, particularly in response to unexpected changes (Davids et al., 2003b; Simbana-Escobar et al., 2017). For example, a tennis player may be able to execute a topspin forehand shot faultlessly from a ball-feeder, which sends the ball on a specific, repeatable trajectory, however if an opponent hits the ball to the player then that player must be able to make adjustments to limb positioning, racquet angle, force, etc., in order to hit the ball accurately. If the player cannot adapt their movement pattern to accommodate to the changing conditions, the movement skill may be performed inadequately. Thus, the completion of truly skilful movement relies on the person interacting with their environment, rather than just the movement itself (Glazier, 2011; Ko et al., 2017; Wagner et al., 2012).

Performing a simple everyday task such as reaching for a glass of water may involve a number of possible positions and orientations that each limb segment could follow to achieve the task. The number of varying configurations that determine the movement of a segment or number of segments is defined as the degrees of freedom (Bartlett et al., 2007). Bernstein (1967) claimed that one of the foremost difficulties in achieving efficient movement is the ability to overcome degrees of freedom that are not necessary for that particular movement (Bernstein, 1967; Button et al., 2003; Dupuy et al., 2000). Research has shown that novices tend to initially freeze the degrees of freedom, and as they become more proficient in the task they begin to release the degrees of freedom (Button et al., 2003; Davids et al., 2004; Latash et al., 2002). Specific degrees of freedom are important for task execution while others are less so, these are known as task-dependent and task-redundant degrees of freedom respectively, and may require differing levels of variability to enable stable performance (Chow et al., 2014; Langdown et al., 2012).

In one of the first studies recognising the importance of movement variability, Bernstein (1930) found that the variability of the tip of the hammer in experienced blacksmiths striking a chisel was less than the spatial and temporal variability within the joints (Latash et al., 2002). Although the individual joint trajectories were variable, they were coupled to allow consistent movement of the hammer. This showed that stable motor performance could result from the variable behaviour of individual components in the movement, and that a change in one of the components could be compensated by a reorganisation in other joints to accomplish an accurate strike of the hammer. More recently, researchers found that variability in specific phases of a precision throwing task increases with skill level, i.e. more skilled performers utilised a level of functional variability to achieve end-point accuracy (Button et al., 2003; Yang & Scholz, 2005). Sim & Kim (2010) found increases in accuracy as directional variability increased in the medio-lateral plane. Such findings suggest that variability in one dimension can be introduced to achieve end-point accuracy when another dimension (plane) is assessed to be more important to the goal (Sim & Kim, 2010).

The execution of a task is influenced by the constraints of that task which are related to external factors, a specific task or skill (i.e. goal of the task). For example, performing a task with extremely high accuracy demands may influence the performer’s movement to be more constrained and pre-planned to produce an accurate performance. When accuracy is the most important goal, it is not yet known whether experts more likely to suppress variability in order to maintain accuracy, or increase variability in task-redundant degrees of freedom (Darling & Cooke, 1987). In precision throwing tasks, researchers found that the variability of the release parameters (angle at release phase) does not change across trials. Instead, athletes compensate with an increase in movement variability in the acceleration 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 skilful athletes to adapt to subtle changes in joints and segments at the release phase (Button et al., 2003; Dupuy et al., 2000; Kudo et al., 2000).

The control of movement variability, also referred to as biological noise, and its effect on sport performance has received a lot of interest in motor control research (Bradshaw et al., 2009; Bradshaw et al., 2007). Biological noise is inherent in most movements (and in the short serve) may have a dual purpose, including variability of endpoint accuracy (i.e. performance consistency) and improvement of movement coordination, and may help to achieve an accurate outcome. Traditionally, discrete analyses of variability have been quantified using the coefficient of variation (CV%) statistic. This measure alone may include technological error (i.e. video set-up, environmental changes) as well as biological movement variability. However, Bradshaw et al. (2007) introduced a method that estimates biological (intraindividual) variability using the standard error of the mean (SEM%) as an assessment of the technological error and then quantifying biological variability (BCV%) as the CV% minus the SEM% (Bradshaw et al., 2007).

The purpose of the present study was to examine the level of biological movement variability in elite badminton players during the short serve through use of the BCV% statistic. The badminton short serve, where the player attempts to land the shuttlecock toward the front of the opponent's service box, is a complex skill that is also affected by various constraints such as the opponent's positioning, fatigue, court conditions, and the time point in the match. Recent research has suggested that a flexible movement strategy would therefore enable the performer to adjust to intrinsic and extrinsic changes, for example by using the net as a visual guide for endpoint accuracy, allowing small adjustments between serves, or in response to the performance level of the opponent (i.e. their strengths or weaknesses) in returning the serve (Glazier, 2011; Muller & Sternad, 2004). Based on previous research it was hypothesised that the more accurate servers within the cohort would display higher levels of biological variability in their joint angles during the backswing phase to ensure reduced variability at the contact point. Racquet-shuttlecock contact is a key event during the short serve as it directly affects the shuttlecock trajectory. On the basis of previous research, we hypothesised that players would vary angles of specific joints at precise time points, as a compensatory mechanism to minimise variability of the most important task parameters (e.g. contact point) (Sidaway et al., 1995). Variability of joint angles, racquet, and timing of the swing phases (backswing and racquet-shuttlecock contact) were analysed, as well as shuttlecock horizontal position relative to the net at its trajectory apex and the vertical position over the net were recorded as indicators of accuracy.

4.2 METHODS

4.2.1 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. All players were free from injury at the time of testing, and all players wore their normal match attire and used their own racquets during the testing. The study was approved by Edith Cowan University human ethics committee and players gave written informed consent prior to testing.

4.2.2 Experimental Design and Protocol

A badminton court was marked out at the Australian Institute of Sport with a net setup in accordance with the International Badminton Federation standards. Twenty-two VICON infrared motion analysis cameras (Oxford Metrics Ltd., Oxford, UK) set at a sampling rate of 250 Hz were positioned around one half of the badminton court. Prior to data collection, the capture volume was calibrated using standard VICON processes. Eighty 14mm reflective markers were placed on specific anatomical landmarks on each participant (see Appendix 6), with an additional three reflective markers placed on the racquet head to determine racquet position, three markers placed along the net, and reflective tape placed on the shuttlecock around the base of the head. Static calibration was performed with the participants standing in the anatomical position. Players completed their standard match-day warm-up and then performed badminton-specific play to familiarise themselves with the court used for testing whilst wearing the reflective markers. During testing, the participants were instructed to attempt to serve the shuttlecock as close to the front edge of the opponent's service square as possible, and the order was randomised and allocated as either (1) a wide serve toward the edge of the opponent's service square or (2) near the line that dissects the service squares, as these are the most common service locations during competition. 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 (30 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.

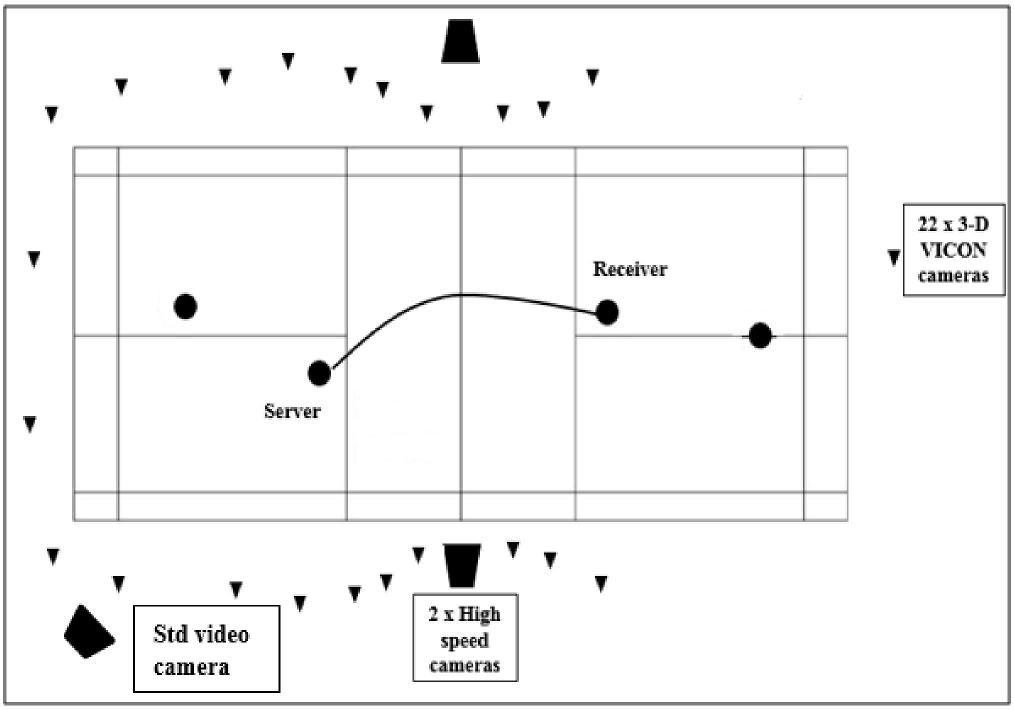

Figure 4.1 Experimental setup – badminton court with infrared cameras positioned around one half to capture the serving player.

4.2.3 Data analysis

The service action comprises of three discrete events, 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 racquet-shuttlecock contact defined the end of the service action, for the purposes of the current study. The follow through was not analysed as it occurs after contact. The three-dimensional coordinate 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 using residual analysis (Yu et al., 1999). The coordinates were imported into Visual 3D software (C-Motion, Inc., Germantown, MD, USA), an upper-body model was created to calculate the short serve kinematics. A segmental coordinate system for the racquet-hand system was created with the long axis originating from the midpoint of the markers placed on each side of the racquet head to the midpoint of the two wrist markers. The action of flexion-extension was determined as the vector cross-product between the long axis and the anterior-posterior (perpendicular to the long axis) axis. The remaining segmental coordinate systems (forearm, upper-arm, and trunk) were created according to Wu et al. (2005). For the wrist and elbow joint angles, a Cardan rotation sequence of X-Y-Z was used, but for the shoulder a Cardan rotation sequence of Z-Y-Z was used in order to determine shoulder elevation and external/internal rotation (Wu et al., 2005) because the arm is abducted between 40-140° during the short serve motion.

4.3.4 Statistical 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. Biological movement variability was calculated by using the individual means ($\overline{X}$), standard deviations (SD), standard error of the mean (SEM% = [(SD / $\sqrt{n}$ / $\overline{X}$] × 100, where n is the number of trials), and coefficients of variation (CV% = SD / $\overline{X}$ × 100). Biological coefficients of variation (BCV% = CV% - SEM%) were calculated for the upper-body kinematics, and timing of the swing of each individual (Bradshaw et al., 2007).

4.4 RESULTS

Differences were found in the variability of joint angles at different phases of the swing; the shoulder joint during the backswing ($p = 0.031$), and contact point ($p = 0.018$), the elbow joint at the start ($p = 0.017$), backswing ($p = 0.036$), and contact point ($p = 0.023$). No significant difference in the wrist ($p > 0.05$) joint angles were found between the sagittal and transverse planes. Table 4.3 shows the time of the backswing and swing time to contact, with all players showing greater variability in the timing of the backswing than variability of racquet-shuttlecock contact ($p < 0.001$). However, no significant difference was found in the variability in the timing of the backswing and contact point between accurate and inaccurate serves ($p < 0.05$). Table 4.1 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 4.2 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. Players were grouped according to the results derived from the principal component analysis in Study I (Ch 3).

Table 4.1 Shoulder, elbow, and wrist angular position (°) – sagittal plane

	Coefficient of variation (%)									Biological coefficient of variation (%)								
Participant	**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 4.2 Shoulder, elbow, and wrist angular position (°) – transverse plane

	Coefficient of variation (%)									Biological coefficient of variation (%)								
Participant	**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 4.3 Variability in the timing of the backswing and time to contact separated into groups from Study II (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	6.5	6.4	7
	7	7.5	5.2	7.5	5
B	2	8.2	11.9	5.8	10.8
	5	9.4	7.5	5.9	5
C	3	13.3	12.1	11	9.6
	8	4.1	12.9	4	9.1
	4	7.5	13.7	5.6	9.8
Mean		8.9	9.8	7	8
SD		2.9	3.2	2.4	2.2

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

Lower joint variability in the sagittal plane was found when compared to the transverse plane ($p < .001$) for the shoulder, elbow, and wrist joints for all players (Table 4.2). 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 4.2). 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.

Study I identified group B as the most accurate servers. Table 4.3 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 ($p > 0.05$).

4.5 DISCUSSION

A central problem in movement coordination is that the number of degrees of freedom often surpasses the dimensionality of the task requirements (Churchland et al., 2006). Recent studies indicate that flexibility and adaptability are characteristics of skilled movements (Bartlett et al., 2007; Srinivasan, Samani, Mathiassen, & Madeleine, 2015). That is, the performer has the ability to correct movements to unexpected changes, and these changes have been shown to lead to improved performance (Diedrichsen et al., 2010). In contrast, if the performer is required to execute a task under extremely high accuracy demands, it may be that a more constrained and pre-determined movement will produce an accurate performance (Sidaway et al., 1995). Task constraints are directly related to the goal of the task and therefore what is required to achieve the goal i.e. accuracy for successful performance and consequently, specific body movements to produce these outcomes (Newell, 1986). Each task constraint requires differing levels of movement variability, by varying individual components this ensures stable performance of task-dependent constraints (Davids et al., 2003b; Newell, 1986). The task constraints of the badminton short serve are determined by the range of paths that the shuttlecock can follow and the movement patterns that can produce these paths.

It was hypothesised that joint angle variability would be higher during the backswing phase, resulting in less variability at the racquet-shuttlecock contact point. In agreement with the hypothesis, 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 is 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).

Since the racquet-shuttlecock impact point determines the flight trajectory of the shuttlecock, players may have given this point of the action priority over the backswing. Variability in the timing of the swing was greatest during the backswing, which in turn reduced variability at racquet-shuttlecock contact. This may possibly be due to the nature of task itself, with the short serve motion lasting <400 ms, which is too short a time for players to adapt the movement pattern in response to proprioceptive feedback (Duncan et al., 2017). Sidaway et al (1995) reported similar findings in a manual reaching task, finding that reaction time increased as the accuracy demand increased, with subjects requiring a longer programming time for more accurate movements. This could suggest that players incorporate variability because the task itself may not require adaptability, but rather stable performance of the task-dependent variables, such as the racquet-shuttlecock contact point.

Although the current study did not compare experts and novices, our results found that the most accurate servers displayed lower joint angle variability in comparison to the less accurate servers. Similar results have been reported in the basketball free-throw, where intertrial variability in the elbow and wrist decreased with an increase in skill level (Button et al., 2003). As previously mentioned, more skilled performers tend to release the degrees of freedom when compared to novices. In the current study, the most accurate servers showed a reduced range of motion, and number of effectors (i.e. freezing degrees of freedom) involved when compared to the less accurate servers. It appears that in skills such as the badminton short serve requires a more task-dependent focus, with greater joint angle and timing variability occurring in less relevant planes, while the task-relevant planes displayed less joint angle variability.

4.6 CONCLUSION

Joint angle variability occurred predominantly in the transverse plane. When considering the cumulative results from Studies II and III, players incorporated variability in the redundant degrees of freedom. Variability in the timing of the swing was greatest during the backswing phase, whereas less variability was present at the contact point. A common strategy amongst all players was the introduction of variability in the timing of the backswing which may have assisted to achieve better consistency (i.e. reduced variability) at shuttlecock-racquet contact ($p < 0.001$), irrespective of serve accuracy. Additionally, variability in the timing of the backswing may play a functional role in the badminton short serve motion in elite players. These results suggest that when learning the short serve, instructors might focus on the task-relevant variables such as sagittal plane movement and key events such as racquet-shuttlecock contact, short serve skill acquisition may occur through the server demonstrating more constraint in sagittal plane movement within the arm joints.

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CHAPTER 5 - DISCUSSION

This master's thesis investigation has contributed towards an increased understanding of accuracy, movement patterns, technique, and movement variability that influence an accuracy-based skill, with the badminton short serve being the chosen skill. This has been achieved through providing a more complete definition of accuracy, developing new methodologies, and the creation of predictive and kinematic modelling using a variety of analytical methods.

5.1 STUDY I

THE IMPORTANTCE OF FLIGHT TRAJECTORY IN MEASURES OF PERFORMANCE ACCURACY IN RACQUET SPORTS

The first step was to determine if there was a disparity between landing locations in training and match conditions. This would determine if the landing location is actually an important measure of accuracy in the short serve. In order to do so, validation of a prediction model was required to enable comparison between training and match landing location of the shuttlecock from the short serve. The full trajectory (without an opponent) was used to create a model to predict the landing location from the flight path. The validated prediction model was then applied to shuttlecock trajectory data with an opponent present to predict landing location. Based on predictions from this model, 69% of all serves performed in a simulated game situation (with an opponent present) landed on or short of the service line. This showed a clear difference in the landing location used in training and match-like settings. It could also suggest that players serving during a match might choose a different flight path because an opponent is present. Nonetheless, this section of the study identified that perhaps landing accuracy is not a good indicator of performance accuracy, and that the trajectory of shuttlecock should be considered when determining short serve accuracy.

The results established the need to measure trajectory of the shuttlecock to classify serve accuracy more appropriately. Therefore, the current study created a more complete definition of accuracy by using the trajectory of the shuttlecock, and a method for measuring these new accuracy parameters. In the present study, the trajectory of the shuttlecock was tracked and the location of the apex, and net clearance height. We used the apex location and height above the net as criteria to classify short serve accuracy. Using a trajectory-based approach presented a number of advantages that encourage its use in the evaluation of accuracy. Firstly, this method of measuring accuracy can be used to assess the short serve in conditions similar to a match when an opponent is present. This is a more appropriate protocol compared to tests where players aim at targets or locations on the ground. Additionally, training to achieve these criteria of optimal apex location and height over the net of the shuttlecock could yield better performance accuracy during a match. The testing procedures established in this study are quick and simple to set up, only requiring a high-speed camera at training, or if permitted during competition. The trajectory can be tracked using free or relatively inexpensive software and analysed using Microsoft Excel, allowing comparison of individual and group accuracy. Furthermore, this method allows coaches to index accuracy of servers throughout a season, allowing reference points of accuracy at various stages of the season.

Comparing the predicted landing and trajectory accuracy results identified that players with better trajectory accuracy were inclined to serve either on or short of the service line. On the other hand, the landing position of the least accurate (trajectory) players was often over the service line. This could suggest that during competition, the players with better trajectory accuracy are more likely to serve on or short of the service line. The implications from this study have revealed that there is a necessity to alter training programs to better reflect match-play. Also, our findings recommend that coaches and players might consider using a training partner, or targets that limit the trajectory of the shuttlecock, when training the short serve for trajectory accuracy.

Athletes adjust their movement pattern based on information from other athletes or objects used in their respective sport (Pinder et al., 2011). Therefore, it is important that a training environment represents situations are similar to those faced during a match. The primary goal of RLD is to ensure that practice replicates the performance environment faced by the athlete (Pinder et al., 2011).

5.2 STUDY II

A SIMPLIFIED MOVEMENT PATTERN RESULTS IN GREATER PERFORMANCE ACCURACY IN A PRECISION-BASED SPORTING SKILL

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 most other sports which utilise push-like movement patterns, specifically involving the upper-arm, all joints are utilised by the performer. 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., 2003b). 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). Additionally, the most accurate players further reduced the number of degrees of freedom involved when compared to the lesser accurate players. Reducing the degrees of freedom involved decreased the complexity of the movement, and it may be that a more simplified movement is related to accuracy. This could mean that the movement pattern is not the defining feature to achieve accuracy, perhaps the level of complexity with which a movement is executed is a key to accuracy. Perhaps reducing the complexity (i.e. degrees of freedom involved) of the movement reduces the likelihood of introducing error into the action itself.

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.

5.3 STUDY III

THE ROLE OF MOVEMENT VARIABILITY IN A MULTI-JOINT PRECISION-BASED TASK

Lastly, we examined the role movement variability plays in accuracy of the short serve. It was hypothesised that joint angle variability would be greatest during the backswing phase, resulting in less variability at the racquet-shuttlecock contact point. In agreement with the hypothesis, 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 a 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.

CHAPTER 6 - SUMMARY AND CONCLUSIONS

6.1 SUMMARY

Due to the related gaps in knowledge, the overall aim of this thesis was to provide a better understanding of accuracy in a task such as the short serve and provide a simple methodology to measure accuracy. The results from Study I revealed a key issue in the current protocols for measuring accuracy in the fact that only the endpoint is used to classify performance accuracy. Therefore, the first aim was to determine if there was a disparity was between the landing locations in training and match environments. When an opponent was present, there appeared to be a bias to serve on or short of the service line for the most accurate servers. Using this information, we provided a more game-specific description of accuracy and method to measure these new key factors. Using these new parameters, an elite group of players performed short serves with an opponent present to illustrate the merits of the new system.

There is a paucity of literature which has investigated movement patterns associated with accuracy, Study II addresses this problem with the creation of a kinematic model of the short serve, and using a principal component analysis. All players used varying versions of a push-like movement pattern, with the most accurate servers further reducing the complexity of the movement through restricting specific degrees of freedom. Sagittal plane movement was a defining feature, specifically in the more accurate servers.

Expanding on Study II, Study III explored how some joints vary in specific planes and phases of the short serve. The task-redundant plane (transverse) had greater variability than the task-dependent plane (sagittal) in all three upper arm joints for all players. Suggesting that players use variability to their advantage, in doing so, this ensures stable performance of the most important components impacting short serve performance (i.e. sagittal plane movement and racquet-shuttlecock contact point).

6.2 CONCLUSIONS

This thesis has addressed the some of the gaps in knowledge in accuracy-based sports. Study I has proposed a more comprehensive description of short serve accuracy, and a simple system for measuring, analysing, and reporting accuracy. This methodology could also be used for skills where the endpoint of the projectile is not known, or if endpoint accuracy is not the only criteria of success. Study II identified that elite badminton players use a push-like movement patterns with varying levels of complexity. Restricting task-redundant degrees of freedom in combination with reducing task complexity resulted in a simplified push-like movement pattern. Our results suggest that this combination is associated with performance in this accuracy-oriented skill. The results are useful for badminton coaches and players and also for other skills that require accuracy. For Study III, when considering the collective results from Studies I and II, players incorporated variability in the redundant degrees of freedom. A common strategy amongst all players was the introduction of variability in the timing of the backswing, which may have assisted to achieve better consistency (i.e. reduced variability) at shuttlecock-racquet contact. These results suggest that when learning the short serve, instructors might focus on the task-relevant variables such as sagittal plane movement, and key events such as racquet-shuttlecock contact. Short serve skill acquisition may occur through the server demonstrating more constraint in sagittal plane movement within the arm joints. Paying particular attention to restricting the movement of the shoulder joint, and using elbow flexion/extension as the primary contributor to the serve motion, whilst minimising the movement of other joints.

6.3 PRACTICAL IMPLICATIONS

There are several practical implications of this master’s thesis and these could be applied to badminton coaches and other sports which have similar constraints. These implications are broadly based around two areas, (i) using the new accuracy parameters and methodology in a competitive season, and (ii) training for accuracy and using a push-like movement pattern, and concentrating on key factors of the short serve motion (i.e. contact point).

6.3.1 Accuracy

It is also recommended for training to focus on improving trajectory accuracy, which can be done with or without an opponent by having targets that limit the area the shuttlecock can travel through. If training without an opponent, this training will still use landing accuracy to some degree, therefore it may be more appropriate to actually measure trajectory accuracy, assessing specific areas which require improvement, providing a more tailored approach.

6.3.2 Movement Pattern

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.

Although our results showed that simplifying the movement to a single joint in a single plane was a common feature amongst the more accurate players, it might be that in a real match the server may adjust their serve in an effort 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.

6.3.3 Varying Movement

Evidence against the idea of a common optimal technique has been thoroughly researched. Because each player may have similar yet slightly different movement patterns, this has important implications for their physical training. For example, exercises performed in training by each player should be done in a way that replicates their individual movement pattern, this ensures movement specificity. It may be useful for coaches to introduce variability into their training programs, perhaps varying the distance of serves, and change the size and distance of the targets for the shuttlecock to travel through. Variability has a functional role in assisting players adapt to a wide variety of changing constraints.

6.4 LIMITATIONS AND DELIMITATIONS OF MASTERS THESIS

While the sample sizes used in the studies within this master's thesis were somewhat small, the sample group at the time of collection were part of the Senior Australian doubles badminton squad, with all of the available players from this squad taking part in this study. Although the squad size was small, the findings from these studies could still be considered successful in enabling the development of better accuracy measures, understanding the movement patterns and variability associated with expert badminton players for the short serve.

One of the most important limitations concerning the investigation into landing location between training and match settings, was the error from the prediction model. Although the prediction model still allowed the prediction within a certain area, we weren't able to pinpoint the specific landing location with complete certainty.

The three-dimensional model developed for Study II allowed assessment of individual movement patterns. However, one limitation was the small number of players available for testing. A larger sample size would have permitted better grouping of players that shared principal components, which would have provided better reporting of the movement patterns associated with accuracy.

Analysing movement variability was relatively simple, biological variability was calculated from standard error of measurement and coefficient of variation. One limitation of this method is that it only identifies variability in specific joints and planes, it is not able to explain whether the variability is a functional component of that movement.

6.5 FUTURE RESEARCH DIRECTIONS

This thesis has identified that an opponent influences the landing location of the short serve. Future research could investigate the specific factors of the opponent that might influence the trajectory, for example their positioning, stance, and anthropometrics (arm span, height etc). Using the newly developed methodology to measure trajectory accuracy, analysing performance of short serve accuracy and training interventions throughout a season would be useful to show which specific interventions might be best for improving accuracy. Researchers investigating other sports which are unable to observe or measure endpoint accuracy may also benefit from the using this methodology, adapting it to suits the requirements of the sport. For example, training for optimal trajectory could involve altering the technique to ensure a more simplified movement pattern, which could lead to greater accuracy.

Since the short serve is a complex movement which uses a push-like movement pattern, it may be relevant to examine what type of movement pattern is used in a more simplified accuracy-based movement. This would provide a foundation to refer back to when assessing more complex push-like movements for accuracy-based skills. It would also be useful to understand which type of accuracy skills reduce or increase complexity of the movement pattern based on the specific task, which could provide a better understanding of how movements are planned, coordinated, and executed.

As mentioned above, the short serve is a complex movement, and the most accurate servers in our study reduced the complexity of the movement. Additionally, these servers also exhibited the lowest joint angle variability in both the task-relevant and task-redundant planes. Perhaps because the short serve requires the manipulation of a racquet to contact the shuttlecock to achieve the desired trajectory, the server minimises variability of the entire movement. Future research could examine whether there is a change in variability if constraints are placed on the trajectory of the serve, for example, constraining the apex location and/or height above the net. This could explain which accuracy measure is more task-dependent. Future research could replicate this study in sub-elite populations to derive further insight regarding the role of expertise and skill level in terms of short serve variability.

APPENDICES

Appendix 1 – Participant information form

EDITH COWAN UNIVERSITY

Information Letter to Participants

The purpose of this document is to explain the study that you are going to participate in. Please read this document carefully and understand the information below, and do not hesitate to ask any questions.

Project Title

Analysis of Badminton skills and investigation into training to improve the short-serve in elite badminton doubles players.

Researchers

Masters Student: Shayne Vial (s.vial@ecu.edu.au)

Lead Researcher and Principal Supervisor: Dr Jodie Wilkie (j.wilkie@ecu.edu.au)

Researcher and Supervisor: Dr James Croft (j.croft@ecu.edu.au)

Supervisor: Professor Tony Blazevich (a.blazevcich@ecu.edu.au)

Researcher: Wayne Spratford (wayne.spratford@ausport.gov.au)

Researcher: Lasse Bundgaard (lasse.bundgaard@badminton.org.au)

This research project is being undertaken as part of the requirements of a Master of Sports Science at Edith Cowan University (ECU), ECU Industry Collaboration Grant and Badminton World Federation Sport Science Grant.

Purpose of the study

The main aim of the project is to understand the specific components needed to perform an accurate and successful short serve in elite doubles badminton players. Additionally it will also analyse other main badminton skills including the return shot and jump smash.

The testing protocol will be conducted at the Australian Institute of Sport (AIS) in Canberra. The AIS has a fully equipped biomechanics laboratory where a badminton court will be marked out. Each participant will have retroreflective markers placed on each joint, allowing us to build a three-dimensional model of each player. With this information we can analyse the movement of each participant and identify key factors that result in a successful short serve and badminton skills during a simulated match. The information from the motion analysis will provide insight for coaches and players of how to train and improve these skills.

Background

Success in doubles badminton is largely dependent on each player's ability to execute a highly accurate back hand short serve. It is often stated that the serve is the most important shot of the rally and can directly affect whether the point is won or lost. An accurate short serve can be defined as a stroke that has a low trajectory, close to the net and drops quickly after going over the net. However, there is currently no research that has endeavoured to identify the key components of the technique that lead to a successful serve. Since the serve has been deemed to affect whether the point is won or lost it is important to understand how to improve the short serve. This research project aims to investigate the components that lead to an accurate serve, which may lead to greater success in overall performance. It has also been identified that the return shot and the jump smash are of important skills in the games and these will also be analysed during this testing, to identify the techniques that are related to performance.

Eligibility

Badminton players must have competed at a national level for Australia. Participants must be free from injury at the time of testing. You will be screened with a generic medical questionnaire consisting of several questions about your health and physical conditions. Once you are found to be eligible for the study, you will be invited to participate as a subject in this study.

Equipment you will need (IMPORTANT)

For this study you will need to wear normal sports footwear used during training or matches, bring your badminton racquet. Please wear the following clothing so we can secure the reflective markers for tracking your movement:

Males: no tops, and short skins or running shorts (with no reflective/silver material).

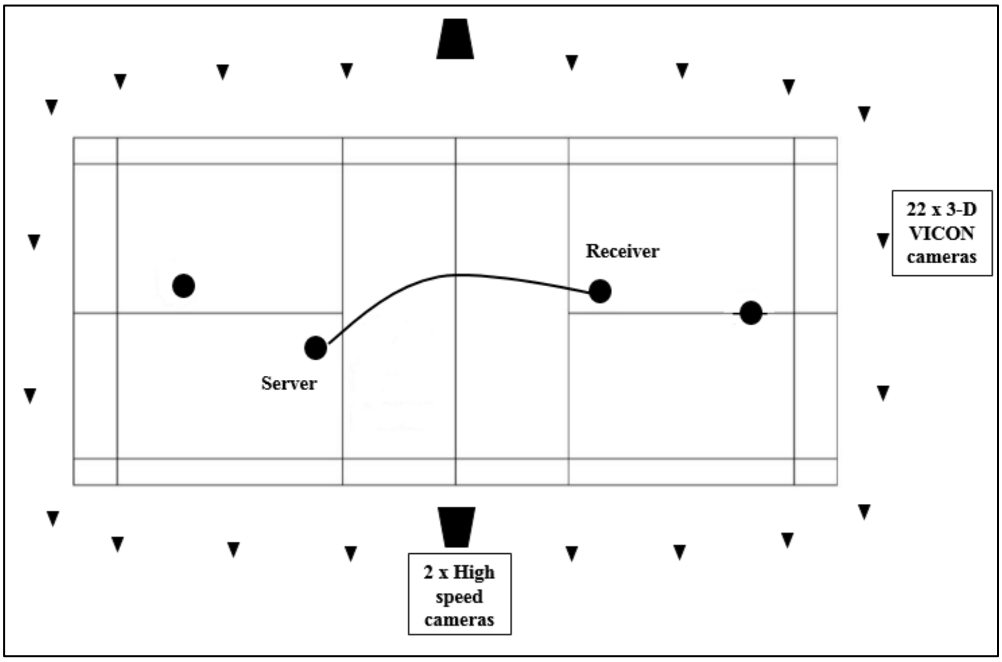
Females: sports crop top and short skins or running shorts (with no reflective/silver material). Please also bring a tight singlet/tank top.

Testing procedures

Should you agree to take part in this project, you will be asked to participate in a baseline-testing session, training intervention and a post-testing session. The baseline and post-testing sessions are identical. The testing session will involve two sections, firstly the pre-test which will involve anthropometric measurements, completing the required documentation, retroreflective marker placement and pre-test warm up. The next section is the actual testing session. A badminton court will be marked out in the biomechanics laboratory at the Australian Institute of Sport (AIS). You will be required to perform certain badminton skills and drills in doubles play. Twenty-two three-dimensional motion analysis cameras will be placed around the court which will capture the joint angles and velocities of the participant.

Drills

You will be required to perform short serve and smash skills during the testing session. The drills you will execute will be explained by your coach at the beginning of the session and you should perform these as you would under normal competition conditions. Your movement will be captured by the three-dimensional motion analysis cameras that will be positioned around the court (picture below).



Training intervention

A training intervention will be developed based on results from the baseline testing session. The training is likely to involve drills aimed at improving variability of your short serve and will be undertaken during your regular training sessions with your coach in Melbourne. Following the training intervention you will be re-tested following the same protocol as explained earlier.

Risks

The risks associated with this study are minimal. These risks are similar to those encountered during training and match conditions. To reduce injury risk, a pre-match warm up will be implemented, and you will be required to stretch before any exercise.

Benefits

You will gain insight into the research process and techniques, and will also gain information about your badminton skills and how you could possibly improve your technique. The results of this study will also be provided to you upon completion of the study.

Confidentiality of Information

All information provided by you will be treated with full confidentiality. Your contact information will only be accessible by the chief investigator during the period of the study. The information and data gathered from you during the study will be used to answer the research question of this study. The data and information will be deidentified as soon as possible. People who will have access to the raw information for this study are only limited to the researchers. Data collected will be stored in a password-protected computer and is only available to the researchers. Hard copy data (paper etc) will only be kept in the researcher’s office and locked in a specific drawer/filing cabinet. All data will be stored according to ECU policy and regulations following the completion of the study.

Results of the Research Study

The results of this study are intended to be published in peer-reviewed journal(s) and in reports and may be presented in conferences/seminars and as magazine articles, as an online article or part of a book section. Part of the results will also be used in a Master’s thesis. Published results will not contain information that can be used to identify participants unless specific consent for this has been obtained. A copy of published results may be obtained by the participants upon request to the lead investigators.

Voluntary Participation

Your participation in this study is voluntary. No monetary reward will be provided. No explanation or justification is needed if you choose not to participate. Your decision if you do not want to participate or continue to participate will not disadvantage you or involve any penalty.

Withdrawing Consent to Participate

You are free to withdraw your consent to further involvement in this research project at any time. You also have the right to withdraw any personal information that has been collected during the research with your withdrawal.

<u>Questions and/or Further Information</u>

If you have any questions or require more information about the research project, please do not hesitate to contact

Dr Jodie Wilkie

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Independent Contact Person

If you have any concerns or complaints about the research project and wish to talk to an independent person, you may contact:

Research Ethics Officer

Edith Cowan University

270 Joondalup Drive

JOONDALUP WA 6027

Phone: (08) 6304 2170

Email: research.ethics@ecu.edu.au

Approval by the Human Research Ethics Committee:

This research project has been approved by the ECU Human Research Ethics Committee.

Appendix 2 – Participant consent form

Informed Consent Form

Project: Analysis of Badminton skills and investigation into training to improve the short-serve in elite badminton doubles players.

I have read the information sheet and understood the points in the informed consent form. I agree to participate in this study with the above title and give my consent freely. I understand that the study will be carried out as described in the information sheet, a copy of which I have retained. I realise that whether or not I decide to participate is my decision. I also realise that I can withdraw from the study at any time and that I do not have to give any reasons for withdrawing. I have had all questions answered to my satisfaction.

Name: ______________________________________ Date: ___________________

Signature: ___________________________________

Parent/ Guardian (only if applicable)

I, ____, as parent / guardian of Mr/ Miss ____, acknowledge that I have read and understood the information sheet and hereby give permission for my child to participate in the study

Signature: ___________________________________

Date: _________________________

Appendix 3 – Ethical approval

HUMAN RESEARCH ETHICS COMMITTEE
For all queries, please contact:
Research Ethics Office
Edith Cowan University
270 Joondalup Drive
JOONDALUP WA 6027
Phone: 6304 2170
Fax: 6304 5044
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270 Joondalup Drive,
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ABN 54 361 485 361

22 December 2015

Dr Jodie Wilkie
Faculty of Health, Engineering and Science
JOONDALUP CAMPUS

Dear Jodie

ETHICS APPROVAL

Project Code:	**13849 WILKIE**	
Project Title:	**Analysis of Badminton skills and investigation into training to improve the short-serve in elite badminton doubles players**	
Chief Investigator:	Dr Jodie Wilkie	
Approval Dates:	From: 22 December 2015	To: 1 July 2017

Funding Source: ECU Industry Collaboration Grant
Grant: G1002173

Thank you for your recent application for ethics approval. This application has been reviewed by members of the Human Research Ethics Committee (HREC).

I am pleased to advise that the proposal complies with the provisions contained in the University's policy for the conduct of ethical human research and ethics approval has been granted. In granting approval, the HREC has determined that the research project meets the requirements of the National Statement on Ethical Conduct in Human Research.

All research projects are approved subject to general conditions of approval. Please see the attached document for details of these conditions, which include monitoring requirements, changes to the project and extension of ethics approval.

We wish you success with your research project.

Yours sincerely

[redacted]

Kim Gifkins
SENIOR RESEARCH ETHICS ADVISOR

Appendix 4 – Coach and player interview

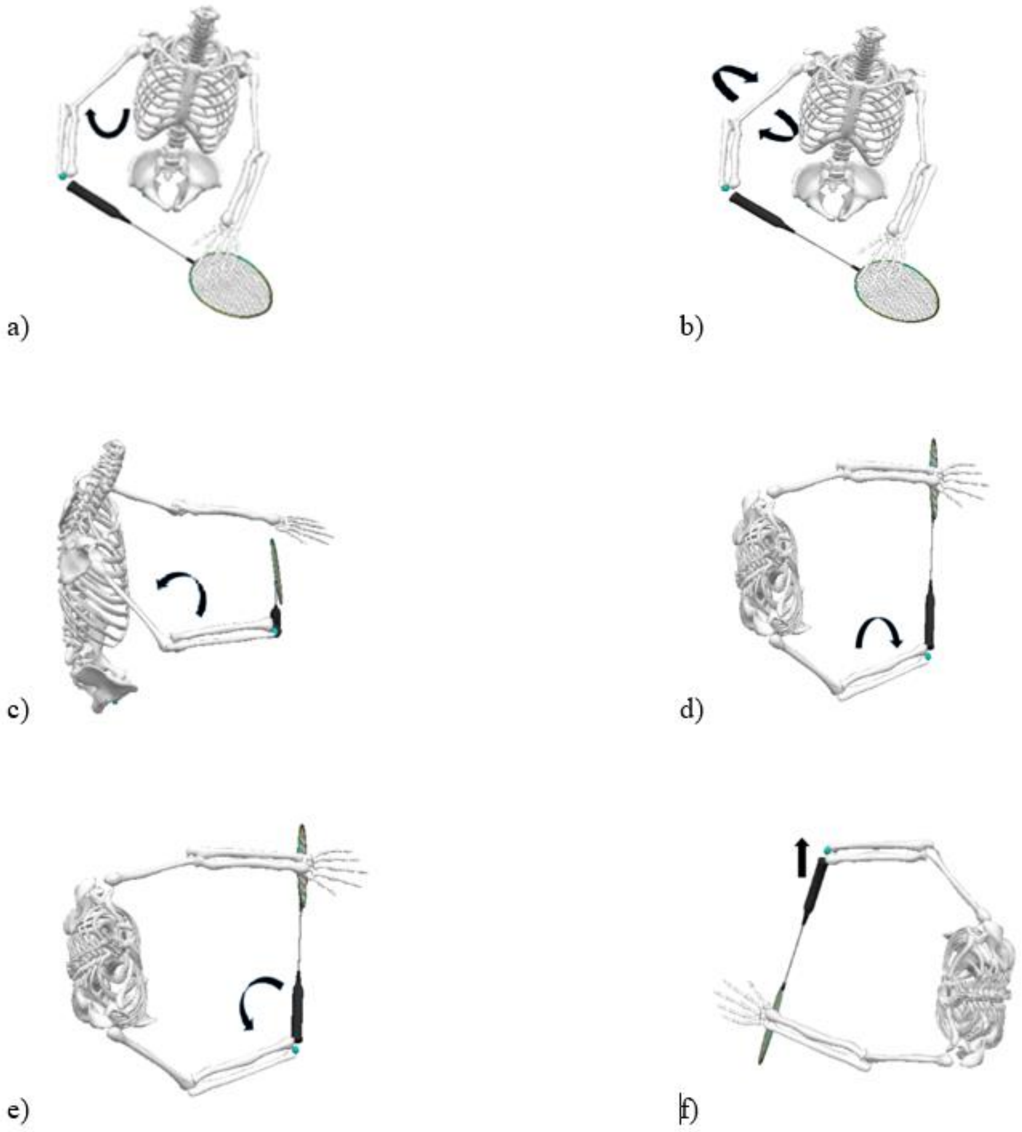
Coach and Player Interview

Question 1	Where do you aim when performing the short serve in training?
Coach 1	Place targets in the service square
Coach 2	Using different size targets in the service square
Player 1	Serving to targets
Player 2	Serve to targets, the coach will tell me if the trajectory is good or bad
Player 3	Place targets in the service square, coaches evaluate the trajectory
Player 4	Small targets near the front middle of the opponent's square
Player 5	Coach tells me to hit it lower or if the top of the serve is too late
Player 6	Place targets in the service square, coach tells me where to improve

Question 2	Where do you aim when performing the short serve in a match?
Coach 1	Positioning of the receiver
Coach 2	How the opponent is positioned
Player 1	Dependent on the opponent, but they are positioned is important
Player 2	Positioning of the receiver, and who the opponent is
Player 3	Position of the opponent, their reach and height is important
Player 4	Who the opponent is
Player 5	How the receiver stands or positions themselves, as well as who the opponent is
Player 6	Dependent on who the opponent is

Question 3	How would you describe the trajectory of an accurate short serve in a match?
Coach 1	Low height, top of the serve before the net
Coach 2	Flat pathway, drops off after going over the net
Player 1	Top of serve before going over the net, harder to return when the shuttlecock is travelling down after the net
Player 2	Close to the net, flat trajectory
Player 3	Apex of the shuttlecock before passing over the net makes it harder to return. Shuttlecock must be travel close to the net.
Player 4	Flat serve, as close to the net as possible
Player 5	Shuttlecock must drop quickly after going over the net, and must be very close to the net
Player 6	Steep drop off after going over the net, makes it difficult to return.

Appendix 5 – Three-dimensional kinematic model (joint angle calculations)



Shoulder elevation angle (+) as the humerus relative to the thorax; internal (+) and external (-) rotation, elbow flexion (+) and extension (-) angle; elbow pronation (+) and supination (-) angle. Wrist flexion (+) and extension (-) angle; wrist adduction (+) and adduction (-) angle.

Appendix 6 – Marker placements and naming conventions

Upper-body marker placements and naming conventions

Segment	Marker	Location
Head	RFHD	Right front head
	RBHD	Right back head
	LFHD	Left front head
	LBHD	Left back head
Thorax	C7	Spinous process of 7th cervical vertebrae
	T10	Spinous process of 10th thoracic vertebrae
	CLAV	Sternal notch
	STRN	Xyphoid process of the sternum
Pelvis	RASI	Right anterior superior iliac spine
	RPSI	Right posterior superior iliac spine
	LASI	Left anterior superior iliac spine
	LPSI	Left posterior superior iliac spine
Right Shoulder	RACR1	Right acromion cluster: posterior
	RACR2	Right acromion cluster: superior
	RACR3	Right acromion cluster: anterior
	RASH	Right anterior shoulder joint centre
	RPSH	Right posterior shoulder joint centre
Left Shoulder	LACR1	Left acromion cluster: posterior
	LACR2	Left acromion cluster: superior
	LACR3	Left acromion cluster: anterior
	LASH	Left anterior shoulder joint centre
	LPSH	Right posterior shoulder joint centre
Right Upper Arm	RUA1	Right upper arm cluster: superior
	RUA2	Right upper arm cluster: intermediary
	RUA3	Right upper arm cluster: inferior
Left Upper Arm	LUA1	Left upper arm cluster: superior
	LUA2	Left upper arm cluster: intermediary
	LUA3	Left upper arm cluster: inferior
Distal Right Upper Arm	dRUA1	Distal right upper arm cluster: superior
	dRUA2	Distal right upper arm cluster: intermediary
	dRUA3	Distal right upper arm cluster: inferior
Distal Left Upper Arm	dLRUA1	Distal left upper arm cluster: superior
	dLUA2	Distal left upper arm cluster: intermediary
	dLUA3	Distal left upper arm cluster: inferior
Right Forearm	RFA1	Right forearm cluster: medial
	RFA2	Right forearm cluster: intermediary
	RFA3	Right forearm cluster: lateral

Left Forearm	LFA1	Left forearm cluster: medial
	LFA2	Left forearm cluster: intermediary
	LFA3	Left forearm cluster: lateral
	RHNR	Right dorsal radial carpal
Right Hand	RHNU	Right dorsal ulna carpal
	RCAR	Right dorsal, distal intermediate carpal
	LHNR	Left dorsal radial carpal
Left Hand	LHNU	Left dorsal ulna carpal
	LCAR	Left dorsal, distal intermediate carpal
	RWRU	Right wrist: ulna side
	RWRR	Right wrist: radius side
Wrist	LWRU	Left wrist: ulna side
	LWRR	Left wrist: radius side

Appendix 7 – Reflective tape place on the shuttlecock

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