

**THE INFLUENCE OF BODY POSITIONING, TRUNK ROTATION (X-FACTOR)
AND TRAINING EFFECT ON QUALITY OF THE BADMINTON FOREHAND
OVERHEAD SMASH**

ZHAO ZHANG

B.Sc., Physical Education, Beijing Sport University, 2012

A Thesis

Submitted to the School of Graduate Studies
of the University of Lethbridge
in Partial Fulfilment of the
Requirements for the Degree

MASTER OF SCIENCE

Department of Kinesiology and Physical Education
University of Lethbridge
LETHBRIDGE, ALBERTA, CANADA

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ZHAO ZHANG

Date of Defence: August 17, 2015

Dr. Gongbing Shan
Supervisor

Professor

Ph.D.

Dr. Mary Dyck
Thesis Examination Committee Member

Instructor

Ph.D.

Dr. Hua Li
Thesis Examination Committee Member

Associate Professor

Ph.D.

Dr. Claudia Gonzalez
Chair, Thesis Examination Committee

Associate Professor

Ph.D.

Abstract

One of the dominant skills in badminton is the forehand overhead smash. This technique accounts for twenty percent of all attacks during a game. Unfortunately, no existing research has used full-body three-dimensional motion capture and modeling to examine the contribution of body positioning, trunk movement and training effect. The aims of the following two studies were to determine the influence of body positioning, trunk rotation and training effect on smash quality. Ten novices and fourteen skilled players were analyzed using three-dimensional motion capture and full-body biomechanical modeling. The results have revealed that the body positioning has a direct influence on shuttlecock release angle and clearance height (Study 1); and the trunk rotation is a key contributor to shuttlecock release speed and a unique whip-like movement (Study 2). In comparing the two groups, the results showed that training effect also has direct influence on smash quality.

Acknowledgements

There are many great people who have helped me a lot in order to allow me to successfully finish my research, and those people deserve my deep appreciation and thanks.

First of all, I would like to thank all the people who are from my department helping me to accomplish my research and project. I am very grateful to my supervisor, Dr. Gongbing Shan who gave his patience, guidance, suggestion, supportive ideas and assistance to mentally and physically help me with my research throughout the course of this project. It is not likely to accomplish the research if without him to be involved.

Secondly, I would like to thank to my committee members, Dr. Mary Dyck and Dr. Ha Li for their great suggestions and supports at the end of the project. In addition, I wish to thank Ms. Brandie Lea and Mr. Shiming Li for their guidance and suggestion.

Finally, I would like to thank all of my subjects who were willing to give their extra personal time participating in my project. Without them, it is impossible to collect all the data that I need to complete my project.

Furthermore, there is a special thanks to my parents, Feng Zhang, and Liping Chen for their perpetual love and encouragement. In addition, another special thanks to my boyfriend, Wenhao Yang for staying along with me in this city and supporting me while I am studying in Canada.

This acknowledgement cannot express fully how thankful I am; however, thank you to all of you because without you, I could not have my study done successfully.

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List of Abbreviations

OCOG – Organizing Committee of Olympic Games.....	2
IBF – International Badminton Federation.....	3
COG – Center of Gravity.....	10
3D – Three-Dimensional.....	15
V_{release} – Shuttlecock Release Speed.....	16
α_{release} – Shuttlecock Release Angle.....	16
H_c – Clearance Height.....	16
SG – Skilled Group.....	16
NG – Novice Group.....	16
X-factor – Trunk Rotation.....	16
ROM – Range of Motion.....	16
BWF – Badminton World Federation.....	20
SSC – Stretch-Shortening Cycle.....	22
EMG – Electromyography.....	22
2D – Two-Dimensional.....	22
Mo-Cap – Motion Capture.....	22
SM – Static-Middle.....	56
SF – Static-Front.....	56
SR – Static-Rear.....	56
D_{a-p} – The Anterior-Posterior Distance between the COG and Shuttlecock.....	56
P.M. – Pectoralis Major.....	58
GLM – General Liner Model.....	63
Dyn – Dynamic.....	67
MG1 – First Moving Group of Joint/Segment.....	73
MG2 – Second Moving Group of Joint/Segment.....	73

Chapter 1 Introduction

Chapter one will begin with a brief introduction of badminton and the subject of this study: the forehand overhead smash. The purpose, significance of the study, hypotheses, and the limitations will be presented.

The Background of Badminton

Badminton skills range from simple to complex and from recreational to professional. The historical development of badminton has experienced three periods: the starting period, the development period, and the mature period. To date, badminton skills have developed and are becoming more popular, competitive, and technical than in past decades.

The Starting Period

Badminton originated more than 2000 years ago in ancient civilizations of Europe and Asia ("Badminton History", 2015). A game known as 'Battledore and Shuttlecock', which involved hitting a shuttlecock with a wooden paddle, was played in ancient China. Around the 11th century, the game moved to Europe and then specifically to the royal courts of England by the 12th century. It remained in Western Europe until the 14th century then moved eastward to Poland in the early 18th century, and eventually to India during the late 19th century. This is where badminton, in its most current form, was realized ("Badminton History", 2015). The basic rule of this game was simple at first: "the participants were required to keep the shuttlecock in play as long as possible" (Zhao, 2007, p, 2).

During the 1860s, the name *badminton* was soon substituted for *battledore and shuttlecock* because the playing area was located in a hall called Badminton House in

Gloucestershire, England (Zhao, 2007). Early photographs of badminton showed the addition of a net, which was simply a string draped across the middle of the hall, to divide the space between the players (Hussain & Bari, 2011; Zhao, 2007). As a result, the net required the playing of the shuttlecock at a minimum height to keep the rally going (Zhao, 2007).

The Development Period

With the development of badminton in several countries, a ball made of feathers and wood, as well as a bat woven with strings, was invented in 1870 (Zhao, 2007). Furthermore, the playing field, initially an hourglass shape, was changed to a square with boundaries in 1901 (Zhao, 2007).

During the past several decades, interest in badminton has substantially increased and the sport has gained more attention from the Organizing Committee of Olympic Games (OCOG) (Zhao, 2007). For example, badminton became a demonstration sport in the 1988 Olympics in Seoul, Korea. This was the first time that badminton was shown to people all over the world.

Badminton was first adopted as a full medal sport for the Olympic Games of 1992 held in Barcelona, Spain (Zhao, 2007). The inclusion of badminton as an Olympic sport secured badminton's future popularity, recognition, and success (Zhao, 2007). New concepts of badminton skills and techniques were created and participation increased in badminton events. The different techniques were named by coaches or athletes such as clear, drop, smash and cut shot. Because of the gripping techniques in badminton, all the technique can be divided into two forms: the forehand and the backhand technique (Hussain & Bari, 2011). Therefore, the forehand overhead smash is one of the smash

techniques. As badminton techniques and game rules developed, the sport entered its current mature period.

The Mature Period

Today, there are several major International Badminton Federation (IBF) events. There are the Men's World Team Badminton Championships for the Thomas Cup, the Ladies' World Team Championships for the Uber Cup, the World Mixed Doubles Championship for the Sudirman Cup, the World Individual Championships, and the World Grand Prix Finals (Zhao, 2007). In addition, there are five badminton events during the Olympics: men's and women's singles, men's and women's doubles, and mixed doubles (Salim, Lim, Salim, & Baharuddin, 2010). Currently, the best players in the world come from China, Europe, Korea, Malaysia, and Indonesia (Zhao, 2007). Surprisingly, a scientific documentation in 2007 shows badminton as the number one participated sport in Great Britain, with almost two million registered players (Zhao, 2007).

Badminton

Badminton is one of the most popular racket sports in the world. The game is played by either two players (singles) or four players (two pairs in doubles), who take positions on opposite halves of a rectangular court with a net in the middle line (Hussain, Paul, & Bari, 2011; Salim, Lim, & Baharuddin, 2010). During the game, the shuttlecock is passed over the net struck by a racket using various stroking techniques that vary from relatively slow to fast, including some strategically deceptive movements. Badminton appeals to people of various ages and different skill levels because it can be played indoors or outdoors for recreation or on a competitive level (Abe & Okamoto, 1989;

Adrian & Enberg, 1971; Brundle, 1963; Lo & Stark, 1991; Tang, Abe, Ae, & Katoh, 1993). Badminton is rapidly growing in popularity after approximately 100 years of vigorous development. Today, it is one of the most popular sports in the world (Liu, Kim, & Tan, 2010; Tsai, Huang, Lin, & Chang, 2000; Yang, 2013). Whether as a recreational fitness activity or as a high level badminton competition, the participants will need to conduct various movements including specialized footwork, jumps, twists, and swings to strike the shuttlecock and keep it moving back and forth on the court.

The Advantages in Recreational Badminton

The amateur badminton players learn and appreciate the social and psychological benefits of playing badminton. For the beginners, it is usually easy to keep the shuttlecock aloft in singles, doubles, or mixed doubles' play. Badminton is an excellent co-educational activity and is enjoyable and rewarding for most age groups (Zhao, 2007). The shuttlecock, unlike other racket sport balls, does not bounce and must be played in the air, thus making for a fast game requiring quick reflexes and some degree of fitness (Zhao, 2007). Moreover, it can exercise and enhance physical functions of the human body (Yang, 2013). Playing badminton keeps participants feeling well, strong, motivated, enthusiastic and young. It helps to ward off depression, anxiety, stress and increase self-esteem (Brundle, 1963). It also supports a better sleep at night, thereby minimizing the incidence of pre-existing illnesses getting aggravated due to lack of sleep. The game can also improve interpersonal relationships and communication skills while playing doubles as there are two people on each team.

The Advantages in Competitive Badminton

Badminton has been internationally recognized as an athletic sport requiring fast

reactions and skilled movements (Zhao, 2007). This is substantiated by the fact that badminton has now been included as a full-fledged medal sport in the Olympic Games following its introduction in the 1988 Olympics (Zhao, 2007). When played by experts, it is considered to be the fastest court game in the world (Zhao, 2007). A high level badminton game demands excellent fitness such as aerobic stamina, agility, strength, speed, and precision (Salim, Lim, Salim, & Baharuddin, 2010). Because of its technical nature, badminton also requires good motor coordination and the development of sophisticated racket movements (Salim, Lim, Salim, & Baharuddin, 2010). In addition, the development of high level sports competition plays a positive role on exploring human limitations and enhancing badminton skill levels.

As badminton can be a highly competitive game, badminton matches have attracted more participants due to its popularity with spectators (Putnam, 1993). More people become interested in participating because they enjoy watching the intense action and strategy. By watching a high level game, amateurs can see how athletes perform in a fluid motion and coordinate their bodies to achieve their goals. The increasing availability of badminton competitions provide amateurs and athletes more opportunities to access future competition.

The requirement of different level of fitness is another advantage to either recreational or competitive badminton players. Because individuals involved in competitive badminton will require rational use of various hitting techniques and footwork which can increase winning opportunities (Yang, 2013), they strive for a higher level of fitness. There are several effective methods to strengthen the body such as daily workouts of arm, leg, and wrist muscles, and by accelerating the systemic blood

circulation during the exercise. Players can also enhance the function of their cardiovascular and respiratory systems (Yang, 2013). A long-term badminton training program that includes comprehensive aspects of workout can improve cardiovascular health and increase vital capacity (Yang, 2013). Other advantages include learning to make judgments on opponents' reaction appropriately and decisively in a short time for both recreational and competitive badminton players. Badminton also improves the sensitivity and coordination of the human nervous system (Yang, 2013). Through exercise and competition, badminton can assist in developing excellent stamina and a competitive spirit (Yang, 2013).

The Forehand Overhead Smash

Badminton offers a wide variety of basic strokes, and players require a high level of skill to perform all of them effectively. The hitting areas (see Figure 1) where the player can reach the shuttle most easily can be roughly divided into the forehand and backhand. The numbers in the figure distinguish between side hand, underhand and overhand; which refer to shuttles hit at the side of the body, at knee/foot level, shoulder level or over the head respectively. Brahms (2014) pointed out that about 75% of a player's range is in the forehand area and about 25% is in the backhand area.

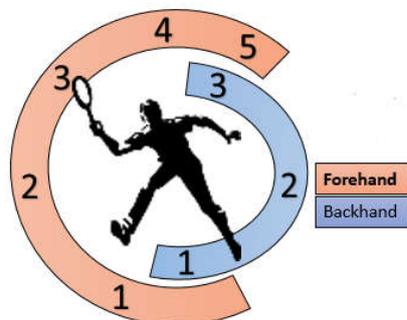


Figure 1. Hitting areas. 1. Underhand; 2. Side-hand/Lateral; 3. Overhand; 4. Overhead; 5. Round the Head. (Brahms, 2014)

With the exception of serving, there are six basic strokes in badminton (see Figure 2). Among these six strokes, the smash is the most typical and powerful offensive badminton technique to defeat the opponent (El-Gizawy & Akl, 2014; Gowitzke & Waddell, 1991; Rambely, Abas, & Yusof, 2008). The smash has been described as a shot toward the opponent's court with a downward power and speed wherein the angle of the shuttlecock's trajectory is very steep (Yap, 2012). The objective of this research thesis examines the forehand overhead smash, which is not only the most common technique used during a badminton rally (Liu, Kim, & Tan, 2010; Teu, Kim, Tan, & Fuss, 2005; Tsai, Huang, Lin, & Chang, 2000), but also it often determines the victor of the game (El-Gizawy & Akl, 2014; Osiński, 2003)

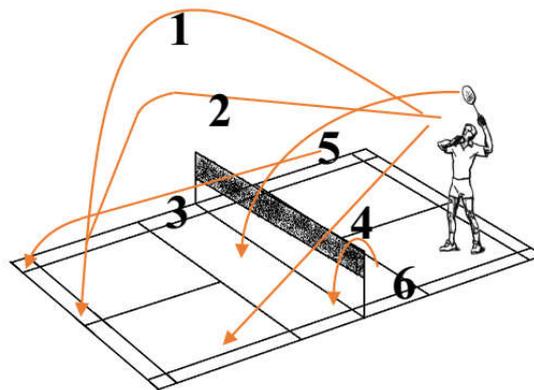


Figure 2. Five basic forehand types of badminton strokes. 1. Defensive Clear; 2. Attacking Clear; 3. Drive/Flick; 4. Smash; 5. Drop; 6. Net Play. (Brahms, 2014)

The forehand overhead smash is similar to the action of throwing a ball. If you can throw a ball well, you shouldn't have problem playing this stroke (Yap, 2012). The forehand overhead smash is regarded as the most powerful stroke of all forehand overhead strokes such as the clear and drop strokes seen in Figure 2 (Jaitner & Gawin, 2010; Kwan, Andersen, de Zee, & Rasmussen, 2008; Salim, Lim, Salim, & Baharuddin, 2010). In addition, Abe and Okamoto (1989), and Lo and Stark (1991) point out that the

smash is a powerful offensive weapon due to the power and speed (Sakurai & Ohtsuki, 2000). In respect to smash shuttle velocity, the IBF stated on its official website that badminton could firmly stake its claim as the world's fastest racket sport (Hussain, Paul, & Bari, 2011).

The Three Phases of Badminton Forehand Overhead Smash

The forehand overhead smash is one of the most effective and useful scoring techniques, however it is difficult for players to correctly master (Yang, 2013). The first step is for players to have a detailed understanding of each movement required to achieve the smash. Understanding the basic characteristics of the smash action is best achieved through a combination of teaching principles and experiences of coaches and teachers, and the analysis of action principles obtained from scientists (Yang, 2013). Today, the most common technique used in smash instruction is described by dividing the method into three action phases: preparation, acceleration (back-swing and forward-swing), and follow-through (Brahms, 2014; “How to hit”, 2014; Yang, 2013; Yap, 2012). Figure 3 displays each stage of the badminton smash for a right-handed player shown in the laboratory setting.

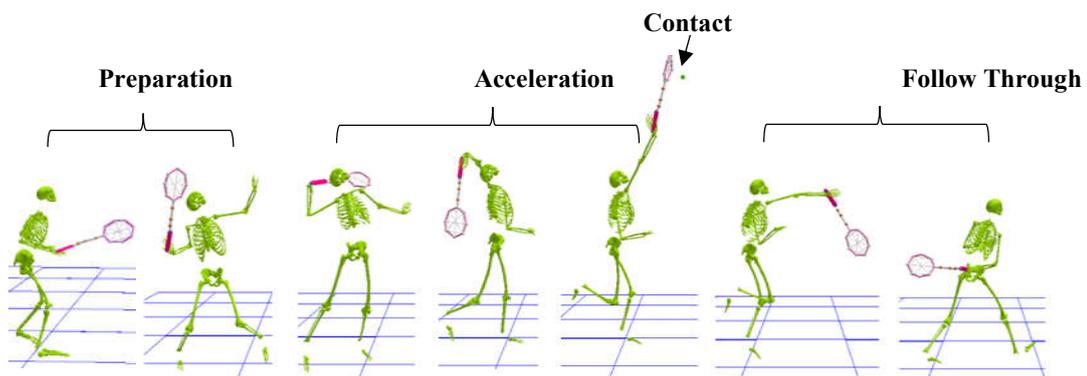


Figure 3. Three phases of the badminton forehand overhead smash with dynamic shuttlecock.

Each stage will be clearly presented and explained for a right-handed player. It is worth noting that there are slight differences between smash and jump smash effectiveness (Hong & Tong, 2000; Jaitner & Gawin, 2010). However, these will also be described in the following section.

Preparation Phase

The smash begins where the player decides to contact the shuttlecock (Yang, 2013). Empirical evidence shows that during a game, no matter what type of smash the player could apply, the player must first adjust his/her body positioning in relation to the incoming shuttlecock in order to produce a powerful and accurate smash (Brundle, 1963; Davidson & Gustavson, 1964; Zhao, 2007).

In the preparation phase, a series of actions are done to lead to an eventual smash. Upon judging the shuttlecock's direction and placement by the opponent's return, the player must assume quickly and effectively in order to adjust their stance. The receiving stance, in which the player's feet are shoulder width apart with knees slightly bent and the dominant foot ahead of the other, is quickly changed to a smash waiting stance. The smash waiting stance leads to the acceleration phase and requires that the dominant foot step backwards, with legs spread, with the non-dominant hand and shoulder pointing towards the shuttlecock. The player's dominant foot and shoulder should be in line with the upcoming shuttlecock by pivoting towards right (or racket arm) at the waist and turning the racket shoulder sideways so the player is standing sideways (Aisheng, 2010; Zhao, 2007). The entire movement should be led with the non-racket arm, with the hand pointing up toward the shuttlecock, while the racket arm is also raised with the elbow bent and wrist unlocked so that the racket is pointing upwards (Aisheng, 2010; "How to

hit”, 2014; Zhao, 2007). The Center of Gravity (COG) is changed during the transfer from receiving to waiting stance. In receiving stance the weight is evenly distributed between both legs and during the transition to waiting stance most of the weight is placed on the back leg (“How to hit”, 2014; Zhao, 2007).

After the player moves into the waiting position, the player must bend his/her knees in order to lower the COG, which is a crucial component of the standing smash (Aisheng, 2010). The purpose of lowering the COG is to reserve potential elastic energy. By actively contracting the knee muscles, the players increase the initial length of quadriceps muscle. Meanwhile, a lower COG prepares for a long swing phase and a powerful knee extension movement (Aisheng, 2010).

The jump smash has more vertical jump with a short aerial suspension compared to the standing smash (Aisheng, 2010). The jump smash needs a lower COG at take-off and longer movement duration than the standing smash. When the player is standing in the waiting position, the COG controls the placement of the body. The player must lower his/her body to the lowest point in preparation phase for the eventual jump (Jin, Jianping, & Xueqing, 2009; Yang, 2013)

Acceleration Phase (Back-Swing and Forward-Swing)

The second stage of the forehand overhead smash is called the acceleration phase, which includes a back-swing and forward-swing. The posture begins with the racket arm up and back and then the hand placed behind the player with the players’ the upper arm near the right ear, and the elbow pointing up (side view in Figure 4). Additionally, the player faces toward the net with the COG on the front or non-dominant foot (Yang, 2013; Zhao, 2007). The top view (Figure 4) shows a ‘shoulder-hip separation’ which appears

in the trunk segment (Roach & Lieberman, 2014). During the shoulder-hip separation, the trunk starts to rotate externally and then internally in the smash waiting stance followed by the forearm quickly back-swing, the wrist extends backward and the elbow point up with the racket head pointing down behind the player (“How to hit”, 2014; Waddell & Gowitzke, 2000; Yang, 2013).

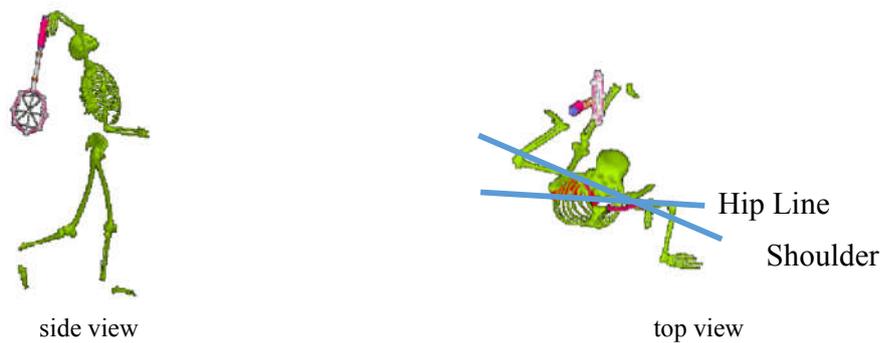


Figure 4. A posture in side view and top view at the end of back-swing to show the ‘shoulder-hip separation’ shape.

The arm movement between the standing and the jump smash is fundamentally the same (Aisheng, 2010). In the jump smash, the same arm movement occurs; the player’s body leaps upward, and the COG reaches its highest point during the body’s upward movement (Yang, 2013).

Once the player finishes the back-swing, the player should initiate a quick forward-swing to make a forceful contact with the incoming shuttlecock (“How to hit”, 2014; Yang, 2013). One should swing the forearm forward with the racket head moving upward at the same time (“How to hit”, 2014; Waddell & Gowitzke, 2000). During this procedure, four key points need to be emphasized:

- 1) Move the racket up to meet the shuttlecock with the elbow leading;
- 2) Swing racket forward and up to make the contact point as high as possible with an outstretched arm;

- 3) Rotate the racket internally and move the racket head downward to make the racket face down;
- 4) Increase the speed of the upper body through the forward-swing with a fast internal rotation from the back-swing in order to generate more momentum (“How to hit”, 2014; Yang, 2013; Zhao, 2007).

There is an efficient way to drive the racket forward to face the shuttlecock. As the player swings his/her arm forward, the player should internally rotate the forearm and straighten the elbow in order to keep the arm high for a higher contact point (“How to hit”, 2014; Waddell & Gowitzke, 2000). In addition, the player could flick his/her wrist before contact to generate extra speed during the smash (“How to hit”, 2014).

The trunk’s internal rotation in a jump smash is the same as the standing smash, which occurs when the player drives the forearm to swing upward to contact the shuttlecock with the racket’s frame (Yang, 2013). The acceleration phase causes an elastic deformation on the racket. This acceleration and deformation will increase the smash velocity by the force interaction between racket and shuttlecock if the timing of the smash is right (Kwan, Andersen, de Zee, & Rasmussen, 2008).

Follow-Through Phase

The follow-through phase begins after contact. It is executed by rapidly pronating the forearm and flexing the elbow (Waddell & Gowitzke, 2000). Before the racket head points downward and across the body to rest near the non-racketed leg, the racket head should follow its trajectory and be in line with the flight of the shuttlecock (“How to hit”, 2014; Zhao, 2007). As the COG shifts from the back to front foot, the non-racketed shoulder and arm will complete a vigorous leg-scissoring action by left

trunk rotation and forward hip flexion. This action propels the player to immediately push off and back toward center court for the preparation of next stroke (Waddell & Gowitzke, 2000; Zhao, 2007). A good follow-through maintains the racket speed as the player hits the shuttlecock (“How to hit”, 2014). As such, using maximum force upon contact will result in an effective follow-through (“How to hit”, 2014).

In summary, a specific and detailed description of how to execute a powerful smash will be of great interest to coaches, players and scientists. Coaches especially, who do not always see the racket position as described above, will benefit from these visual cues of body movement to ascertain players’ performance in order to improve their smash action and to increase the power or accuracy of the smash (Waddell & Gowitzke, 2000). Hence, studies are needed on the aspects of the player’s body such as trunk rotation and body positioning in relation to the contact point to provide different cues for evaluating the player’s performance.

The Advantages of the Forehand Overhead Smash

Throughout badminton’s technical development, the smash has been used as a common stroke for scoring and has become a necessity and favourite for both amateurs and professionals. In addition, no stroke in the game of badminton is as spectacular and aggressive as the smash (Zhao, 2007). Because the power of a forehand overhead smash has one of the highest tip-speed motions among various hitting motions of all racket sports, it has become the standard of judgment regarding a player’s technique and skill (Koike & Hashiguchi, 2014; Liu, Kim, & Tan, 2010; Teu, Kim, Tan, & Fuss, 2005; Yang, 2013).

Among the many strokes of badminton, an effective smash is said to be an

especially important means of gaining points to win a game (Adrian & Enberg, 1971; Brundle, 1963; Davidson & Gustavson, 1964; Gowitzke & Waddell, 1979a; Gowitzke & Waddell, 1979b; Jack & Adrian, 1979; Sakurai & Ohtsuki, 2000). In a game, the smash can lead to a direct score or put the opponent in a passive defensive situation. Therefore, the smash has better efficacy than any other badminton attack technique as there are a number of possible outcomes: 1) points can be directly obtained with the smash; 2) smashes can create favourable opportunities to score; 3) smashes may inhibit the opponent's attacks; 4) smashes may transform the situation between defense and offence (Aisheng, 2010; Jin, Jianping, & Xueqing, 2009).

Smashes are considered to be the most effective technique in badminton, especially during doubles (Jaitner & Gawin, 2010; Zhao, 2007). The strategy behind the use of smashes in singles and doubles is different ("How to hit", 2014). In singles, smashes are executed sparingly and should only be used when the player feels confident of the opponent's weak return or the player is in the correct position to complete the smash ("How to hit", 2014). In mixed doubles, male players in the back court should smash more often in order to make the strong returns ("How to hit", 2014).

The Performances of Smash between the Skilled Players and the Novices

The main purpose of smashing is to hit the shuttlecock as fast as possible (Jaitner & Gawin, 2010). According to the IBF, the world's fastest badminton smash in men's doubles was calculated to be 332 km/h by Chinese doubles star Fu Haifeng, men's singles at 298 km/h by Denmark's Kenneth Jonassen and women's singles at a speed of 257 km/h by Huang Sui ("Chinese Fu Clocks", 2005; "How to hit", 2014; Rasmussen, Kwan, Andersen & de Zee, 2010). In 2005, a world-record tennis ball speed of 246 km/h

was recorded from the tennis star Andy Roddick which shows the difference between the speed of tennis ball and shuttlecock (“Chinese Fu Clocks”, 2005). In several studies, shuttlecock velocities from 250 to 414 km/h have been reported (e & Gawin, 2010; Tsai, Chang, & Huang, 1998).

Novice players often demonstrate incorrect techniques and poor stroke production in executing the smash and have trouble creating adequate speed for the racket head (Sørensen, de Zee, & Rasmussen, 2010; Zhao, 2007). Skilled players are characterized by their ability to generate great speed and precision as they are able to perform a successful smash with apparent ease (Kwan, Andersen, Cheng, Tang, & Rasmussen, 2011; Lo & Stark, 1991; Putnam, 1993; Sakurai & Ohtsuki, 2000). Even when skilled experts face challenges in situations where physical fatigue or the player’s range of motion (ROM) imposes limitations, these players still have the capability to adjust quickly to the situation and fake a smash shot to perform a drop shot (Huynh & Bedford, 2011; Kwan, Andersen, Cheng, Tang, & Rasmussen, 2011). Ito (1996) indicated that the skilled experts had already established a motor program of automated voluntary movements in the badminton smash (Sakurai & Ohtsuki, 2000). In light of those observations, one should keep in mind that differences exist between the skilled experts and the novices.

One standard to distinguish the smash from other forehand overhand strokes is to hit the shuttlecock downward with the highest possible speed (Sørensen, de Zee, & Rasmussen, 2010). Due to the great variation of smash techniques and proficiencies among different players, a more in-depth understanding as a result of comprehensive research of the badminton smash is required. This study will benefit novices, athletes, coaches and scientists.

Research Intent

This thesis focuses on the study of the badminton forehand overhead smash by using 3D Mo-cap system and a full-body modeling. It explores and determines the major influential parameters in relation to the smash quality such as shuttlecock release speed (V_{release}), shuttlecock release angle (α_{release}) and clearance height (H_c) by use of the biomechanics and kinematic. Biomechanics is the study of the structure and function of biological systems such as humans, animals, plants, organs, and cells by means of the methods of mechanics (Alexander, 2005; Hatze, 1974). Kinematics is the branch of classical mechanics which describes the motion of points, bodies (objects) and systems of bodies (groups of objects) without consideration of the causes of motion (Whittaker, 1952; Wright, 1898).

The thesis was divided into two studies, Study 1 and Study 2, which required two groups of participants, a skilled group (SG) and novice group (NG). The study also identified three key factors: 1) body positioning, 2) trunk rotation (X-factor) and 3) training effect in relation to the final smash speed (V_{release}), and accuracy (α_{release} and H_c). The aim of Study 1 is twofold. The main aim of Study 1 was to initiate a three-dimensional (3D) full-body motion analysis to quantify the relationship between body positioning and smash quality. Additionally, correct body positioning should be a result of training effect. As a result, there was a secondary aim of Study 1, which was to compare characteristics of body positioning found in both NG and SG in order to reveal the effect of training effect.

The first purpose of Study 2 was to examine and compare the difference in the body movement parameters (X-factor and ROM of upper limb movement) in relation to

smash quality between the NG and SG in SR body position. The second purpose of Study 2 was to quantitatively describe the kinematic characteristics of a smash by applying a 15-segment, full-body model.

Significance

Badminton has experienced change for more than a century. Because of the rapid growth of badminton popularity, it is crucial to synchronize scientific research and the technical aspects of the game. Unfortunately, for badminton, the scientific understanding has lagged behind its practice so that most players and coaches acquire skills through individual experiences rather than through research-based instruction. Therefore, research-based instruction not only can be used to meet the needs of players who want to master a skill or tactic but it also satisfies the coaches who want to find a new way to train learners and design new drills effectively. Coaches also want to prove the validity of their teaching methods. As such, research-based instruction also reflects that there is the ability to improve relationships among players, coaches, and researchers.

Players at different skill levels have various stroke techniques (Sørensen, de Zee, & Rasmussen, 2010) thus making it hard to quantify. Since diversity exists within different skills and players, it is somewhat difficult to evaluate what the specific differences are during a training session (Sørensen, de Zee, & Rasmussen, 2010). The reason for this phenomenon might be due to the complicated movements and various coordination possibilities, and the many degrees of freedom in the involved joints (Sørensen, de Zee, & Rasmussen, 2010). The sports researchers can explain the phenomenon to players for better self-evaluation.

During competition, smashes occur in roughly 0.1 seconds. It is impossible to see

the racket's movement with the naked eye when players spin and initiate impact with the shuttlecock. It is also impossible to take note of body position cues, which decide the correct execution of the overhead smash. High-speed cinematography or videography on the court will solve a major problem for players/coaches and allow them to observe and correct or even improve smash production (Waddell & Gowitzke, 2000).

From the coaches' perspective, there is a common question of "how do I train my athlete to improve his/her smash?" (Waddell & Gowitzke, 2000, p.3). This question reveals that clarifying the nature of sport biomechanics and the importance of how to use and incorporate biomechanical principles in training and teaching is needed (Waddell & Gowitzke, 2000). The scientists can help the coaches solve actual training problems and give feedback of training method by applying scientific solutions. The study of the full-body kinematic characteristics of the overhead forehand smash provides crucial information, while parameters related to smash quality would be of great interest to badminton coaches (Abernethy & Zawi, 2007; Teu, Kim, Tan, & Fuss, 2005). Furthermore, by comparing the effect of techniques executed by the NG and SG, the tested parameters influencing smash quality have the potential to assist quantitative evaluations of the smash skills.

Finally, it would be of great interest and application to create guidelines for better teaching and improve the professional knowledge for better understanding (Chen, Pan, & Chen, 2009; Hussain, Paul, & Bari, 2011; Liu, Kim, & Tan, 2010; Sørensen, de Zee, & Rasmussen, 2010). Generally speaking, when teaching the badminton smash, coaches must emphasize how to sequentially and optimally use, the rotation of each body segment for energy and power generation, with the energy finally transferring to the racket head.

Technical understanding and learning should follow a process that starts with segmental motion and finish with complete motion which the sports scientists can help the coaches with understand.

This thesis mainly focuses on finding the influential parameters (body positioning in Study 1 and X-factor in Study 2) in relation to badminton smash quality in order to make a meaningful contribution for the better development of badminton skills. The result was obtained by using of biomechanics theory and kinematic principles with high-technique instruments such as a 3D motion-capture system. Application of those new results at the earliest stages of skill acquisition can assist the coaches and players with the design of training programs based on quantitatively determined 'ideal' body positioning and the creation of goal-oriented drills, as well as presumably speeding up the players' learning process. It is valuable that new inquiries illuminating body positioning and trunk movement during the badminton smash will lay the foundation for further exploration of the badminton forehand overhead strokes from a whole-body perspective. Therefore, the results are extremely beneficial for sports scientists, badminton coaches, and players.

Hypotheses

Researches support that badminton players will first adjust his/her body position in relation to the coming shuttlecock in order to produce a powerful and accurate smash (Brundle, 1963; Davidson & Gustavson, 1964; Zhao, 2007). A large X-factor at the top of backswing is also known to be a key point in generating a greater golf club head velocity at impact in golf (McTeigue, Lamb, & Mottram, 1994). In addition, the whip-like movement as a wave movement from the proximal to the distal end of the whip tail simultaneously increases velocity in throwing and striking techniques (Putnam, 1993;

Rasmussen, Kwan, Andersen, & de Zee, 2010; Sørensen, de Zee, & Rasmussen, 2010; van den Tillaar & Ettema, 2009). Three hypotheses, therefore, are expected to be supported in current thesis:

- Body positioning in Study 1 would have a direct influence on the quality of a smash, especially on α_{release} and H_c .
- The execution of X-factor in Study 2 would highly influence the final quality in the aspect of V_{release} and the formation of the whip-like movement.
- Training effect would highly influence the smash quality as well as have close relationship with the choice of body positioning in Study 1 and execution of X-factor in Study 2.

Limitations

There were three limitations in the current thesis, most of them related to the experiment set-up.

- The experiment replicated most of the physical components of badminton with in a standard court size, racket and shuttlecock. The lab did not meet the space height set forth by Badminton World Federation (BWF) of at least 9 meters high without any obstacles.
- In the experiment, the 39 body markers were used to build a 15-segment full-body biomechanical model. The test garment was designed to be like a second skin. Sometimes markers displaced and this caused errors to the raw data (Liu, Kim, & Tan, 2010; Lu & O'Connor, 1999).

- The sample size is a limitation. A larger sample size would allow a more comprehensive analysis in later study.

Chapter Summary

This chapter presents a brief overview of badminton in three development periods, the characteristics of both recreational and competitive badminton and the forehand overhead smash. Chapter one also points out the purpose and significance of the study. Finally, the three hypotheses and three limitations of the study are outlined. Next, an in-depth review of previous literature will be presented.

Chapter 2 Literature Review

This chapter will review literature regarding the badminton smash and other related sports. First, the development of various methods of biomechanical analyses will be introduced. These methods had been used in different studies in terms of badminton or other racket sport during the past 40 years. Secondly, theories and principles such as the proximal-to-distal principle and the Stretch–shortening Cycle (SSC) that exist in previous research and influence the smash performance will be described.

The Biomechanical Analyses of Badminton in the Past, Present and Future

Biomechanics is one of the branches of sports science. In this study, biomechanics is concerned with the techniques used to perform various badminton skills and tries to identify the mechanical characteristics that affect and improve performance (Lees, 2003). Biomechanical analyses of badminton has a relatively long history, yet the body of knowledge is still small, and contains less descriptive studies on the forehand overhead badminton smash than other badminton techniques (Teu, Kim, Tan, & Fuss, 2005). In earlier biomechanical analyses, badminton techniques were usually qualitative in nature (Liu, Kim, & Tan, 2010; Teu, Kim, Tan, & Fuss 2005). By reviewing previous research between 1970 and 2014, the studies can be classified: 1) by the spatial dimension; 2) by partial or full body; 3) by male or female; and 4) by motion capture (Mo-Cap) with or without the Electromyography (EMG) or force platform. Such classification reflects a development of biomechanical analyses as well as addresses insufficiencies such as outdated equipment in the past badminton studies. The next sections will review research using two dimensional (2D) or 3D motion analysis.

2D Motion Analysis of Badminton Stroke's Kinematics

Thirty years ago, very little researches had been done biomechanically to explain the 'fast' strokes of the game (Waddell & Gowitzke, 2000). There were limited ways for the players and the coaches to pass along their knowledge of performing a smash because high-speed cameras and other scientific instruments were not available (Waddell & Gowitzke, 2000). Instead, many static photographs of players' performances were used to analyze the strokes (Waddell & Gowitzke, 2000). Due to the lack of subjects at an advanced level of badminton, as well as the lack of scientific instruments, the main method before the 1970s for the 2D kinematic analysis was by way of black and white film cameras (Poole, 1972; Waddell & Gowitzke, 2000).

Traditionally, photography has been the preferred method to capture and analyze human motion. Although widely adopted, it has limitations (Hussain, Paul, & Bari, 2011; Tsai, Huang, & Chang, 2005). Researchers typically face many problems such as occlusion, inadequate sampling frequency, poor picture quality, tedious post-processing and so forth (Teu, Kim Tan, & Fuss, 2005). Other previous studies used the 2D model to describe the smash strokes (Adrian & Enberg, 1971; Gowitzke & Waddell, 1979a; Hussain & Bari, 2011; Poole, 1972; Salim, Lim, Salim, & Baharuddin, 2010; Tsai, Huang, Lin, & Chang, 2000; Tsai, Huang, & Chang, 2005; Tsai, Chang, & Huang, 1998). However, the question of whether 2D analysis is a sufficient method to assess smashes without losing important characteristics to describe the joint actions was broached in the early 1980s, when 3D planes were introduced (Hussain & Bari, 2011; Shan & Westerhoff, 2005). This technological development in particular, allowed and enabled the 3D kinematic analysis to be undertaken with at least two high-speed cameras (Lees, 2003)

High-Speed Cameras 3D Motion Analysis of Badminton Stroke's Kinematics

The inclusion of the 3D analysis after the 1980s was revolutionary in the study of badminton. It is advantageous to see movements in all planes when simultaneous recordings are conducted from at least two cameras (Gowitzke & Waddell, 1979a). Early research focused on the overhead power strokes performed in the laboratory using two cameras located ninety degrees apart and synchronized with each other. This was the common method of kinematic data collection during experiments (Gowitzke & Waddell, 1979a, 1991). Two Locom 16-mm cameras operating at 400 frames per second were used to record the forehand overhead clear and smash, and backhand overhead clear and smash in Gowitzke and Waddell's experiment (1991). The film revealed that there were certain details that were impossible to be recognized by the naked eye (Gowitzke & Waddell, 1977, 1979a, 1991; Gowitzke & Waddell, 1979b). Sakurai, Ikegami and Yabe (1989) provided perhaps the first attempt to determine the changes of the upper body joint angles of the drop shot and the cut shot by using the 3D cinematography techniques. Also, Sakurai et al (1989) studied cut and drop shots by performing a 3D analysis of some of the strokes employed in badminton. Tang et al. (1995) provided a 3D cinematographic analysis of the badminton forehand smash, focusing on the forearm and the hand. Earlier work of Poole (1972), show photographic kinematic analyses on the biomechanics of stroke production.

From 1994 to 1997, several researchers used the 3D model to measure the rotation of forearm and wrist and also compared the standing smash and jump smash of elite players (Hussain & Bari, 2011; Liu, Kim, & Tan, 2010; Tsai, Huang, Lin, & Chang, 2000; Tsai, Huang, & Chang, 2005; Tsai, Chang, & Huang, 1998).

To date, even though different badminton techniques have been studied by many researchers, the studies almost solely focused on the 3D analysis in the arm movement (Hussain & Bari, 2011; Hussain, Paul, & Bari, 2011; Liu, Kim, & Tan, 2010; Tsai, Chang, & Huang, 1998; Waddell & Gowitzke, 2000) or the low extremity (Tsai, Yang, Lin, Huang, & Chang, 2006). Such limitation would lead to an incomplete understanding of joint coordination and motor control for the smash skill because they fail to determine the contribution of whole body movement during smashing. The main reason for neglecting trunk movement is that it is not easy to collect unconstrained data using full-body model in 3D space due to laboratory settings or experimental design (Shan, Bohn, Dust, & Nicol, 2004). However, the full-body 3D analysis provides a more effective means to examine badminton smash than 2D motion analysis in the partial body model. The full-body 3D analysis provides information regarding the contribution of trunk control in the effectiveness of smashes. Consequently, the full-body analysis is the next step for advancing knowledge in the biomechanical analysis of badminton.

Dynamic badminton movements are generally analyzed by high-speed cameras in spatial and temporal resolution and provide detailed insight in to underlying kinematics. Certain limitations still exist (Jaitner & Gawin, 2010), for example, almost all experiments are conducted in a laboratory environment which does not adequately simulate real game conditions.

3D Analyses of Badminton Stroke's Kinematics Using Mo-Cap System

Over the past 15 years, a completely new technology was introduced to assist with assessing movement among other things. Mo-Cap is the process of recording the movement of objects or people, in three dimensional spaces. It is used in a wide range of

applications such as military, entertainment, sports, medical applications, and also for computer vision and robotics (Noonan, Mountney, Elson, Darzi, & Yang, 2009). In Mo-Cap sessions, movements of one or more actors can be sampled many times per second instead of using images from multiple cameras to calculate 3D positions. For scientists interested in badminton science, Mo-Cap has become their integral means of determining and measuring the movements of the players.

Sørensen et al (2010) used Mo-Cap to collect data that was recorded using a Qualisys Oqus 300 system (Gothenburg, Sweden). This system consisted of eight high-speed cameras sampling at a maximum frame rate of 500 Hz to capture the high-speed racket movements. The subject's upper body movements on which reflective spherical markers were attached was also recorded. Rasmussen et al (2010), used the same Mo-Cap system and number of cameras to record an Olympic class badminton player smashing a shuttlecock with maximal effort. Kwan et al (2008), captured ten trials of a smash stroke performed by an advanced player using a Qualisys ProReflex system of eight cameras at the maximum frame rate of 240 Hz. Kwan et al (2011) measured racket kinematics during several smash strokes performed by three players of different skill levels. The objective of his paper was to use Mo-Cap to measure racket kinematics and show that the Mo-Cap can be used to evaluate badminton smash kinematics (Kwan, Andersen, Cheng, Tang, & Rasmussen, 2011). No studies were located using full-body Mo-Cap in badminton strokes. The current study using full-body Mo-Cap of the badminton smash will supply more information on normative characteristics found in highly-skilled players. Though Mo-Cap is an ideal means of studying badminton stroke techniques, other instruments have also been used.

Mixed Methods with Muscle Activity Studies Using EMG and Kinetic Explorations Using Force Measurements

Advanced technology has facilitated the 3D kinematic analysis of badminton skills (Lees, 2003). These technologies have also been able to emphasize specific kinetic characteristics of badminton skills and enabled scientists to investigate the underlying movements used in performing badminton skills (Lees, 2003). In order to characterize activation, coordination and intensity of selected muscles, several studies have used EMG measurement (Besier, Lloyd, & Ackland, 2003; Dørge, Andersen, Sørensen, Simonsen, Aagaard, Dyhre-Poulsen, & Klausen, 1999; Taube, 1972; Zhang, Guo, & Chen, 1999). Sakurai and Ohtsuki (2000) reported EMG data on the muscles that control wrist actions (the extensor carpi radialis and flexor carpi radialis) in the 180 kph smash speed before impact (Lees, 2003). Sakurai and Ohtsuki (2000) also found that in skilled players, the muscle activity was well defined and consistent in a sequence in skilled players, but muscle activity was less defined and inconsistent in unskilled players (Lees, 2003). Therefore, Lees suggest that the reason the unskilled players easily lost power in their smashes is that the unskilled players had not been able to adequately control the important final motions before impact (Lees, 2003).

In addition, some researchers have synchronized EMG data with 2D motion analysis to link muscle activities to joint kinematics. These studies, however, did not involve the full-body view that can be provided by 3D modeling based on 3D motion capture. Thus, some researchers combined the EMG with 3D kinematic analysis in their study. For instance, Tasi et al (2006) calculated 3D kinematic data by using the Kwon3D system with two Redlake 1000 high-speed digital cameras (Motion Scope, San Diego,

USA, in 250Hz) and the EMG data of the lower extremities of the subjects were computed by using the DASY Lab system for four elite college badminton players in Taiwan. The essential weakness of these studies was that none used full-body modeling to identify the contribution of individual muscles because the only viewable results showed the net effect of muscle groups surrounding the joint.

Gowitzke and Waddell (1980) analyzed the ground reaction forces obtained by the use of a force platform. A force platform measures the ground reaction forces generated by a body standing on or moving across it, to quantify balance, gait and other parameters of biomechanics. Force platform studies concluded that overhead power strokes were played with the body elevated and COG transformation between both feet. The force platform study supported that contact with the shuttlecock was made during the last phase while the body was descending from its high point (Gowitzke & Waddell, 1980). During the jump smash, for instance, the contact force platform was initiated before an airborne movement when both feet take-off the floor. The largest reaction force appeared at this point, they found that a lower COG and longer movement duration are more effective for the jump smash than the standing smash. Previous literature rarely involves a force platform during the badminton smash experiments because the badminton smash is a high speed technique that requires complex and quick footwork. It has a low success rate related to shuttlecock contact which is compounded by inconvenient equipment set-up and makes it difficult for subjects to make appropriate contact with force platform.

Due to the significance of smashes during the badminton games, factors that affect the quality of badminton smash must be fully explored and understood. Previous

analyses of this technique have been discussed; and we will now consider aspects that influence smash quality.

Influential Factors in Relation to Smash Quality

First of all, a comprehensive description of the badminton smash is required in order to understand the various factors that influence it. Previous papers have outlined that the smash must be rapidly executed by hitting fast and downward with force. Though the shuttlecock is hit with power, the players should correctly assess their timing and balance before trying to achieve excessive speed on their smashes (Jin, Jianping, & Xueqing, 2009; Zhao, 2007). The smash is always a challenge for both amateurs and skilled players to accomplish with precision and quality due to the high demands of physical exertion, such as speed, power, smash precision, flexibility and coordination, (Zhao, 2007). Once a high quality smash is executed, the opponents will have very little time to react (Zhao, 2007). Zhao (2007) indicates that the smash is a strategy that “the more accurate your smash, the more court your opponent has to cover” (p.86).

Previous researchers have divided the influential quality factors into two aspects, namely speed and accuracy (Sørensen de Zee, & Rasmussen, 2010). Speed and accuracy are often used to evaluate effectiveness of many sport skills (Ballreich & Schöllhorn, 1992; Chang, Evans, Crowe, Zhang, & Shan, 2011; Reilly & Williams, 2003; Shan, 2009; Shan, Visentin, Zhang, Hao, & Yu, 2015; Shan, Zhang, Li, Hao, & Witte, 2011; Wąsik & Shan, 2015; Yu, Yu, Wilde, & Shan, 2012).

Smash power is the factor which primarily affects the quality of the smash (Yang, 2013). However, from the training and teaching perspective, power cannot alone compose a high quality smash because smash accuracy also assists players to make a

more aggressive smash. Coaches will tell the players that the badminton smash should be executed with a high velocity, downward angle below the horizontal trajectory, and land within the constraints of a legal court (Strohmeyer et al., 2009).

In the next section, the specific influential factors and previous findings in relation to the badminton smash quality will be systematically summarized. The influential factors also involve several biomechanical principles.

Intersegment Coordination

Intersegment coordination used in the production of complex, forceful movements has been discussed in the biomechanical literature for a long time (Bird, Hills, & Hudson, 1991). A bold presumption surfaced around the 1980s that the optimal pattern of coordination was sequentially timed with simultaneous and sequential order, as all segments concurrently contribute and each segment serially contributes (Bird, Hills, & Hudson, 1991; Bunn, 1972; Kneip & Barthels, 1981; Morehouse & Cooper, 1950). Niesner (1982) referred to sequential intersegment coordination of continuous action as 'the loop' and also emphasized that there must not be any break between the preparatory movement and the force producing movement (Waddell & Gowitzke, 2000). Hudson et al (1991) initially reported the effect of intersegment coordination of a skill that should be sequential in its exhibition. This sequence timing closely matched the standard sequential movement model developed by Morehouse and Cooper (1950). Upon further examination, Hudson et al (1991) pointed out that when individuals performed with the net in place, they exhibited a sequential pattern. The timing of segmental contributions, however, was not as closely aligned to this model. Individuals, executing the badminton smash without a net, were more sequential in their exhibition of Intersegment

Coordination patterns and more closely aligned to the model.

Strohmeier et al (2009) confirmed that the badminton smash is a sequential intersegment coordination pattern of movement. But Strohmeier's study lacked the final determination of whether the power or accuracy is affected by intersegment coordination patterns (Strohmeier, Armstrong, Litvinsky, Nooney, Moore, & Smith, 2009). Therefore, many recent studies and experiments have been undertaken on the badminton forehand overhead smash in order to determine the relationship between powerful smashes and intersegment coordination patterns. Several other studies attempted to characterize activation, coordination and, intensity of selected muscles by using EMG to link muscle activities and joint kinematics in the 2D motion analysis (Besier, Lioyd, & Ackland, 2003; Dørge, Andersen, Sørensen, Simonsen, Aagaard, Dyhre-Poulsen, & Klausen, 1999; Shan & Westerhoff, 2005; Zhang, Guo, & Chen, 1999). By using EMG, results show that the electrographic activity of the proper intersegment coordination was far more constant and efficient with time and energy use than that of the improper intersegment coordination (Sakurai & Ohtsuki, 2000).

Other experiments were designed to compare performance between different groups of subject, such as between beginners and advanced players (Abernethy & Zawi, 2007; Bird, Hills, & Hudson, 1991; Hirashima, Kadota, Sakurai, Kudo, & Ohtsuki, 2002; Huynh & Bedford, 2011; Sakurai & Ohtsuki, 2000; Shan & Westerhoff, 2005; Sørensen, de Zee, & Rasmussen, 2010; Tsai, Chang, & Huang, 1998). For example, timing body segmental movement would be simultaneous for a beginner while the advanced performer would be sequential (Bird, Hills, & Hudson, 1991). Furthermore, Bird et al (1991) point out that when performers choose their timing pattern of body segmental

movement, it depends on individual talents and training such as shoulder-girdle strength or training effect. The beginners have a less fluid motion through the smash, even though it is almost the same sequence, the smash takes a longer time than advanced performers, and the simultaneous-sequential continuum of coordination differed between these two groups (Bird, Hills, & Hudson, 1991). The smoother and more fluid the motion, the faster and more consistent the smash will be (“How to hit”, 2014). In other words, a proper coordination in both the pattern and the timing is now known to contribute to the skillful execution of various movements. Good sequential intersegment coordination patterns can assist in the accomplishment of complicated skills; however, little is known about how intersegment coordination works. Almost all studies lack full-body examination and in-depth results that can be implied and gained by 3D modeling based on 3D Mo-Cap. Intersegment coordination is the fluid progress of technique and leads us to further discussion on the kinetic chain of the forehand overhead smash.

Kinetic Chain

The terminology ‘kinetic chain’ was originally defined by Steindler (1970) as a combination of several arranged joints successively constituting a motor complex. Later, kinetic chain has appeared in many other articles (Kibler, Press, & Sciascia, 2006; Putnam, 1993; Young, 2014). Moreover, the kinetic chain is one of the mechanisms offering the effective transfer of power generated from the lower extremities to the upper body, and then from the upper body segments to the racket, and finally to the shuttlecock (Kwan, Andersen, Cheng, Tang, & Rasmussen, 2011; Young, 2014). Hirashima et al (2008) investigated the kinetic chain phenomenon, and describes a the whip-like movement which concentrates kinetic energy towards a targeted item or area (Rasmussen,

Kwan, Andersen, & de Zee, 2010). In the next part, the proximal-to-distal movement leading to the whip-like movement and kinetic energy transfer will be mentioned.

Proximal-to-Distal Principle

By using the kinematic method, the racket sports requiring high end-point velocity have been found to employ of specific joint movements and the proximal-to-distal coordination (Lees, 2003). The general idea of the proximal-to-distal principle is that the large and heavy segments transfer energy to the subsequent lighter segments (Lees, 2003). The muscles around each joint are constantly weakening from the proximal to the distal point. The larger muscle section is called ‘the large joint’, and similarly the smaller muscle section is the called the ‘small joint’. The force on each muscle moves from large to small, decreasing from trunk to wrist (Hirashima, Kudo, Watarai, & Ohtsuki, 2007; Hirashima, Yamane, Nakamura, & Ohtsuki, 2008; Putnam, 1993; Sørensen, de Zee, & Rasmussen, 2010; Yang, 2013). The movement should start from the large, heavy , and slow central body segments such as the trunk to smaller, lighter and faster segments such as the wrist (Marshall & Elliott, 2000; Putnam, 1993; Sørensen, de Zee, & Rasmussen, 2010). Furthermore, the distal joint actions such as forearm pronation and wrist actions play a key role in the precise execution of generating racket head speed and achieving accurate performance (Sakurai & Ohtsuki, 2000; Teu, Kim, Tan, & Fuss, 2005). Marshall and Elliott (2000) indicated that using the proximal-to-distal principle to describe the complexity of racket shots was inadequate. In order to better understand the role of forearm pronation, researchers must combine with other theories when coaching the badminton smash and developing training programs (Lees, 2003; Sørensen, de Zee, & Rasmussen, 2010; Zhao, 2007).

Playing a forehand or backhand smash requires power. Another basic biomechanical principle emerges that power is created through a ‘whip-like movement’ (Gowitzke & Waddell, 1979; Lee, 1993; Waddell & Gowitzke, 2000). The whip-like movement has been documented in both beginners and advanced players. The movement is initiated by propulsion followed by a proximal-to-distal sequence (Bird, Hills, & Hudson, 1991). There are many studies supporting the contribution of the proximal and distal segment, as well as the exploitation of intersegment force transfer (Abernethy & Zawi, 2007; Gowitzke & Waddell, 1979; Gray, Watts, Debicki, & Hore, 2006; Kreighbaum & Barthels, 1996).

Whip-Like Movement

The law of conservation of momentum applies in whipping action processes, in which the body’s hip joint makes a pivoting trunk with the action of the dominant arm, and the right arm is thrown out along the tangent of the right shoulder, like a whip, from the hip to the right shoulder (Yang, 2013). Yang (2013) explained the mechanical principle of the whip-like movement:

“First the whip root acquires angular momentum through accelerated waving, then stops, and then the angular momentum transfers toward the direction of whip slightly, finally make the end joint with the minimum quality produce great moving velocity and striking strength” (p.175).

It should be noted that the smashing arm movement, similar to the kicking leg movement, appears like an open mechanical chain, and change in any segment has an influence on the remaining segments. Hence, the whip-like movement can be applied in many sports, including throwing and striking sports, as this movement is characterized by

a wave movement from the proximal to the distal end of the whip tail, while increasing velocity (Putnam, 1993; Rasmussen, Kwan, Andersen, & de Zee, 2010; Sørensen, de Zee, & Rasmussen, 2010; van den Tillaar & Ettema, 2009). The human arm is a discrete system which consists of rigid segments and articulating joints so that a whip-like movement, to some extent, supports the motor skills behind fast strokes, as this movement requires precise coordination (Rasmussen, Kwan, Andersen, & de Zee, 2010). Therefore, the whip-like movement is an interesting phenomenon for badminton researchers and coaches to explore not only due to the generation of velocity, but energy transfer as well.

Kinetic Energy Transfer

Transfer of energy within segments, and between kinetic and potential energy is essential in any sport. The transfer of energy plays a significant role in the performance of a wide variety of human motions, including high speed movements such as strokes, pitches, and kicks (Rasmussen, Kwan, Andersen, & de Zee, 2010). The momentum generated by larger segments, such as the pelvis and the trunk, is transferred to the adjacent distal segments with appropriate timing. The transfer of torques across linked segments in a proximal-to-distal manner characterizes movement production in most racket sports (Abernethy & Zawi, 2007; Aguinaldo, Buttermore, & Chambers, 2007; Putnam, 1993). The proximal-to-distal principle in relation to the energy transfer between body segments relies on the joint reaction forces from the proximal segments (Rasmussen, Kwan, Andersen, & de Zee, 2010; Sørensen, de Zee, & Rasmussen, 2010; van den Tillaar and Ettema, 2009; Zhao, 2007). Later, Rasmussen et al (2010) reported a similar energy transfer pattern on the badminton smash for players at the Olympic level.

In order to achieve high velocities, the badminton player is recommended to start the smash by generating a maximum impulse within a minimum amount of time in order to achieve high velocities (Jaitner & Gawin, 2010; Waddell & Gowitzke, 2000). Lowering the body to conserve energy and then releasing power is typical for all skilled players during the action portion. Using these the two steps is an effective strategy to gain a higher shuttlecock velocity at the beginning of the movement (Tsai, Chang, & Huang, 1998). During the smash process, the trunk has the primary role of generating power but its multifunction makes it difficult to analyze and measure (Young, 2014). In particular, the trunk segment contributes to the total body angular momentum in the sagittal plane during the performance of overhead movements, such as the badminton smash and tennis serve (Aguinaldo, Buttermore, & Chambers, 2007; Bahamonde, 2000; Dapena, 1978; Putnam, 1991, 1993). But when controlled power, rather than full power is needed, not only is the proximal segment required, but also the terminal elements of the sequential action are used (Waddell & Gowitzke, 2000). When performing an attack a player will want to deceive his/her opponent by holding back on the hip and intervertebral joints, but fully extending the distally located joints and muscles in order to maximize the impulse to perform this stroke (Waddell & Gowitzke, 2000).

The highly dynamic movement of the upper limb is the process of continued velocity and energy propagation, which begins mainly from the proximal to the distal forearm. The movement then reaches the first impulse peak at the gleno-humeral joint followed by the elbow and then from the wrist joint to the racket, and finally to the shuttlecock (Jaitner & Gawin, 2010; Kwan, Andersen, Cheng, Tang, & Rasmussen, 2011; Sørensen, de Zee, & Rasmussen, 2010; Yang, 2013). Rasmussen et al (2010) states that

the peak power at the wrist reached values around 1 kW and, consequently, energy must be transferred from the proximal segment instead of being generated by the wrist joint alone. The proximal segment suddenly loses energy while the distal segment shows a great outward flow of energy from the thorax to the upper arm, forearm, hand, and racket handle (Rasmussen, Kwan, Andersen & de Zee, 2010; Sørensen, de Zee, & Rasmussen, 2010). However, it would be reasonable to assume that skilled players have a greater extent and more efficient proximal-to-distal sequence compared to the less skilled players. Since skilled players experience greater energy transfer due to joint reaction, novice players are encouraged to practice more sequential joint control in order to make their energy transfer more efficient (Sørensen, de Zee, & Rasmussen, 2010). In order to convey how greater muscle torques can generate greater joint work during smashing, the SSC will be explained.

Stretch–Shortening Cycle (SSC)

Yang (2013) indicated that skeletal muscles have three properties: extensibility, viscosity and elasticity. The extensibility of the skeletal muscles means the extent to which the muscle can be stretched. The ability for the muscle to restore itself to its original state without harm or injury to the muscle itself after the external force disappears is called elasticity, while the muscle's viscosity refers to the viscoelastic properties of the muscle which the tissues' length-tension characteristics differ during loading and unloading (Yang 2013). SSC refers to the process whereby a muscle and tendon complex when preloaded and then stretched, can generate a greater force at the start of the forward movement than when the muscle and tendon complex were not preloaded (Lees, 2003). Tang et al (1995) found that in assessing the forearm pronation,

wrist flexion-extension and ulnar and radial deviation, and wrist joint motion in relation to the forehand smash, the most important movement was the pronation of the forearm in the forehand smash. Later, Tang et al (1995) further suggested that forearm pronation was an efficient way to constitute a SSC by increasing supination of the forearm just before its rapid pronation, which assisted in the speed of the smash movement. The effective use of the SSC of muscular contraction that generates greater muscle torques and involves more joint work was found in the skilled players. The skilled players showed a greater range of motion for the majority of segment and joint movement. For example, some principles that could also be considered a typical adaptation for skilled players were the initiation of the stretch reflex, in which the muscle stretches to its optimal length while storing elastic energy following the movement (Sørensen, de Zee, & Rasmussen, 2010; Zatsiorsky, 1998).

Several studies provide results by using EMG in selecting muscles in three different badminton techniques: smash, clear and drop stroke (Figure 2). One study verified the performance of biceps and the wrist extensor in the eccentric contraction around contact indicated that the EMG signal of a smash was significantly greater than that of a drop shot (Tsai, Huang, & Chang 2005). They also found that in both kinds of strokes, the greatest velocity and power value was exerted in the wrist joint caused by the wrist extensor of eccentric contraction rather than the elbow and shoulder (Tsai, Huang, Lin, Chang, & Cheng, 2001; Tsai, Huang, & Chang, 2005). For the badminton smash stroke, the extensor carpi radialis and the biceps are two major muscles to engage in the eccentric contraction during the contact phase (Tsai, Huang, Lin, Chang, & Cheng, 2001; Tsai, Huang, & Chang, 2005). In addition, concentric contraction is followed by the

eccentric contraction just before contact is made in the smash. Because the wrist joint exerts the greatest velocity and power in all three strokes, more than the elbow and shoulder, the wrist joint movements are the reason why beginners suffer pain in the wrist extensors. Coaches must incorporate wrist extensors exercises as a part of regular training in order to reduce the likelihood of injury and minimize muscle pain from the eccentric contraction during the acceleration phase (Tsai, Hung, Lin, & Cheng, 2000).

As mentioned above, the optional smash maximizes the acceleration of force, time, and momentum of body weight by delivering great force over the shortest time possible; in other words, a maximum impulse in a minimum time (Gowitzke & Waddell, 1979). Therefore, there must be no hesitation between the backswing and the forward swing. The movement must be rapid. A long backswing is suggested in order to stretch the muscles. This motion takes advantage of the elastic properties of the muscles and inherent proprioceptive reflexes (Gowitzke & Waddell, 1979) and leads to the influential factor of arm rotation.

Arm Rotation

The arm rotation pattern contributes to maximum racket-head speed which also is of considerable interest to both players and coaches (Sprigings, Marshall, Elliott, & Jennings, 1993). However, it is difficult to estimate the individual contribution of segment rotation in relation to racket-head speed because the segments frequently overlap with one another (Sprigings, Marshall, Elliott, & Jennings, 1993). Researchers confirm that the angular velocity patterns obey the rule of the kinetic chain with the shoulder have greater angular velocity than the elbow and the elbow having greater angular velocity than the wrist (Sprigings, Marshall, Elliott, & Jennings, 1994). Using 3D

models, the players exhibited a greater range of motion for upper and forearm segment during the badminton smash (Aguinaldo, Buttermore, & Chamber, 2007; Gowitzke & Waddell, 1979a; Gowitzke, Waddell, Watkins, Reilly, & Burwitz, 1986; Hussain & Bari, 2011; Lees, 2003; Salim, Lim, Salim, & Baharuddin, 2010; Sprigings, Marshall, Elliott, & Jennings, 1994; Tang, Abe, Katoh, & Ae, 1995; Tang, & Toyoshima, S., 1997; Teu, Kim, Tan, & Fuss, 2005; Tsai, Huang, Lin, & Chang, 2000; C. Tsai, Chang, & Huang, 1998).

The upper arm internal rotation is the most important contributor to the racket head speed and the final forward velocity (Liu, Kim, & Tan, 2010; Salim, Lim, Salim, & Baharuddin, 2010). Researchers using basic 3D analyses have recorded aspects of ball speed, joint angle, linear and angular velocities of the tennis serve (Elliott, Marshall, & Noffal, 1996; Lees, 2003; Papadopoulos, Emmanouilidou, & Prassas, 2000; van Gheluwe & Hebbelinkck, 1985), the tennis backhand drive (Elliott, Marsh, & Overheu, 1989a), the tennis forehand drive (Elliott, Marsh, & Overheu, 1989b) and the tennis volley (Elliott, Overheu, & Marsh, 1988). This research on fast shots such as the tennis serve and the badminton smash support the importance of wrist flexion, pronation of the forearm, and rotation of the upper arm (Lees, 2003).

Specifically, some joint movements during the badminton smash showed the importance of wrist flexion, pronation of the forearm, and end of rotation of the upper arm. The forearm rotation and full stretch during shuttlecock contact can result in a great range of motion. It is strongly recommended by coaches in order to provide a maximum forward swinging momentum and to increase the velocity of the shuttlecock while attempting a rapid smash to attack the player's opponent (Elliott, Marshall, & Noffal,

1996; Gowitzke & Waddell, 1979a, 1991; Lees, 2001; Lees, 2003; Sakurai, Ikegami, & Yabe, 2008; Salim, Lim, Salim, & Baharuddin, 2010; Sørensen, de Zee, & Rasmussen, 2010; Tang, Abe, Katoh, & Ae, 1995; Tsai, Chang, & Huang, 1998; Waddell & Gowitzke, 2000). Liu et al (2010) determined that the main contributors to smash efficiency were the gleno-humeral internal rotation (66%), the elbow pronation (17%), and the hand flexion (11%). In addition, the elbow is flexed during the shoulder rotation portion of the stroke (Hussain & Bari, 2011). As well as, Liu et al (2010) reports that the radio-ulnar pronation angle between the racket and the forearm was maximized. Another study with similar results was executed by Chang (2002) showing a wider extension of the upper arm, a sharper angle at elbow joint, and an accelerated wrist angular velocity.

It is understandable that the rotation of arm segments would offer major contributions. Following the kinetic chain, the energy shifts along with and then away from the hand into the racket (Kwan, Andersen, Chen, Tang, & Rasmussen, 2011). Even though these results make the relative importance of individual segment motion worthy and valuable to determine the end-point velocity, some of these results are insufficient as they do not take into account the movement of the thorax and other involved joints.

In other words, in order to achieve a fast shuttlecock speed for a badminton smash, the racket head must accelerate to about 50 m/s before the impact (Jaitner & Gawin, 2010). The initial data reveals that the racket accelerates rapidly just before the time of impact and then decelerates immediately following impact (Koike, & Hashiguchi, 2014; Kwan, Andersen, de Zee, & Rasmussen, 2008; Rasmussen, Kwan, Andersen, & de Zee, 2010). Quantitative video analyses shows that racket tip acceleration is dominated by the

angular accelerations more than the linear due to the arm rotation (Jaitner & Gawin, 2010; Kwan, Andersen, de Zee, & Rasmussen, 2008).

Additionally, skilled subjects with higher acceleration in the sagittal plane performed by an extended arm at impact with a higher flexion in the parallel plane. This demonstrated that, in the parallel plane, the higher peak acceleration coincides with a reduced extension of the arm combined with a pronounced final rotation of the elbow and the shoulder (Jaitner & Gawin, 2010; Kwan, Andersen, de Zee, & Rasmussen, 2008). But, differing performances between skilled and unskilled subjects showed a deceleration or stooping of the lower and upper arm following the stroke. This seems to be closely related to racket acceleration, and should be considered as an influencing factor on the transfer of energy and impulse on the racket (Jaitner & Gawin, 2010). Since arm rotation has, to an extent, been found to influence smash quality, trunk rotation can also be found to influence quality. The following section will discuss impact of trunk rotation.

Trunk Rotation (X-factor)

The above studies provide only a partial perspective in terms of arm movement during badminton smashes. The studies fail to examine the contribution of other bodily aspects, such as trunk, to the final smash performance. The badminton smash is a complex skill that requires many components of movement, and trunk movement, must not be neglected. The popular term, 'X-Factor' was largely applied to golf research and was defined as the relative rotation of shoulders with respect to hips during the golf swing, specifically at the top of backswing (Cheetham, Martin, Mottram, & St Laurent, 2001). From the technical aspect, the large degree X-factor during initial acceleration is better to achieve high momentum storage. During the forward swing to impact, the

players need to rotate fast in order to release enough momentum to effectively swing the racket forward (Yang, 2013). However, trunk movements, such as rotation, are hardly addressed in existing badminton research.

A number of studies on other sports skills, such as golf swing, tennis serve, squash strike, baseball pitch/batting and volley spike, concluded that trunk movement contributed to specific techniques within the respective sport. A quicker and more sequential trunk rotation was found in professional golfers compared to amateur golfers (Chu, Sell, & Lephart, 2010; McTeigue, Lamb, Mottram, & Pirozzolo, 1994; Robinson, 1994; Yontz, 2010; Zheng, Barrentine, Fleisig, & Andrews, 2008). In addition, the degree of X-factor was the most noticeable cinematographic differences between professionals and amateur golfers. The amateurs had less than half of the trunk rotation compared with the professionals executing the golf swing (Pink, Perry, & Jobe, 1993). Thus, X-factor was regarded as a key variable and contributor to increasing club head velocity.

A higher club head velocity at ball contact optimizes the potential for greater driving distance (Pink, Perry, & Jobe, 1993; Quintavalla, 2006; Yontz, 2010). McTeigue et al (1994) discovered that long hitters in golf generated more of the rotation from the X-Factor than the rest of the group by studying 51 PGA (Professional Golfers' Association) tour professionals and 46 senior PGA tour professionals. McTeigue et al (1994) concluded that a large X-factor at the top of backswing was a key point in generating a greater golf club head velocity at impact. In the same study, McTeigue, et al (1994) also found that hips leading the shoulders occurred in the majority of tour players during the downswing (Cheetham, Martin, Mottram, & St Laurent, 2001). There are also several studies which

suggested a scientific order during the golf downswing, including initiating pelvic rotation back towards the impact position, immediately followed by upper torso rotation, and movement of the arms, wrists, hands and club (Hogan, 1985; McTeigue, Lamb, & Mottram, 1994; Myers, Lephart, Tsai, Sell, Smoliga, & Jolly, 2008).

In baseball pitching, Young (2014) indicated that for a typical throwing skill, the trunk segment in pitching plays a vital role to transfer the power generated in the lower extremities up through the arm, stabilizing the body and allowing the arm to undergo a whip-like movement to generate velocity. Based on the results from Young's study, the transverse X-factor accounted for 69% of the variability in ball velocity for the pitchers (Young, 2014). The trunk plays a major role in transferring power from the lower extremities to the upper extremities and creating a large ROM in the X-factor for a high velocity ball release. Young (2014) hypothesizes that, "If a player is unable to utilize the power created in their lower extremity to create trunk rotation, they likely will not be able to throw the ball with a high velocity relative to a player that is able to create the rotation" (p.20). During the pitching process, a 'lag' refers to the motion when the throwing arm increasingly lags behind X-factor during the pitching cycle (Aguinaldo, Buttermore, & Chambers, 2007; Putnam, 1993). This lag further benefits pitching speed by causing external rotation of the shoulder beyond the active ROM, which is achieved by the external rotator muscles and into the passive range (Miyashita, Urabe, Kobayashi, Kokoe, Koshida, Kawamura, & Ida, 2008a, 2008b; Roach & Lieberman, 2014). Although the pitching motion largely consists of trunk movement in the transverse plane unlike other racket sport techniques such as a tennis serve and badminton smash, the contribution of the X-factor to the total body momentum and final ball speed is significant in the

primary plane of movement (Aguinaldo, Buttermore, & Chambers, 2007).

Similarly, in tennis and badminton, almost all strokes are characterized by trunk and upper limb rotations (Nechita, 2009). Using the tennis groundstrokes as an example, trunk and upper limb rotations achieve approximately 120° of the X-factor from the preparatory position to the completion of the backswing (Elliott, 2000; Elliott & Christmass, 1995; Elliott, Marsh, & Overheu, 1989a; Elliott, Marsh, & Overheu, 1989b). Takahashi, Elliott and Noffal (1996) indicated that approximately 30° of X-factor in the tennis forehand has the effect of stretching muscles and associated tissues, which also showed that the upper trunk (shoulder alignment) was rotated more than the lower trunk (hips) at the completion of the backswing (Elliott, 2000). In another study, Bahamonde (2000) reported a large amount of angular momentum in the sagittal plane was majorly generated by the trunk in a tennis serve (Aguinaldo, Buttermore, & Chambers, 2007). In summary, the X-factor during the tennis serve and groundstroke is an integral aspect of the generation of power and transfer of energy up through the kinetic chain from the lower to upper extremities (Ellenbecker & Davies, 2001; Ellenbecker & Roetert, 2004; Roetert & Groppe, 2001)..

Adrian and Enberg (1971) pointed out that as one skill reaches an extremely high level; similar movement patterns might actually replicate the one best skill. In other words, in the waiting stance, knee and hip flexion, spinal rotation, left and right arm action, and even head position are very similar when comparing the badminton smash, tennis serve and volleyball spike. For example, the sequence of movements in the volleyball spike was typically reported as the same as a badminton smash and tennis serve: X-factor, followed by upper arm, forearm and hand movement (Elliott, 2000;

Maxwell, 1982). Therefore, the trunk's role in the hitting movement should be emphasized since roughly 20% of the velocity of the hitting arm originated in the shoulder (Abendroth-Smith & Kras, 1999).

There are relatively few studies focused on what influence the X-factor will have on the speed or quality of the badminton smash. But previous studies in other sports conclude that the trunk is the main source of large momentum generation and is an important influence on the proximal segments in order to transfer power to the distal limbs and resulting in a powerful stroke.

Body Positioning

Some training books point out an earlier contact time and higher contact point will be extremely helpful in accomplishing a higher quality smash (Zhao, 2007). One aspect that could influence the smash quality (e.g. affecting the release speed and release angle of a shuttlecock as well as clearance height) is the body position immediately before a smash (Stage three in the acceleration phase as depicted in Figure 3).

Empirical evidence indicates that body positioning could have a direct influence on the quality of a smash, specifically on smash accuracy. The choice of body positioning and smash opportunity are important aspects of the smash; the closer the player is from the shuttlecock, the less steep the smash will be (Zhao, 2007). Tong (2004) supports this by stating that the power and angle of the smash can affect the speed and trajectory of the shuttlecock. Since body positioning could be closely linked to smash quality in badminton and is hardly addressed in existing research, an understanding of effective smash control will remain incomplete for the skill before the role of body positioning can be revealed. Furthermore, this result should be helpful for training and in games

that utilize strategic plans (Chen, Pan, & Chen, 2009).

The Lack of Previous Scientific Researches

Research on badminton skills is hardly proportional to badminton's popularity. The literature on biomechanical investigations is relatively small. On the contrary, there are many analyses of the physiological and biomechanical factors that characterize racket or club sport in general. Research have been carried out much more on tennis and golf participants (Huynh & Bedford, 2011; Manrique & Gonzalez-Badillo, 2003).

Previous studies are either inadequate (e.g. partial body analysis, qualitative description, or brief conference abstracts) or outdated due to the early and somewhat archaic measuring technologies applied (Brundle, 1963; Gowitzke & Waddell, 1979, 1991; Hussain, Paul, & Bari, 2011; Jack & Adrian, 1979; Kwan, Andersen, de Zee, & Rasmussen, 2008; Poole, 1972; Salim, Lim, Salim, & Baharuddin, 2010; Sørensen, de Zee, & Rasmussen, 2011; Tang, Abe, Katoh, & Ae, 1995; Teu, Kim, Tan, & Fuss, 2005; Tsai, Huang, Lin, Chang, & Cheng, 2001). Consequently, there is a lack of scientific research and limited data on the assessment of which the biomechanical factors are necessary and desirable in badminton as compared to other racket sports (Hussain, Paul, & Bari, 2011; Huynh & Bedford, 2011; Liu, Kim, & Tan, 2010; Teu, Kim, Tan, & Fuss, 2005).

There are numerous factors which could affect the smash quality. Some practical relevant parameters include stance, racket swing speed, striking height, racket angle, racket string tension and grip. Some previous researches indicated that skillful players employed a side stance (Downey, 1984; Zhao, 2007; Zhu, 2013a), then swing the racket in a whip-like movement (Zhu, 2013a; Zhu, Dapena, & Bingham, 2009). Another study

revealed that racket swing speed seemed to depend more on racket mass-distribution rather than on racket mass (Cross & Bower, 2006). Studies related to striking height unveiled that experienced badminton players aimed to hit the shuttlecock at the highest point, as such their arm and racket outstretched when hitting the shuttlecock (I. Hussain & Bari, 2011; C-L Tsai, Yang, Lin, Huang, & Chang, 2006). Rossi et al. used a force-sensor based analysis to suggest that grip force applied on the handle was strongly dependent upon the types of stroke (Rossi, Foissac, Baly, Vigouroux, & Grelot, 2010). Most recently, Zhu initiated scientific studies on the relationship among striking height, racket angle and racket string tension with focus on whether players adjusted the action at their wrist and fingers during impact based on the perception of the affordance of string tension (Zhu, 2013a, 2013b). However, the body positioning and X-factor is hardly addressed in existing badminton research. Actually, a search of literature has shown that there is a lack of study on this fundamental aspect. As such, an understanding of smash control in relation to smashing quality will remain incomplete unless a completion of investigation on this issue takes place.

Therefore, new systematic studies are needed to investigate fundamentals of badminton skills in order to identify factors which are dominant and desirable in the improvement of the badminton smash during learning and training. It is becoming possible to fill the gap with scientific investigations of how to execute a high quality badminton smash by incorporating biomechanical technologies (Liu, Kim, & Tan, 2010; Sørensen, de Zee, & Rasmussen, 2010; Teu, Kim, Tan, & Fuss, 2005).

Chapter Summary

In this chapter, first, the biomechanical analyses in the past, present and future in the field of badminton was described. Secondly, the research on the influential factors of speed and accuracy in the badminton smash and other related sports were classified and summarized. Lastly, several reasons were stated regarding the reason there is limited research on badminton skills.

In the next chapter, the method of Study 1 (body positioning) and Study 2 (trunk rotation) will be described in detail including subjects, protocol, data collection and data analysis.

Chapter 3 Method

This thesis focuses on the study of the badminton forehand overhead smash by using 3D full-body modeling. Through the use of biomechanics and kinematics, the current study explores and determines the major influential parameters in relation to the smash quality. The thesis is divided into Study 1 and Study 2. The subjects were grouped by training effect; novice group (NG) and skilled group (SG).

Subjects

A total of 24 participants were recruited from the University of Lethbridge and local badminton clubs. The NG did not have any formal badminton training after secondary school. For the NG, the researcher invited students from beginner and advanced badminton university classes. Participants were also recruited from undergraduate Kinesiology classes by asking instructors for permission to speak to the class about participating in the study. The researcher provided a brief handout with contact information for students to volunteer for the study. In addition, the researcher asked the course instructors for permission to post a poster on the class websites (see Appendix A).

The SG required a minimum of four years in a competitive badminton training environment. The researcher invited participants from the secondary schools Badminton Championship. A poster was placed in the gymnasium where the tournament took place (see Appendix A). To recruit skilled players, who were not in secondary school, the researcher contacted the Communication Coordinator for provincial badminton association and the poster was emailed to the members. The

researcher also displayed the poster in common areas within the University of Lethbridge advertising the study.

Once a subject, in either group, expressed an interest in participating in the study, the researcher provided an invitation letter (see Appendix B) and consent form (see Appendix C). All participants completed the informed consent documents (see Appendix C). The Ethics Review Committee on Human Experimentation of the Graduate School of Arts and Sciences of the University of Lethbridge approved the experimental project and procedure.

3D Motion Capture and Laboratory Set-up

A 3D Mo-Cap system was used to measure full-body movement using 56 reflective markers – 39 on the body (diameter = 9 mm), 13 on the racket (4 mm tape), 3 on the net (12 mm) and 1 on the shuttlecock (7 mm tape). The laboratory was set up with a ten-camera VICON MX40 motion capture system (VICON Motion Systems Oxford Metrics Ltd., Oxford, England, www.vicon.com) which was used to track the markers at a rate of 200 frames/s. The high frame rate was necessary to capture the majority of the high-speed racket movement from the position of holding the racket to the smashing motion. This Mo-Cap system quantitatively determines the entire body kinematic characteristics and records the 3D kinematics data during each smashing movement. Calibration residuals were determined in accordance with VICON's guidelines and yielded positional data accurate within 1 mm.

It is worthy to mention that Mo-Cap technology permits considerable freedom of movement for the participant without negatively influencing the accuracy of data.

Taking advantage of this, the researcher placed no restrictions on the participants' movements within the capture volume in an effort to preserve their normal style.

A half standard badminton court (6.7m in length, 6.0 m in width and 1.55m in net height) was set up in order to mimic a real badminton play environment in both tests of static and dynamic shuttlecock (BWF, 2014). The static shuttlecock test required the subjects to execute a smash with a static shuttlecock hanging from the ceiling (Figure 5, left). The dynamic shuttlecock test required the subjects to execute a smash with a dynamic shuttlecock served from the other side of the net (Figure 5, right). A subjects' smashing area (S1) in the right rear court (~4 m far away from net and ~1.3m from the right side line for single) was set for the static shuttlecock test as well as the dynamic one. The setup is illustrated in Figure 5, which also shows a 3D computer reconstruction of the skill using collected marker positions.

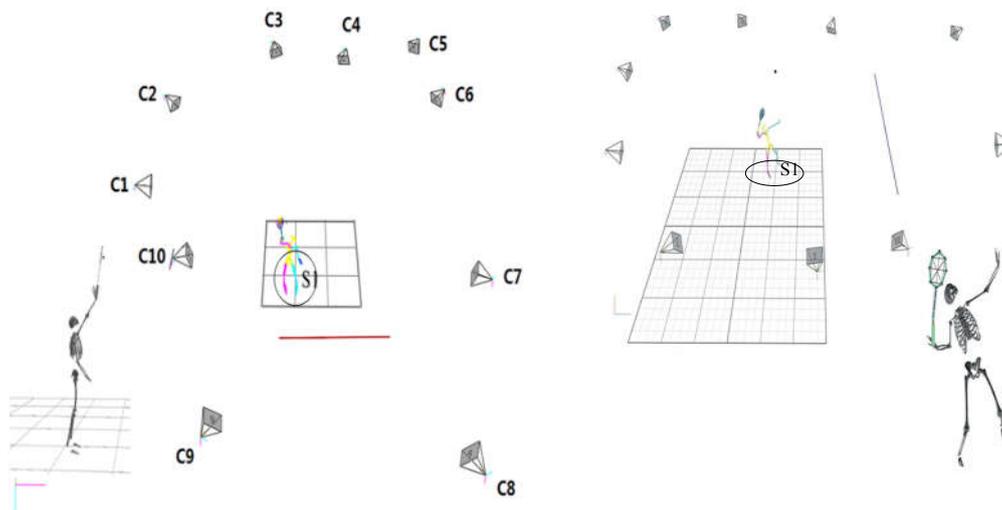


Figure 5. The set-up of synchronized 3D cameras (C1-C10) with subject and equipment. A wire frame mesh reproduction of a static shuttlecock (left) and dynamic one (right).

Table 1. *The Placement of Spherical Markers on the Body*

Segment	Marker	Landmark
Head (Left and Right)	FHD	Temples
	BHD	Parietal Bone
Upper Trunk	C7	C7
	T10	T10
	STRN	Sternal Notch
	CLAV	Xiphoid Process
	RBAK	Right Back
	SHO	Acromion Processes
Arm (Left and Right)	UPA	Upper Arm
	ELB	Lateral Epicondyles of The Humerous
	FRM	Lower Arm
	WRA	Styloid Processes of The Radius
	WRB	Styloid Processes of The Ulna
	FIN	Third Metacarpophalangeal Joints
	Lower Torso /Pelvis (Left and Right)	ASI
PSI		Posterior Superior Iliac Crest
Leg (Left and Right)	THI	Upper Leg/Thigh
	KNE	Lateral Condyle of The Tibia
	TIB	Tibia
	ANK	Lateral Malleolus of The Fibula
	HEE	Calcaneal Tuberosity
	TOE	Head of Halluces

In addition, an experimental YONEX ARCSABER 001 series racket (weight: 85-89 g, length: 684mm, material: graphite) was outfitted with 13 reflective adhesive markers as shown in Figure 7. Two of the reflective adhesive markers were located on the handle wherein one spherical marker was fixed at the base, and 11 reflective adhesive tapes were placed on the racket frame - three on the shaft and eight on the head. The racket was modeled as a flexible, multi-body system where the handle was considered a

rigid segment. A universal joint between the handle and shaft allowed for transverse and lateral movement, approximating transverse and lateral deflection. The system also tracked the badminton shuttlecock using reflective adhesive tape, since ascertaining shuttlecock release speed can be difficult. Standard YONEX shuttlecocks (weight: 4.74-5.50 g) were used in this project. One piece of reflective adhesive tape was placed on the cork of the shuttlecock and three spherical markers were placed on the net. For this experiment, all participants used the same equipment to avoid potentially confounding factors from racket and shuttlecock differences.

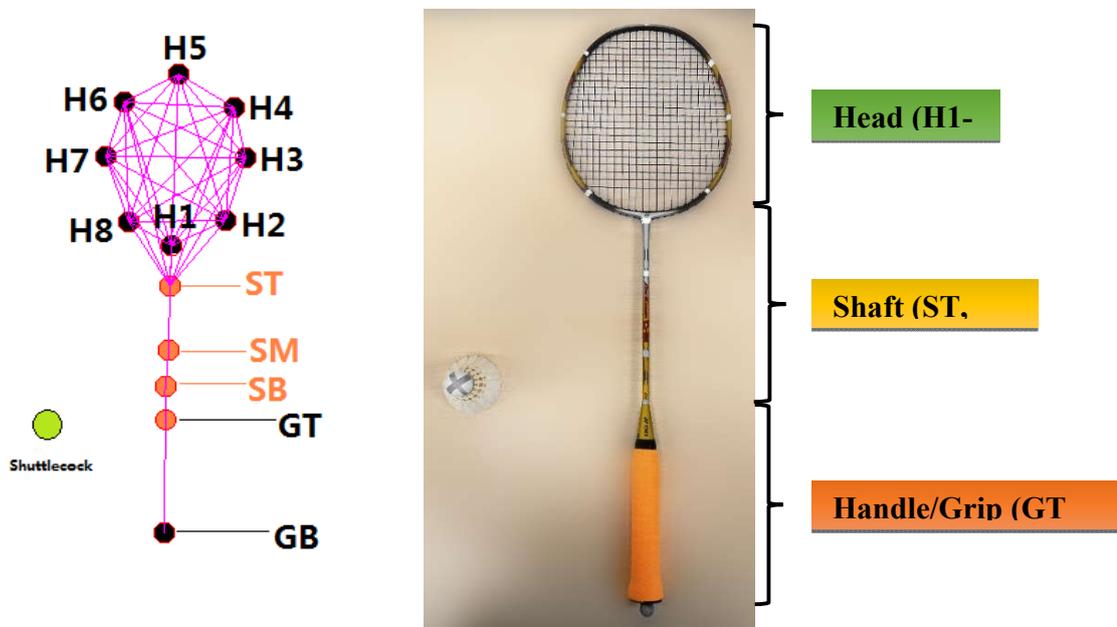


Figure 7. The placement of reflective spherical markers on racket and shuttlecock. Total 14 reflective adhesive markers: 1) racket: one 7 mm marker at the handle base; 12 tapes (three one the shaft and eight on the head); 2) shuttlecock: one tape on the cork.

Data collection

All the data collection was done by the researchers in the Biomechanics Lab in the Department of Kinesiology and Physical Education at the University of Lethbridge. Before the test, the calibration of the VICON system and measurements of all participants' anthropometry was done by the researcher. Anthropometric

measurements were used to establish the individual modeling for post-data output analysis.

For quantifying the influence of positioning, a static shuttlecock and dynamic shuttlecock were tested. The smashes toward the static shuttlecock were performed in three different body positioning (Figure 8). A self-selected comfort position was considered to be Static-Middle (SM) where the shuttlecock contact point was in front of the body ($D_{a-p} > 0$). Static-Front (SF) in which the contact point was right above the head ($D_{a-p} < 0$) was calculated by using 20% of his/her body height and moving that far in front of the selected middle positioning. The third position was Static-Rear (SR) where the shuttlecock contact point was in front of the body ($D_{a-p} > 0$) which was calculated by standing 20% of his/her body height behind the selected middle position. The anterior-posterior distance (D_{a-p}) between the center of gravity (COG) and the shuttlecock was selected to quantify the difference among body positioning (see Figure 8). The 15-segment biomechanical model used in the experiment provided the relative data and accurately determined the D_{a-p} .

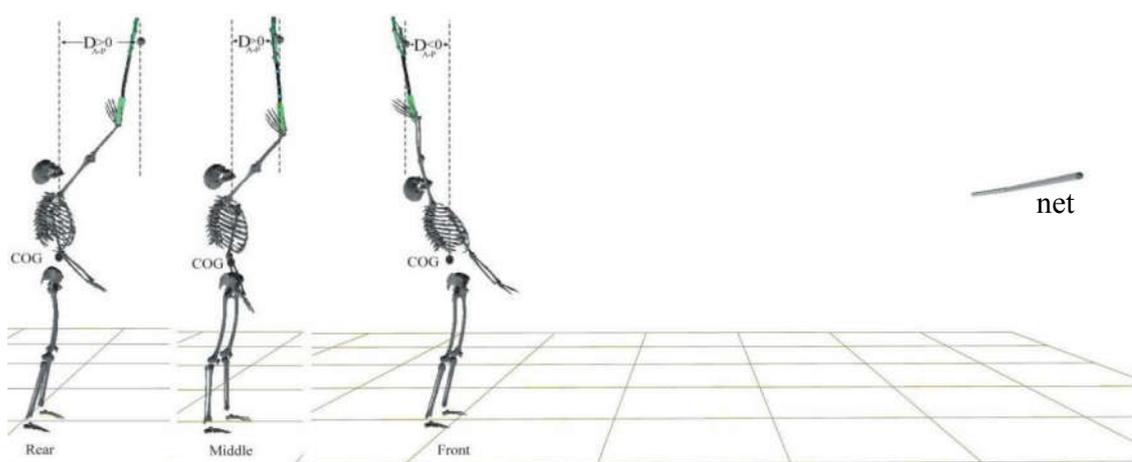


Figure 8. The three static body positions tested in the study (left: Static-Rear; middle: Static-Middle; right: Static-Front). D_{a-p} -The anterior-posterior distance between the COG and shuttlecock.

The reasons for choosing to study a standing smash are 1) to standardize the test and 2) to minimize the effect of confounding variables (e.g. jumping). The standardization of body positioning using body height is critical because parameters influencing human motor control, such as upper limb length, lower limb lengths and stride length, are highly correlated to body height (Shan & Bohn, 2003). The use of 20% of the body height to determine the other two body positioning was decided by a pre-test of six subjects, which conducted in both static and dynamic shuttle tests was used for standardization of test condition.

The static shuttlecock test required the shuttlecock to be hung vertically by a string from the ceiling and 4 m from the net. This placement is selected because most of the smashes in the real game are performed in middle/rear court. Participants selected the shuttlecock height because of different preferences in which they felt most comfortable.

After researcher introduced test procedures, each subject did an individualized warm-up. After the warm-up, each subject completed a total of 20 smashes with the static shuttlecock (five smashes for each body positioning) and five smashes with a dynamic shuttlecock. It is important to note that in the tests with the static shuttlecock, the body positioning remained unchanged once the location of each positioning was established. After the testing of the static shuttlecock smashes were completed, the testing of the dynamic shuttlecock began. The data collection of a smash in a dynamic environment can be used to determine the most similar relationship between the three static body positions in the two subject groups. This can assist to determine which body positioning is the better choice for training practice.

In order to provide a stable and consistent serve for the dynamic shuttlecock test, a highly trained person was chosen to hit a high serve, or in badminton terms, ‘lift’ the shuttlecock in the air for each subject. Subjects were able to jump, stand or strike the shuttlecock to their liking in order to produce their hardest smash in the dynamic smash test. No other limits were imposed.

Since a smash results in power/speed in the studied badminton skill, the simple advice given to the subjects during both static and dynamic shuttlecock tests was “to smash/hit the shuttlecock as hard as you can”. Under this simplified demand, the subjects employed their normal “motor control style” to perform the skill. Therefore, the collected data was used to reveal the relationship between smash quality and training level.

A successful smash for the static shuttlecock test and the dynamic shuttlecock test was made when the shuttlecock was struck, went over the net and landed on the other side of the net. Twelve out of 20 successful smashes for each subject were selected for later analysis in Study 1; nine static shuttlecock smashes (three for each body positioning) and three dynamic shuttlecock smashes. The data collection in Study 2 only used the raw data collected from the SR body position (Figure 8). Three successful smashes for each subject in SR were selected for analysis in Study 2.

Parameters

The parameters used in Study 1 and 2 were divided into two categories: smash quality parameters and movement parameters. The smash quality parameters include shuttlecock release speed (V_{release}), shuttlecock release angle (α_{release}) and clearance height (H_c). The movement parameters included trunk rotation (X-factor) and ROM of shoulder, elbow, wrist and pectoralis major (P.M.).

Parameters in Study 1

In Study 1, the three smash quality parameters were selected to determine the Influence of training effect on the badminton smash quality. Empirical evidence indicate that a good attack should generate a release shuttlecock toward the opponent's court as fast as possible, as steep downward as possible and as close over the net as possible. Therefore, these three key smash quality parameters: shuttlecock release speed (V_{release}), shuttlecock release angle (α_{release}) and shuttlecock clearance height (H_c) are directly related to the quality of a smash.

Smash quality parameters:

1. Shuttlecock release speed (V_{release})

The V_{release} is the magnitude of shuttlecock' velocity (the rate of change of shuttlecock's position) after contact (Figure 9). Shuttlecock release speed is a major parameter that is able to directly reflect the athlete's technical level. When the shuttlecock travels at high velocity towards an opponent, the speed of the shuttlecock often challenges the opponent's reaction time. If the opponent has insufficient time to defend, the participant can score directly or get new opportunity to win in the next rally by smashing again.

2. Shuttlecock release angle (α_{release})

The shuttlecock release angle is decided by the angle between the direction of shuttlecock flight and horizontal plane (Figure 9). A positive value will be used for upward flight direction of the shuttlecock and a negative value will be used for downward flight direction of the shuttlecock. Thus, choosing both the α_{release} and H_c as two parameters will be reasonable and effective to show their close and

complementary relationship, but will also make the evaluation criteria of smash quality more comprehensive.

3. Clearance height (H_c)

The H_c is determined by the vertical distance between the shuttlecock and the top of the net at the movement when the shuttlecock passes above the net (Figure 9). The definition of a good quality badminton smash is one that is hit fast, downward with force, and at a steep angle. The H_c is a way to understand the relationship between the smash performance and training effect, because a better smash quality has shorter H_c . With a smaller H_c it can be assumed that the opponent will have a more difficult time reacting to the smash and in turn increase the chances of gaining a point or receiving possession for the offensive player.

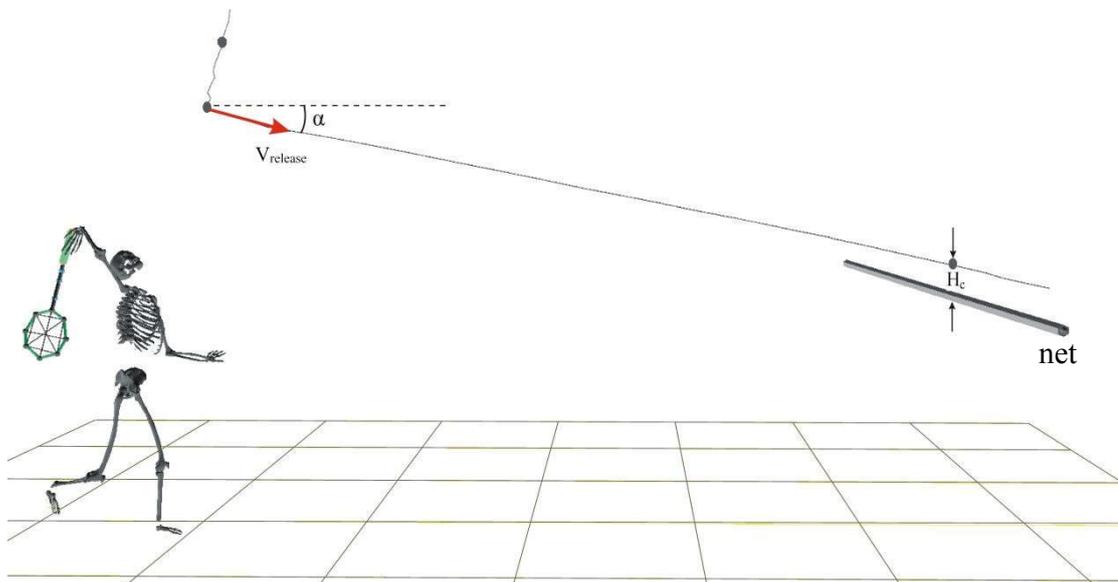


Figure 9. Parameters of the smash quality. V_{release} – release speed; α_{release} – release angle; and H_c – clearance height.

Parameters in Study 2

Both smash quality parameters (as mentioned above) and movement parameters were used in Study 2. The data represented movement in the SR body position. The

definitions of the movement parameters are interpreted as follows:

1. Trunk Rotation (X-factor)

This study utilized advanced lab equipment and a creative experimental design to Collect 3D motion capture data with full-body movement, including the segment of the trunk. The rationale for studying the X-factor was from the observation of the real game, which demonstrates a common movement among badminton athletes. Firstly, they turn their bodies sideways toward their dominant hand direction, and then they turn back to smash the shuttlecock. Secondly, the VICON motion capture systems further displayed that, when the body turned back, the shoulder movement was delayed for a short period after the hip turned. According to these two phenomena, trunk rotation was quantified using a defined angle between a line connecting the anterior superior iliac crest markers in the pelvic area (hip line) and a line connecting the acromion markers in the upper torso area (shoulder line). Therefore, calculating the angle between these two lines projected into the horizontal plane created the X-factor (Meister, Ladd, Butler, Zhao, Rogers, Ray, & Rose, 2011). Figure 10 shows the trunk rotation angle (α).

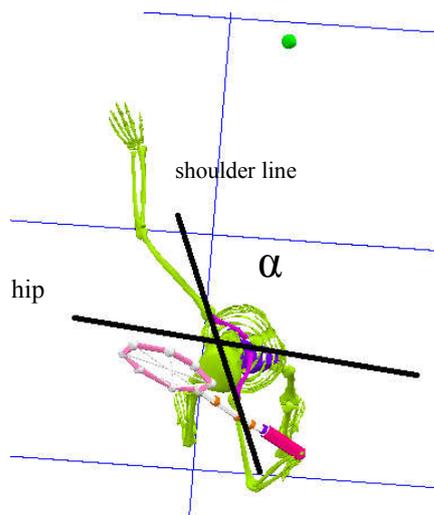


Figure 10. X-factor. The angle (α) of trunk rotation

2. The ROM of Shoulder, Elbow, Wrist and the Pectoralis Major

ROM is how far the person's joints can be moved in different directions. The movement of each joint, therefore, reflects a person's range of motion, capability and training. Movements included in the ROM are flexion/extension, abduction/adduction, rotation for the shoulder and flexion/extension for elbow and wrist. The pectoralis major (P.M.) has three actions, which are primarily responsible for movement of the shoulder joint. The P.M. is also responsible for keeping the arm attached to the trunk of the body (Saladin, 2010). The four actions are: 1) flexion of the humerus (throwing a ball side-arm); 2) adduction of the humerus (flapping the arms); 3) rotation of the humerus (arm-wrestling) (Hamilton, Weimar, & Luttgens, 2002). The P.M. reflects the movement of the shoulder joint from the respect of muscular contraction.

Statistical Analysis

Based on pervious researches, a sample size of 24 subjects has a statistical power of over 90% when looking at comparisons, standard deviation and significance levels (Dixon & Massey, 1969; Wilkinson & Strkalj, 2005). The raw data was exported by VICON Mo-Cap system and was processed by a five-point smoothing filter. The raw data supplied primary information such as marker positions in X, Y and Z axis, the degree of each joint angle and major muscle length for building the 15-segement biomechanical model (Figure 5. The model segments were identified as follows: head, upper trunk, lower trunk, upper arms, lower arms, hands, thighs, shanks and feet. The 15-segment biomechanical model used in the experiment could determine most motor control skills in sports and provide the relative data and

accurately determine the center of gravity. In such a biomechanical model, inertial characteristics of the body are estimated using anthropometric norms found through statistical studies (Shan & Bohn, 2003). The analysis of General Liner Model (GLM) with three times value for each subject was applied to obtain the results within-group. The GLM is a generalization of multiple linear regression model to the case of more than one dependent variable (Christensen, 2002). The T-test with average value in each subject was used to gain the results between-groups. All methods of data analysis such as General Liner Model (GLM), t-test and the Pearson correlation coefficient as well as descriptive statistics such as averages and standard deviation were derived using SPSS Statistics V 22.0 (SPSS Inc., Chicago, IL) for Study 1 or Study 2. Statistical significance is defined as $p < 0.05$ for both Study 1 and 2.

Statistical Analysis in Study 1

The aim of Study 1 was twofold. The first objective in Study 1 was to quantify the relationship between body positioning and smash quality. For quantifying this relationship between body positioning and smash quality to answer the first research purpose, several analyses were applied. Firstly, the data assessing the COG and shuttlecock (D_{a-p}) was determined using the 15-segment biomechanical model, which supplies a mathematical way for quantifying the body positioning related to the shuttlecock (Figure 8). The GLM (repeated measures) was applied to analyze within-group significances influences related to positioning (i.e. Dynamic, SF, SM and SR) and training effect (NG and SG) on smash quality parameters. For showing significant changes, indications of an 'increase' (percentage change) of average value in D_{a-p} was calculated using the formula $|(large\ value - small\ value) / small\ value|$. This formula

was used for determining the percentage differences of D_{a-p} between-groups.

The second aim of Study 1 was to reveal the influence of training effect by comparing the NG and SG. A between-groups comparison of each smash quality parameters in Dynamic, SF, SM and SR was applied using t-tests with a significances level of $p < 0.05$.

Statistical analysis in Study 2

The aim of Study 2 was to examine and compare differences in the body movement parameters (X-factor and ROM of upper limb movement) in relation to smash quality between the NG and the SG in SR body position ($p < 0.05$). T-tests were applied to contrast the differences between the NG and SG of each body movement parameter. In addition, a correlation analysis was calculated within-groups between the X-factor and V_{release} , X-factor and α_{release} , X-factor and H_c , X-factor and the ROM of shoulder (flexion/extension, abduction/adduction, and twist), elbow (flexion/extension) and wrist (flexion/extension), and X-factor and P.M. using the Pearson correlation coefficient (Lawrence & Lin, 1989; Stigler, 1989).

A second aim of Study 2 was to describe the kinematic characteristics of the forehand overhead smash based on the joint angle change over time. The description of two characteristics in terms of each movement parameter were summarized in the results section based on the performance of the SG as collected in the lab setting.

Chapter Summary

In this chapter, the subjects' recruitment, the laboratory set up and data collection /analysis were also discussed. Through statistical analysis, the quantification of smash quality parameters (V_{release} , α_{release} and H_c), and movement

parameters (X-factor and ROM of shoulder, elbow, wrist and P.M.) was provided. The smash quality with a static shuttlecock in three different body positions and smash quality with a dynamic shuttlecock were analyzed in Study 1. Both smash quality and movement parameters only in the SR body position were analyzed in Study 2. The performance between the NG and SG in both studies was analyzed to determine the influence of training effect on body positioning and smash quality. Based on the joint angle change over time, two characteristics about body segment movement of each movement parameter were summarized in the results section. The results of those investigation are presented in the next chapter.

Chapter 4 Results

A 3D full-body Mo-cap system captured data on the badminton forehand overhead smash. Two studies determined major influential parameters in relation to the smash quality, and compared results between a NG and a SG . The results of the two studies is presented in Chapter 4.

Subjects

Subjects ranged from ages 20-35 years. Of the 24 participants, 10 were in the NG, while 14 were in the SG. The subjects' demographic information is summarized in Table 2. Specific information on each subject is found in Appendix D.

Height and weight of each subject was measured by the researcher. There were substantial body weight and height variations between the two groups ($P= 0.0076$ and $P= 0.014$).

The sample was comprised of 7 females and 17 males. To identify the influence of gender, the GLM analysis was performed. The results of GLM analysis proved that there is no significant influence of gender on results (within-subjects: $p=.884$ in D_{a-p} ; $p=.160$ in $V_{release}$; $p=.194$ in $\alpha_{release}$; $p=.401$ in H_c ; $p=.244$ in X-factor; between-subjects: $p=.887$ in D_{a-p} ; $p<0.05$ in $V_{release}$; $p=.187$ in $\alpha_{release}$; $p=.354$ in H_c ; $p=.363$ in X-factor). Therefore, the mixed gender groups were used in Study 1 and 2 to verify the effects of body positioning, X-factor, ROM and training effect.

Table 2. *Age, Body Height, Weight and Training Period*

Group	n	Age (yrs.)	Height (m)	Weight (kg)	Training Period (yrs.)	Gender	
						Female	Male
NG	10	24.3±4.7	1.71±0.07	62.05±9.24	0	6	4
SG	14	23.2±2.8	1.77±0.05	71.56±7.73	6.6±3.1	1	13

Results of Study 1

The first objective in Study 1 was to quantify the relationship between body positioning and smash quality. In order to investigate the influence of body positioning, the D_{a-p} (means \pm SD) at the movement before contact the shuttlecock (the stage three in the acceleration phase) was calculated in the four selected positions for the two tested groups (Table 3). The GLM (repeated measures) analyzed within-group significance in terms of D_{a-p} Dynamic (Dyn) and D_{a-p} between SF/SM/SR. This determined the percentage differences of D_{a-p} between-groups. Results from the GLM analysis were applied to compared the Dyn with SF/SM/SR and revealed that for both NG and SG, there were highly significant differences between Dyn and SF, as well as Dyn and SR ($p < 0.01$). There was no significant difference for both groups between Dyn and SM ($p > 0.05$). In addition, the D_{a-p} in Dyn for NG (0.45 m) and SG (0.46 m) was between the D_{a-p} in SM and SR.

Table 3. Comparison of D_{a-p} between Dynamic (Dyn) and the Three Static Positions

	Dyn	D_{a-p} (m)		
		SF	SM	SR
NG	0.45 \pm 0.22	- 0.08 \pm 0.11**	0.41 \pm 0.11	0.67 \pm 0.09**
SG	0.46 \pm 0.11	- 0.00 \pm 0.14**	0.42 \pm 0.08	0.70 \pm 0.10**
Difference	2.22%	1%	2.43%	4.48%

* – significant ($p < 0.05$), ** – highly significant ($p < 0.01$)

Distinguishable kinematic data (means \pm SD) of smash quality parameters in Dyn and static body positioning in both NG and SG were displayed in Table 4. The SG have a significantly faster $V_{release}$ in each positioning when compared to the NG as shown in Table 4. The $\alpha_{release}$ in the SG in each positioning were sharper than that in the NG (-

3.75°). The H_c of the SG in each positioning were a smaller clearance height than the NG, with no more than 0.6 m to the net.

GLM (respective measures) was used to reveal the significance of each of the smash quality parameters among body positioning parameters in the SG and NG respectively. For the NG, the following characteristics of the three key smash quality parameters in static body positioning parameters were revealed: 1) V_{release} increases gradually from SF, SM to SR, but the increase was not significant ($p>0.05$) (Table 4 and 5); 2) The opposite trend as V_{release} was found for α_{release} which was significant between SF and SR ($P<0.05$) (Table 4 and 5); 3) H_c was found to have the same decreased tendency as α_{release} . Similar trends were revealed by the data of the SG: 1) V_{release} increases gradually from SF, SM to SR with no significances ($p>0.05$) (Table 4 and 5); 2) α_{release} and H_c decreased from SF, SM to SR continuously; but, the significances were only found between SF and SR for both α_{release} ($p<0.05$) and H_c ($p<0.01$) (Table 4 and 5).

Table 4. *Kinematic Data of Smash Quality Parameters (negative α : downward)*

Group	Position	Smash Quality		
		V_{release} (m/s)	α_{release} (°)	H_c (m)
NG	Dyn	36.65±8.47	8.8±11.8	1.16±0.86
	SF	30.18±8.15	7.1±8.1	1.24±0.68
	SM	32.69±7.48	1.9±8.9	0.86±0.50
	SR	34.64±8.88	- 3.7±5.2	0.49±0.25
SG	Dyn	58.86±9.59	- 9.1±4.1	0.12±0.28
	SF	41.80±9.85	- 7.4±9.0	0.55±0.58
	SM	44.15±9.47	- 11.1±9.7	0.43±0.67
	SR	45.31±7.81	- 14.8±8.0	0.08±0.49

Table 5. *The Significant Influences of Static Body Positioning*

		$V_{\text{release}}(\text{m/s})$		$\alpha_{\text{release}} (\text{°})$		$H_c (\text{m})$	
		SF	SM	S F	SM	SF	SM
NG	SM	ns		ns		ns	
	SR	ns	ns	*	ns	*	ns
SG	SM	ns		ns		ns	
	SR	ns	ns	*	ns	**	ns

ns – no significant, * – significant ($p < 0.05$), ** – highly significant ($p < 0.01$)

Thirdly, the GLM (respective measures) was applied to reveal the significance of smash quality parameters between Dyn and the static positions in the SG and NG respectively. Comparison between NG dynamic and NG static shuttlecock found that the SR would create a V_{release} close to the Dyn (Table 4 and 6). The SR improved the α_{release} and H_c significantly ($p < 0.05$), better than the dynamic shuttlecock (Table 4 and 6). For the SG, the V_{release} generated by the dynamic posture was significantly faster than those of static postures ($p < 0.01$) (Table 4 and 6); and 4). Smash quality was close to the dynamic posture in the SM position for α_{release} and the SR position for H_c (Table 4 and 6).

Table 6. *Smash Quality Parameters Compared between Dynamic and Static Shuttlecock*

		V_{release}	$\alpha_{\text{release}} (\text{°})$	$H_c (\text{m})$
		(m/s)	Dyn	Dyn
NG	SF	ns	ns	ns
	SM	ns	ns	ns
	SR	ns	*	*
SG	SF	**	ns	**
	SM	**	ns	*
	SR	**	ns	ns

ns – no significant, * – significant ($p < 0.05$), ** – highly significant ($p < 0.01$)

The second aim of Study 1 was to reveal the influence of training effect by comparing the NG and SG. A between-groups comparison of each smash quality parameters in Dyn, SF, SM and SR was applied using t-tests with a significance level of $p < 0.05$. When comparing the smash quality using the three key parameters (V_{release} , α_{release} and H_c), there were highly significant differences between the two groups for both Dyn and static body positions ($p < 0.01$) (Table 7).

Table 7. *The Influence of Training effect on the Smash Quality*

		Smash Quality		
Position		V_{release} (m/s)	α_{release} (°)	H_c (m)
NG vs. SG	Dyn	**	**	**
	SF	**	**	**
	SM	**	**	**
	SR	**	**	**

** – highly significant ($p < 0.01$)

Two hypotheses were presented for Study 1. The hypothesis that body positioning would have a direct influence on the quality of a smash, especially on α_{release} and H_c was supported. Secondly, the hypothesis that training effect would highly influence the smash quality as well as have close relationship with the choice of body positioning was also supported.

Results of Study 2

The first aim of the Study 2 was to examine and compare differences in the body movement parameters (X-factor and ROM of upper limb movement) in relation to smash quality between the NG and the SG in SR body position ($p < 0.05$). The results of the distinguishable kinematic data (means \pm SD) of X-factor and ROM of upper limb movement are shown in Table 8. T-test displayed a significant difference in the

degree of X-factor between the NG (36.7°) and SG (46.9°) ($P < 0.01$).

The ROM of shoulder for both groups remained under a 55° rotation for NG and 120° rotation for SG, 30° flexion/extension for both groups, and 20° abduction/adduction for both during the smash process. For the ROM of shoulder rotation, there were significant differences ($p < 0.01$) between the NG (47.7°) and SG (107.5°) which was almost twice the value in NG. T-test showed no significant shoulder ROM of flexion/extension and abduction/adduction differences ($p = .578$ and $p = .214$) between the two groups. Comparing elbow and wrist flexion/extension between the two groups, both groups had significant differences during smash ($p < 0.01$). The SG had better elbow and wrist flexion/extension control than those in NG (70.6° and 54.0°, respectively). The P.M. in Table 8 represents the percentage between the P.M. length increases compared to its original length in a static situation. The percentage of 41.3 in SG was larger than the percentage of 29.2 in NG ($p < 0.01$).

Table 8. *Kinematic Data Comparison between NG and SG in the Movement Parameters Flex/Ext - Flexion/Extension; Abd/Add – Abduction/Adduction*

		NG	SG	p
	X-factor	36.7±8.2	46.9±11.2	**
ROM	Shoulder Flex/Ext	20.9±12.9	25.8±16.1	ns
	Shoulder Abd/Add	13.8±6.4	14.6±6.0	ns
	Shoulder Rotation	47.7±20.4	107.5±30.9	**
	Elbow Flex/Ext	54.0±22.9	70.6±9.1	**
	Wrist Flex/Ext	31.7±23.7	85.9±50.4	**
	P.M.	29.2%±10.9%	41.3%±10.9%	**

ns – no significant, **– highly significant ($p < 0.01$)

In addition, the Pearson correlation analysis was calculated within-groups between the X-factor and V_{release} , X-factor and α_{release} , X-factor and H_c , X-factor and the

ROM of shoulder (flexion/extension, abduction/adduction, and twist), elbow (flexion/extension) and wrist (flexion/extension), and X-factor and P.M. in order to determine the relationship between X-factor and other selected parameters. The results of a correlational statistical analysis between selected variables are displayed in Table 9.

Significant positive correlations were found in V_{release} ($r=0.60$, $p\leq 0.01$), and shoulder rotation ($r=.60$, $p=0.013$) of the SG. Negative correlations were found between X-factor and α_{release} in SG, X-factor and H_c in NG, X-factor and shoulder flexion/extension and abduction/adduction in NG, X-factor and shoulder rotation in NG, X-factor and elbow flexion/extension in both groups and X-factor and wrist flexion/extension in SG

Table 9. Summary of the Correlational Analysis between X-factor and Selected Parameters in the SG and NG

		NG	SG	
Smash Quality	V_{release}	0.09	0.60**	
	H_c	-0.04	0.15	
	α_{release}	0.26	-0.1	
ROM	Shoulder	Flex/Ext	-0.12	0.23
		Abd/Add	-0.39	0.17
		Rotation	-0.19	0.60*
	Elbow	Flex/Ext	-0.44	-0.02
		Wrist	Flex/Ext	0.24
	P.M.		0.04	0.22

* – significant ($p<0.05$), ** – highly significant ($p<0.01$)

A second aim of Study 2 described the kinematic characteristics of the forehand overhead smash based on the joint angle change over time. The results appear in Figure 11. The smash performance in SG had the following characteristics.

- 1) At the acceleration from 0s to 0.75s, an increase in the angle of the X-factor was formed by the upper torso rotating away from the hitting direction.

During the same time period, rotation was increased in the shoulder by way of external extension and adduction, elbow flexion and wrist extension.

- 2) A whip-like movement was performed by the SG. During the acceleration phase from 0.75s to 0.9s, The highlight positions in the Figure 11 showed that the X-factor and shoulder movement as seen the first moving group of joint/segment (MG1) accelerated to swing forward while the elbow and wrist as seen the second moving group of joint/segment (MG2) completed a reverse rotation with extension in both elbow and wrist. As a result, a ‘lag’ took place resulting in a hip-shoulder separation.

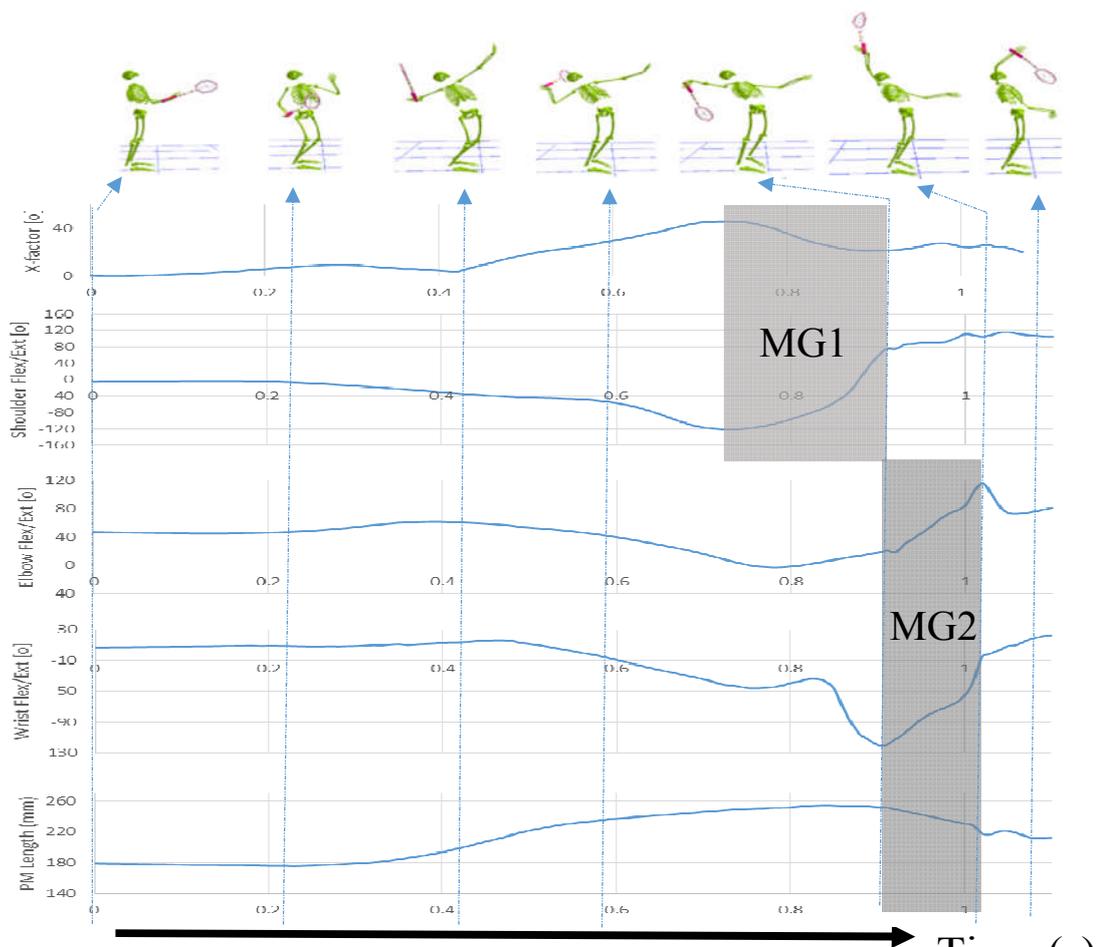


Figure 11. Body segment movement in SG. The changing trend of movement parameters and smash performance of SG in lab setting.

Two hypotheses were presented for Study 2. The hypothesis that the execution of X-factor would highly influence the final quality in the aspect of V_{release} and the formation of the whip-like movement was partially supported. Secondly, the hypothesis that training effect would highly influence the smash quality as well as have close relationship the execution of X-factor was supported.

Chapter Summary

In this chapter, the results in Study 1 and Study 2 have been presented. In the Study 1, for both NG and SG, the D_{a-p} in Dyn were between the D_{a-p} in the SM and the SR. The V_{release} increased gradually from SF, SM to SR. There was a continual decrease in α_{release} and H_c from the SF, SM to SR body position. Comparison between dynamic and static shuttlecock found that the NG in a SR position would create a V_{release} close to results from the Dyn and a better α_{release} and H_c than in the Dyn. In the SG, the V_{release} generated by the Dyn was significantly faster than those of static positioning. In addition, the position of the SG that had a similar smash quality to the dynamic smash was the SM for α_{release} and SR for H_c .

The results of Study 2 demonstrated that SG had a larger degree of X-factor and the ROM of shoulder (flexion/extension, abduction/adduction and rotation), elbow (flexion/extension), wrist (flexion/extension) and P.M. than the NG. Furthermore, a positive high correlation existed between X-factor and V_{release} as well as X-factor and shoulder rotation was found in the SG. The discussion of these results for Study 1 and 2 will be presented in the next chapter.

Chapter 5 Discussion

In this chapter, the results in Study 1 and 2 will be discussed. Furthermore, the discussion will demonstrate how the results supported or partially supported the three hypotheses.

Study 1

The aim of Study 1 was, first to initiate a 3D full-body motion analysis to quantify the relationship between body positioning and smash quality and, second to reveal the influence of training effect on smash quality. The results of smash quality (Table 4 and 7) indicated that the SG had a much higher smash quality as demonstrated by a more powerful V_{release} , a deeper downward α_{release} and smaller H_c than that in the NG. According to empirical evidence, smash quality is of paramount significance when evaluating the badminton forehand overhead smash and it represents one's skill level (REFERENCE this empirical evidence). The results found in Table 4 and Table 7, therefore reflect that training effect was a major contributor to the smash quality between NG and SG.

The results revealed that positioning (i.e. SF, SM and SR) has no significant influence on power generation (Table 5, represented by V_{release}). The current study found that body position influenced the α_{release} and H_c of a smash. The result of smashes towards a static shuttlecock revealed that positioning had a significant influence on the α_{release} for both groups between the SF and SR (Table 5). Generally speaking, a position of a half meter behind the shuttlecock or more generated a better attack angle for a smash, i.e. a steeper downward angle (Table 3 and 4). Zhu (2013a), using a dynamic situation, confirmed that the higher smash quality is typically

associated with a more downward angle. The SG consistently produced a downward angled shuttlecock, however, the NG only created a downward shuttlecock in the SR position (Table 4). For the rest of the positions, the NG completed smashes with an upward α_{release} . Since the test conditions were identical for both groups, the results suggests that body positioning plays a role for beginners in learning a proper smash α_{release} .

As anticipated, training effect has significant effect on the improvement of smash quality. Beginners have difficulty producing a powerful and accurate smash due to power and accuracy tradeoffs (Magill, 2001). For instance, the NG in the dynamic shuttlecock had the highest V_{release} but the worst-attack α_{release} (Table 4). Contrary to the SG's downward smashes towards the static shuttlecock, the NG moved the racket face for shuttlecock contact in either a horizontal or upward motion to assure a hit. This resulted in a flat or upward release of the shuttlecock by the NG. Such difference in the racket movement between the two groups is attributed to training effect.

The impact of positioning and training effect on H_c are observable between the two groups (Table 4). Regardless of the training effect, both groups show a continuous improvement (i.e. the smaller the H_c is, the higher the smash quality) in the H_c when smashing from SF, SM to SR. The best positioning for a low H_c is the SR. When considering the static and dynamic trials together, the performances of the each group demonstrated opposite trends: for the NG, the smash towards the dynamic shuttlecock has a similar quality as the SF; while, for the SG the quality of the dynamic one is comparable to the SR. In conjunction with the discussion of α_{release} , the results suggest that the body positioning toward the SR would increase the smash quality in both

α_{release} and H_c .

Summarizing the discussion above, the best positioning for smashing would be between SM and SR. The results appear to recommend that, in general, one could use a static comfortable selection (i.e. SM) for learning to smash. Such a selection is easily done in practice. On the other hand, judging from the smash quality (i.e. α_{release} and H_c), positioning the body 0.35 m (20% of body height) behind one's static comfortable selection would be better than SM. In this case, based on an anthropometrical study (Shan & Bohn, 2003), a learner should step back by about one and half feet (the average foot length of a 1.71 m person is 24.5 cm) from the static comfortable selection (SM).

Interestingly, both groups showed a higher smash quality in the SM and SR in which the shuttlecock contact point was in front of body ($D_{a-p}>0$) rather than the smash quality in the SF in which the shuttlecock contact point was right above the head ($D_{a-p}<0$). When comparing the relationship between body positioning and shuttlecock in the real game, there were several disadvantages revealed when smashing in the SF.

Firstly, if a smash takes place in SF, the players' eyes have to look upward so they would only see the ceiling. This is detrimental because they would not be able to see their opponent's position and anticipate his or her movement at the same time. However, when the shuttlecock is hit between SM and SR, they are much more able to see their opponent's movement in order to take advantage strategically anticipate and plan for next shot. Secondly, if a shuttlecock is above the players' head, they could easily lose their balance after the hit because of an imbalanced COG. If they strike the

shuttlecock in front of them they are more easily able to move forward and prepare for their next shots more easily. Lastly, it is difficult to transfer the power into a powerful smash in SF because the power goes in more of an upward direction when hitting the shuttlecock above their head. In order for the shuttlecock to go forward when hitting from a SF position, the players will have to move up and then forward, which is much more difficult. Conversely, if a smash is executed between the SM and SR, with a changing of COG, a powerful smash will be executed by a concentrated power outbreak. These three important reasons support that for achieving a high smash quality, the shuttlecock should be hit in front of one's body in a body position between the SM and SR. Therefore, choosing a proper body positioning which influences the D_{a-p} is paramount for learning to smash.

Collectively, the results of Study 1 would imply that, for accelerating the skill acquisition, the learners could select their static comfortable selection and then step back by a foot. This perceptual marker could be applied in guiding the learning and training of beginners. As the learners gain experience through repetitive training with a static shuttlecock, improved limbs' coordination would further increase smash quality. Subsequently, combining the arm action with footwork with a dynamic shuttlecock, and trying to make contact at a point in front of the body, would result in more effective smash technique.

Study 2

The first purpose in Study 2 was to examine and compare differences in the body movement parameters (i.e. X-factor and ROM of upper limb movement) in relation to smash quality between the NG and SG in the SR body position. In addition, the

kinematic characteristics of a smash were also revealed based on the joint angle change over time.

The movement parameter results revealed that the angle of X-factor (46.9° in Table 9) was a notable contributor to skill effectiveness. The SG used shoulder external rotation, adduction, and elbow flexion to form a large degree of X-factor at the beginning of the acceleration phase. Almost the same angle of X-factor was found in golf research by Egret, Dujardin, Weber and Chollet (2004). They demonstrated that expert and experienced golfers achieved a similar X-factor with 47.7° and 46.2° , respectively, at the top of the backswing (Egret, Dujardin, Weber, & Chollet, 2004). However, such trunk segment control is hardly noticeable in the NG, and previous studies overlook this important parameter by only using 2D motion analysis or partial body models such as the upper limbs (Reference these previous studies you are referring to).

Figures 12 and 13 clearly illustrate the typical difference in performance of a subject in the NG and SG and the change trend of X-factor over time. Interestingly, during the smash, except for a large angle of X-factor formed at the beginning of acceleration by the SG, a second slight increased degree of X-factor existed after contact due to the force interaction. These characteristics were absent in the NG. Perhaps this indicates that more attention from coaches and researchers should be paid to the anatomical rotation of the body segments such as X-factor since it contributes to the final V_{release} in phase 2.

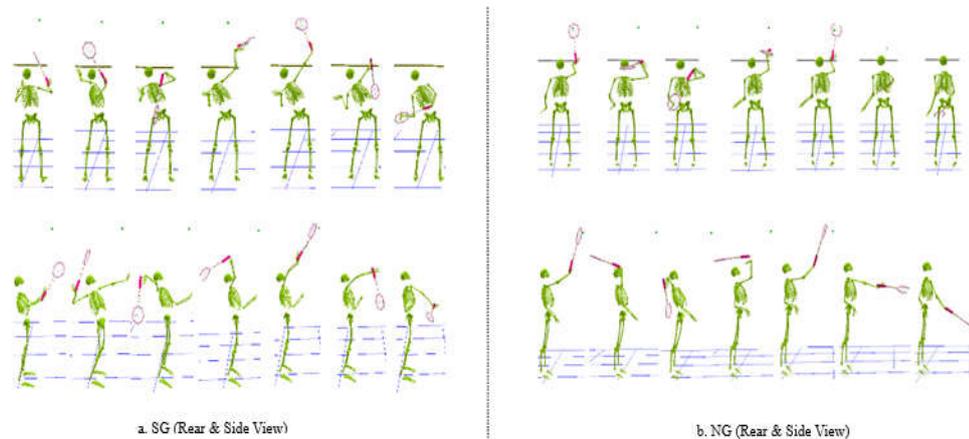


Figure 12. The typical difference in performance of a subject from NG and SG in back view and side view.

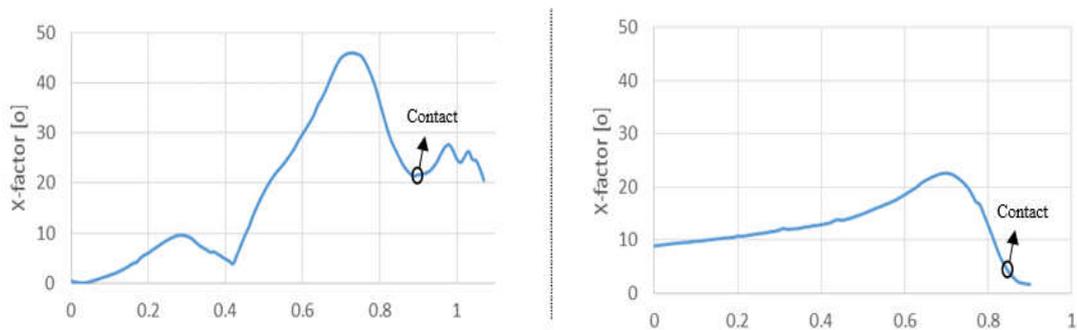


Figure 13. The difference of X-factor over time between a subject from NG and SG.

Besides the contribution of X-factor, the higher ROM of wrist flexion/extension shown in Table 9 would be another reason that a more powerful V_{release} existed in the SG than in the NG. The extent of wrist flexion/extension can be seen as the final moving body segment before contacting the shuttlecock. The wrist joint exerted greater velocity and power than the elbow and shoulder because of an eccentric contraction found from the extensor muscles of muscles before contact. Broer and Zemicke (1979) stated that the difference between the novice and skilled badminton players was the degree to which the wrist snap was used. Broer and Zemicke (1979) also mentioned that just before impact, the wrist snap movement was the most essential action for badminton strokes. In addition, the SG had a larger ROM of elbow flexion/extension than the NG. These differences

between the two groups may have been influenced by training effect. Because the NG is only in the first stage of the skill learning process, they may have lacked effective body control and coordination between each segment. On the contrary, the SG had a high degree of automatic action and a high efficiency of body control.

The high correlation between X-factor and V_{release} for the SG in Table 9 also suggests that the X-factor highly influenced the final quality of the V_{release} . This finding has also been reported by Teu et al., (2005). Teu et al., (2005) indicated that the X-factor contributed to more than 50% of the racket head's forward velocity. The other proximal joint actions (shoulder internal rotation), and distal joint actions (elbow extension and forearm rotation) served to position and move the arm in the general direction of the target. In addition, this high correlation between X-factor and V_{release} was supported by Bahamonde (1999). Bahamonde stated, "one of the most important elements of the forehand and backhand strokes was the development of optimal trunk rotation" (p.12).The trunk has been shown to significantly contribute to the total body angular momentum by creating the large degree of X-factor. The result was also demonstrated in other sport techniques such as high jump, tennis serve, and soccer kicking (Aguinaldo & Chambers, 2007; Bahamonde, 2000; Dapena, 1978; Putnam, 1991, 1993).

In this study, there was also a high correlation between the X-factor and shoulder rotation in the SG. The X-factor primarily generates and stores storage elastic energy at the shoulder. During the backswing, through the coordination of adducting shoulder and extending the elbow, , the forearm mass was positioned away from the shoulder and the racket head was pointed downward. This motion allows the subjects to reach a large degree of X-factor with a peak angular velocity It is worthy to mention a 'lag' situation in

the SG is supported in other overhead throwing and hitting skills such as pitching in baseball (Aguinaldo, Buttermore, & Chambers, 2007). During the backswing from 0.75s-0.9s in Figure 10, the elbow and wrist lagged behind and made a reversed rotation while the trunk was rotating forward. During this 'lag' period, the angle of X-factor was slightly increased to the highest extent and decreased thereafter. Such movement increases the moment of inertia and keeps the forelimb from lagging behind the accelerating X-factor. This lag caused a larger degree of X-factor in stretching the trunk rotator muscles to provide more momentum. The momentum was sequentially transferred into the upper limb for the completion of a new type of whip-like movement. Dillman et al., (1993) proposed that the reason for a forelimb's mass lag was due to the P.M. generating substantial torque around the dominate shoulder and stretching elastic elements to increase the shoulder-hip separation in pitching.

The new quasi whip-like movement in Study 2 shown by the skilled subjects seems to group the joints' movement (i.e. simultaneous X-factor and shoulder flexion, followed by explosive elbow extension and wrist flexion) (Figure 10). Previous studies related to the whip-like movement in sports, indicate that a whip-like movement would be initiated at the trunk (Shan, Visentin, Zhang, Hao, & Yu, 2015; Shan & Westerhoff, 2005; Zhang & Shan, 2014). This whip-like motion can be traditionally characterized as a wave movement where the only forces acting between each segment of the whip are joint reaction forces from the proximal to the distal end of the whip tail while increasing its velocity (Rasmussen, Kwan, Andersen, & de Zee, 2010). The quasi whip-like movement found in Study 2 followed the proximal-to-distal principle and also showed a new type of whip-like movement which made a sequential transfer of energy and

momentum from Movement Group 1 (trunk and shoulder) to Movement Group 2 (elbow and wrist). According to the proximal-to-distal principle, the large segment of the trunk and shoulder has much more muscle force to generate momentum by muscle contraction. This momentum is transferred to the small distal joint of elbow and wrist as a result of interaction (Kibler, Press, & Sciascia, 2006; Young, 2014). The proximal-to-distal principle, therefore, explains the contribution of the trunk to influence the formation of the quasi whip-like movement in the badminton forehand overhead smash. Therefore, such findings as found in Study 2, only partially support the second hypothesis in terms of the whip-like movement.

The quasi whip-like movement reported in Study 2 was also caused by the SSC. Moreover, based on SSC, this kind of dynamic muscle pre-lengthening phenomenon was reported in terms of trunk flexors, hip flexors and quadriceps indicating that it should generate larger muscle forces and increase the effectiveness of kicking (Shan & Westerhoff, 2005). In the current study, the 'lag' situation was a continued muscle pre-lengthening process, which created a larger angle of X-factor and ROM of shoulder flexion for better momentum accumulation and release and release between 0.75s and 0.9s. This process transferred momentum to MG2 for a rapid elbow extension and wrist flexion from 0.9s to 1.01s (see Figure 11). In addition, Figure 10 illustrates that the X-factor, shoulder flexion/extension, wrist flexion/extension and contraction of P.M. all followed the SSC. After a long pre-lengthening process from 0-0.75s in X-factor increase, shoulder flexion, a rapid contraction happened within 0.15s; and after a pre-lengthening process from 0 to 0.9s in wrist extension, a sharp flexion within 0.1s happened. However, the change of elbow flexion/extension is an abnormal SSC as a slow

elbow extension exists from 0.8s to 0.9s before a quick extension from 0.9s to 1.01s. The slow elbow extension is used to assist with the maximum wrist extension in order to decrease the inertia and then increase the torque of the shoulder extension. The percentage of P.M. length was selected as an additional parameter to analyze the contribution of shoulder movement in the formation of the X-factor. Moreover, the percentage of P.M. length provides evidence that P.M. may contribute to the internal rotation of upper arm followed by forearm internal rotation and wrist flexion by a rapid contraction between 0.9s and 1.01s. Except for the results of P.M. in this study, a quantification of lengths in other relative muscles is needed in order to determine whether the existence of X-factor leads to the generation of a maximal force during smashing. Therefore, further and more in-depth studies will be required in badminton.

Collectively, the results in terms of X-factor confirm significant differences existed between the NG and the SG, especially in relation to the quasi whip-like movement. These findings also suggest that full-body 3D analysis provides a more effective means to examine the maximal forehand overhead smash than 2D motion analysis and the partial body models. Partial body models typically neglect information about trunk control and its contribution to final smash speed and quality.

Chapter Summary

In this Chapter, the discussion about Study 1 supported the first hypothesis that body positioning has direct influence on α_{release} and H_c . The finding of D_{a-p} between Dyn and SF/ SM /SR showed that smashing the shuttlecock in front of body with a body positioning between SM and SR for both the NG and SG is better for creating a high

quality smash, especially the α_{release} and H_c . This was also later found and discussed related to the real effect in different choices of body positioning in Study 1.

The discussion from Study 2 found that the X-factor was a main contributor to the V_{release} and a paramount component in the formation of a quasi whip-like movement. Such findings partially supported the second hypothesis in Study 2. The comparison data in both Study 1 and 2 between the NG and SG proved that only the SG had capabilities to quickly make a change in body position in the dynamic test before a smash, or to effectively execute the X-factor in static test during smashing which supported the third hypothesis. The conclusion including the application and future study will be presented in the next chapter.

Chapter 6 Conclusion

Previous studies in terms of body positioning and trunk movement have failed to identify and examine key aspects related to smash quality such as shuttlecock release speed (V_{release}), shuttlecock release angle (α_{release}) and clearance height (H_c). The aim of this thesis was to determine the influence of body positioning, trunk rotation (X-factor) and training effect on forehand overhead smash using a 3D Mo-Cap system and full-body modeling. The findings from Study 1 have divulged that the body positioning has direct influence on α_{release} and H_c .

The findings from Study 2 found that the X-factor was a main contributor to the V_{release} . From the perspective of D_{a-p} between Dyn and SF/ SM /SR in Study 1, the smash quality could be largely influenced by different body positioning. Smashing the shuttlecock in front of body with a body positioning between SM and SR is correct guidance for both the SG and NG to create a high quality smash.

In Study 2, the optimal smash technique was displayed by the SG, which showed a quasi whip-like movement following the proximal-to-distal principle. It can be considered quasi whip-like due to the grouping of movement in segments from trunk and shoulder to elbow and wrist. In addition, the quasi whip-like movement can be considered a characteristic of the smash that the SG used to create an effective SSC producing a 'lag' related to X-factor, shoulder, elbow and wrist in order to generate a more powerful muscular contraction force during the acceleration phase. Though the X-factor has no correlation with α_{release} and H_c , research showed that the X-factor highly influenced the formation of the quasi whip-like movement.

The comparison data in both Study 1 and 2 proved that only the SG had capabilities to quickly make a proper change in body position in the dynamic test before a

smash, or to effectively execute the X-factor in static test during smashing. Hence, a high quality smash in both speed and accuracy is not only in direct proportion to the contribution of body positioning and trunk rotation but also in relation to personal training effect.

Implications for Practitioners

The results from Study 1 and 2 suggest that for training beginners to smash, a practitioner might request a player to self-select a comfort position towards a statically hanged shuttlecock and then take a one-foot step back. This practical reference marker would be useful for teaching positioning to beginners. As one gains experience through repetitive training, improved trunk and limbs' coordination would further increase smash quality.

For teaching and learning, the results in Study 2 provide a valuable and clear guide on the use of X-factor and the relevance between X-factor and subsequent upper limb movement. In addition, the new findings, in terms of a quasi whip-like movement in badminton, encourage coaches to pay more attention to the training of partial body segments such as trunk and shoulder, and elbow and wrist. As a result, coaches could create new drills to first develop the trunk and shoulder movement or elbow and wrist movement and then put the movements together to train for the smash. The findings from this thesis will benefit coaches for developing effective training programs for beginners.

Implications for Future Research

To understand technical aspects of a sport and how to coach for it, learning technologies should follow an analytical process that starts with large segmental motion to

the smaller finishing moves in order to define the complete motion. Study 2 focuses on the research of the upper body as a key object.

In order to keep the analysis simple and clear, the supplementary motor control of the lower extremity was not accounted for. In order to ensure a hard smash force and high contact accuracy, the subject stood in a position facing the net with legs shoulder width apart. This position easily guaranteed that the smash had power and a successful hitting rate. If the subject's legs were allowed to move during the test, such as turning sideways at the start of a smash, the leg movement could influence the execution of smash power, contact accuracy and experimental standardization to some extent. In other words, if the subjects cannot ensure smash strength and accuracy, their data analysis would be negatively affected.

Further studies on body positioning using more professionals are needed to substantiate the results. Recruiting and testing professional badminton players with a longer training period is necessary to deeply investigate the training effect of smashing.

Future studies can explore the influence and contribution of the lower extremity to a badminton smash or other strokes. The experiment could look at stroke execution between two different start positions. The first position may be the standing smash (facing the net without feet movement during a whole smash as same as performed by subjects in this paper). This position may be compared to a smash starting in the same position but the subjects can turn sideways by moving one foot during the preparation phase. A larger sample size would be needed to validate the findings of this study. As well, the impact of gender on smash technique warrants further investigation.

References

- Abe, K., & Okamoto, S. (1989). *Badminton*. Tokyo, Japan: Gyosei.
- Abernethy, B., & Zawi, K. (2007). Pickup of essential kinematics underpins expert perception of movement patterns. *Journal of Motor Behavior*, 39(5), 353-367.
- Abendroth-Smith, J., & Kras, J. (1999). More B-BOAT: The volleyball spike: Bump set spike! *Journal of Physical Education, Recreation & Dance*, 70(3), 56-59.
- Adrian, M. J., & Enberg, M. (1971). Sequential timing of three overhand patterns. In Carol J. Widule (Ed.), *Kinesiology Review* (pp. 1- 9). Washington, D.C. : The Council on Kinesiology of the Physical Education Division.
- Aguinaldo, A. L., Buttermore, J., & Chambers, H. (2007). Effects of upper trunk rotation on shoulder joint torque among baseball pitchers of various levels. *Journal of Applied Biomechanics*, 23(1), 42.
- Aisheng, Y. (2010). The analysis of badminton smsh in rear court. *Sport*, 3, 20-21.
- Alexander, R. M. (2005). Mechanics of animal movement. *Current biology*, 15(16), 616-619.
- Badminton History (n.d.). BWF (Badminton World Federation). Retrieved from <http://www.bwfbadminton.org/page.aspx?id=14887>
- Bahamonde, R. (1999). Producing an explosive forehand and backhand. In George K. Hung, Jani Macari Pallis (Eds.), *Applied Proceeding: Tennis of the XVII* (pp. 17-25). Australia: International on Biomechanics of Sports.
- Bahamonde, R. E. (2000). Changes in angular momentum during the tennis serve. *Journal of Sports Sciences*, 18(8), 579-592.
- Ballreich, R., & Baumann, W. (1996). *Grundlagen der Biomechanik des Sports (The basics of biomechanics in sports)*. Stuttgart, Germany: Enke Verlag.
- Ballreich, R., & Schöllhorn, W. (1992). Golf. In R. Ballreich & A. Kuhlow-Ballreich (Eds.), *Biomechanik der Sportarten* (pp. 30-108). Stuttgart, Germany: Enke Ferdinand.
- Besier, T. F., Lloyd, D. G., & Ackland, T. R. (2003). Muscle activation strategies at the knee during running and cutting maneuvers. *Medicine and Science in Sports and Exercise*, 35(1), 119-127.

- Bird, M., Hills, L., & Hudson, J. L. (1991). Intersegment coordination: An exploration of context. In C. L. Tant, P. E. Patterson & S. L. York (Eds.), *Biomechanics in Sports IX* (pp. 233-237). Ames, IA: International Society of Biomechanics in Sports.
- Brahms, B.-V. (2014). *Badminton Handbook*. Maidenhead, UK: Meyer & Meyer Verlag Sport Ltd..
- Brundle, F. F. (1963). *Badminton*. London, England: Acro Publications.
- Bunn, J. W. (1972). *Scientific principles of coaching*. Englewood Cliffs, NJ: Prentice-Hall.
- Chang, S. (2002). *Kinematical analysis via three-dimensional cinematography for two types of forehand smash stroke in senior high school badminton players* (Unpublished master's thesis). National Taiwan Normal University, Taiwan.
- Chang, S., Evans, J., Crowe, S., Zhang, X., & Shan, G. (2011). An innovative approach for real time determination of power and reaction time in a martial arts quasi-training environment using 3D motion capture and EMG measurements. *Archives of Budo*, 7(3), 185-196.
- Cheetham, P. J., Martin, P. E., Mottram, R., & St Laurent, B. (2001). The importance of stretching the “X-Factor” in the downswing of golf: The “X-Factor Stretch.” In P.R. Thomas (Ed.), *Optimising Performance in Golf* (pp. 192-199). Brisbane, Australia: Australian Academic Press.
- Chen, L.-M., Pan, Y.-H., & Chen, Y.-J. (2009). A study of shuttlecock’s trajectory in badminton. *Journal of Sports Science & Medicine*, 8(4), 657-662.
- Chinese Fu Clocks Fastest Smash at Sudirman Cup. (2005, May 14). Xinhua News. Retrieved from <http://china.org.cn/english/sports/128755.htm>
- Christensen, Ronald (2002). *Plane Answers to Complex Questions: The Theory of Linear Models (Third ed.)*. New York, USA: Springer.
- Chu, Y., Sell, T. C., & Lephart, S. M. (2010). The relationship between biomechanical variables and driving performance during the golf swing. *Journal of Sports Sciences*, 28(11), 1251-1259.
- Dapena, J. (1978). A method to determine the angular momentum of a human body about three orthogonal axes passing through its center of gravity. *Journal of Biomechanics*, 11(5), 251-256.
- Davidson, K. R., & Gustavson, L. R. (1964). *Winning badminton*. Pennsylvania, USA: Athletic Institute.

- Dillman, C. J., Fleisig, G. S., & Andrews, J. R. (1993). Biomechanics of pitching with emphasis upon shoulder kinematics. *Journal of Orthopaedic & Sports Physical Therapy*, 18(2), 402-408.
- Dixon, W. J., & Massey, F. J. (1969). *Introduction to statistical analysis*. New York, USA: McGraw-Hill.
- Downey, J. (1984). *Winning badminton doubles*. London, England: Adam & Charles Black.
- Dørge, H. C., Andersen, T., Sørensen, H., Simonsen, E. B., Aagaard, H., Dyhre - Poulsen, P., & Klausen, K. (1999). EMG activity of the iliopsoas muscle and leg kinetics during the soccer place kick. *Scandinavian Journal of Medicine & Science in Sports*, 9(4), 195-200.
- Egret, C., Dujardin, F., Weber, J., & Chollet, D. (2004). 3-D kinematic analysis of the golf swings of expert and experienced golfers. *Journal of Human Movement Studies*, 47(3), 193-204.
- El-Gizawy, H., & Akl, A.-R. (2014). Relationship between reaction time and deception type during smash in badminton. *Journal of Sports Research*, 1(3), 49-56.
- Ellenbecker, T. S., & Davies, G. J. (2001). *Closed kinetic chain exercise: A comprehensive guide to multiple joint exercise*. Champaign, USA: Human Kinetics.
- Ellenbecker, T. S., & Roetert, E. P. (2004). An isokinetic profile of trunk rotation strength in elite tennis players. *Medicine and Science in Sports and Exercise*, 36(11), 1959-1963.
- Elliott, B. (2000). Hitting and kicking. *IOC Encyclopedia of Sports Medicine: Biomechanics in Sport*, 6, 487-504.
- Elliott, B., & Christmass, M. (1995). A comparison of the high and low backspin backhand drives in tennis using different grips. *Journal of Sports Sciences*, 13(2), 141-151.
- Elliott, B., Marsh, A., & Overheu, P. (1989a). The topspin backhand drive in tennis-A biomechanical analysis. *Journal of Human Movement Studies*, 16(1), 1-16.
- Elliott, B., Marsh, T., & Overheu, P. (1989b). A biomechanical comparison of the multisegment and single unit topspin forehand drives in tennis. *International Journal of Sport Biomechanics*, 5(3), 350-364.
- Elliott, B., Marshall, R., & Noffal, G. (1996). The role of upper limb segment rotations in the development of racket - head speed in the squash forehand. *Journal of Sports Sciences*, 14(2), 159-165.

- Elliott, B., Overheu, P., & Marsh, P. (1988). The service line and net volleys in tennis: a cinematographic analysis. *Journal of Science and Medicine in Sport*, 20, 10-18.
- Fitts, Paul M. (1954). The information capacity of the human motor system in controlling the amplitude of movement. *Journal of Experimental Psychology*, 47(6), 381-391.
- Gowitzke, B., & Waddell, D. (1977, September). *The contributions of biomechanics in solving problems in badminton stroke production*. Paper presented at the International Coaching Conference, Malmo, Sweden.
- Gowitzke, B., & Waddell, D. (1979, June). *Qualitative analysis of the badminton forehand smash as performed by international players*. Paper presented at the Proceedings of the National Symposium on the Racket Sports. University of Illinois Press, Urbana Champaign, IL.
- Gowitzke, B., & Waddell, D. (1979a). Technique of badminton stroke production. In J. Terauds (Ed.), *Science in Racket Sports (pp. 17-41)*. Del Mar, San Diego: American Publishers.
- Gowitzke, B. A., & Waddell, D. (1979b). Biomechanical principles applied to badminton stroke production. *Science in Racket Sports*, 1, 7-16.
- Gowitzke, B., & Waddell, D. (1991, July). Biomechanical studies of badminton overhead power strokes: A review. In Tant, P. Patterson and S. York (Eds.), *Biomechanics in Sports IX (pp. 267-272)*. Ames, IA: International Society of Biomechanics in Sports.
- Gowitzke, B., Waddell, D., Watkins, J., Reilly, T., & Burwitz, L. (1986). The biomechanics of underarm power strokes in badminton. In J. Watkins, T. Reilly and L. Burwitz (Ed.), *Sports Science (pp. 137-142)*. London, England: E & FN Spon.
- Gowitzke, B. A., & Milner, M. (1980). *Understanding the scientific basis of human movement*. Baltimore, Maryland: Williams and Wilkins Co.
- Gowitzke, B. A., & Waddell, D.B. (1980, June). *A force platform study of overhead power strokes in badminton*. Paper presented at the Proceedings: International Symposium on the Effective Teaching of Racket Sports, The University of Illinois, Urbana-Champaign, IL.
- Gray, S., Watts, S., Debicki, D., & Hore, J. (2006). Comparison of kinematics in skilled and unskilled arms of the same recreational baseball players. *Journal of Sports Sciences*, 24(11), 1183-1194.
- Cross, R., & Bower, R. (2006). Effects of swing-weight on swing speed and racket power. *Journal of Sports Sciences*, 24(1), 23-30.

- Hamilton, N., Weimar, W., & Luttgens, K. (2002). *Kinesiology: Scientific basis of human motion*. London, England: McGraw-Hill Humanities/Social Sciences/Language.
- Hatze, H. (1974). The meaning of the term 'biomechanics'. *Journal of Biomechanics*, 7(2), 189-190.
- Hirashima, M., Kadota, H., Sakurai, S., Kudo, K., & Ohtsuki, T. (2002). Sequential muscle activity and its functional role in the upper extremity and trunk during overarm throwing. *Journal of Sports Sciences*, 20(4), 301-310.
- Hirashima, M., Kudo, K., Watarai, K., & Ohtsuki, T. (2007). Control of 3D limb dynamics in unconstrained overarm throws of different speeds performed by skilled baseball players. *Journal of Neurophysiology*, 97(1), 680-691.
- Hirashima, M., Yamane, K., Nakamura, Y., & Ohtsuki, T. (2008). Kinetic chain of overarm throwing in terms of joint rotations revealed by induced acceleration analysis. *Journal of Biomechanics*, 41(13), 2874-2883.
- How to Hit a Great Smash in Badminton (2014, September 9). Hubpages. Retrieved from <http://badmintondoubles.hubpages.com/hub>
- Hogan, B. (1985). *Ben Hogan's five lessons: The modern fundamentals of golf*. New York, USA: A.S. Barnes and Company.
- Hong, Y., & Tong, Y. (2000). The playing pattern of the world's top single badminton players in competition-A notation analysis. *Journal of Human Movement Studies*, 38(4), 185-200.
- Hudson, J., Bird, M., Strohmeyer, H., Horna, F., Hills, L., Rife, D., Clifton, R., & Walters, M. (1991, July). *Coordination: Some questions and case studies*. Paper presented at the 9th International Symposium on Biomechanics in Sports, Iowa State University, Ames, Iowa, USA.
- Hussain, I., & Bari, M. A. (2011). Kinematical analysis of forehand and backhand smash in badminton. *Innovative Systems Design and Engineering*, 2(7), 20-25.
- Hussain, I., Paul, Y., & Bari, M. (2011). Videographical analysis of drop and cut shot in badminton: Sport science. *African Journal for Physical Health Education, Recreation and Dance*, 17 (2), 860-865.
- Huynh, M. V., & Bedford, A. (2011). Evaluating a computer based skills acquisition trainer to classify badminton players. *Journal of Sports Science & Medicine*, 10(3), 528.
- Ito, M. (1996). *Knowing, Creating and Defending the Brain, Part 2*. Tokyo, Japan: Gyosei.

- Jack, M., & Adrian, M. (1979, June). *Characteristics of the badminton smash stroke*. Paper presented at the Proceedings of a National Symposium on Racket Sports: An Exploration of Research Implications and Teaching Strategies, Urbana-Champaign, IL: University of Illinois.
- Jaitner, T., & Gawin, W. (2010). A mobile measure device for the analysis of highly dynamic movement techniques. *Procedia Engineering*, 2(2), 3005-3010.
- Jin, D., Jianping, Z., & Xueqing, W. (2009). Training badminton of basic training counseling seminars V: Badminton smash technology. *China School Physical Education*, 6, 65-67.
- Jobe, F. W., & DR, M. (1986). *30 Exercises For Better Golf*. Inglewood, CA: Champion Press.
- Kibler, W. B., Press, J., & Sciascia, A. (2006). The role of core stability in athletic function. *Sports Medicine*, 36(3), 189-198.
- Koike, S., & Hashiguchi, T. (2014). Dynamic contribution analysis of badminton-smash-motion with consideration of racket shaft deformation (A Model Consisted of Racket-side Upper Limb and a Racket). *Procedia Engineering*, 72, 496-501.
- Kreighbaum, E. (1996). Biomechanics: A qualitative approach for studying human movement. *Quest*, 38(1), 80-81.
- Kreighbaum, E. & Barthels, K. M. (1981). *Biomechanics: A qualitative approach for studying human movement*. Minneapolis, MN: Burgess.
- Kugler, A., Krüger-Franke, M., Reininger, S., Trouillier, H., & Rosemeyer, B. (1996). Muscular imbalance and shoulder pain in volleyball attackers. *British Journal of Sports Medicine*, 30(3), 256-259.
- Kwan, M., Andersen, M., de Zee, M., & Rasmussen, J. (2008). Dynamic model of a badminton stroke. *The Engineering of Sport*, 7, 563-571.
- Kwan, M., Andersen, M. S., Cheng, C.-L., Tang, W.-T., & Rasmussen, J. (2011). Investigation of high-speed badminton racket kinematics by motion capture. *Sports Engineering*, 13(2), 57-63.
- Lawrence, I., & Lin, K. (1989). A concordance correlation coefficient to evaluate reproducibility. *Biometrics*, 45, 255-268.
- Larson, S. (1993). Functional morphology of the shoulder in primates. In Gebo DL (Ed.), *Postcranial Adaptation in Nonhuman Primates (pp.45-69)*. DeKalb, Illinois: Northern Illinois University Press.

- Larson, S. G. (2007). Evolutionary transformation of the hominin shoulder. *Evolutionary Anthropology: Issues, News, and Reviews*, 16(5), 172-187.
- Lee, B. K. (1993). The effects of the kinematic link principle on performance. In Hamill J, Derrik TR, Elliott EH (Eds.), *Biomechanics in Sports XI* (pp.239-242.). Amherst: ISBS.
- Lees, A. (2001, July). *What biomechanics can tell the badminton coach*. Paper presented at the Communication to the IVth International Badminton Federation World Coaches Conference, Seville, Spain.
- Lees, A. (2003). Science and the major racket sports: A review. *Journal of Sports Sciences*, 21(9), 707-732.
- Liu, X., Kim, W., & Tan, J. (2010). *An analysis of the biomechanics of arm movement during a badminton smash* (Unpublished master's thesis). Nanyang Technological University and National Institute of Education, Singapore.
- Lo, D., & Stark, K. (1991). Sports performance series: The badminton overhead shot. *Strength & Conditioning Journal*, 13(4), 6-15.
- Lu, T.-W., & O'connor, J. (1999). Bone position estimation from skin marker co-ordinates using global optimisation with joint constraints. *Journal of Biomechanics*, 32(2), 129-134.
- Magill, R. A. (2001). *Motor learning concepts and applications* (6th ed.). Boston, Massachusetts: McGraw-Hill.
- Manrique, D. C., & Gonzalez-Badillo, J. (2003). Analysis of the characteristics of competitive badminton. *British Journal of Sports Medicine*, 37(1), 62-66.
- Marshall, R., & Elliott, B. (2000). Long-axis rotation: the missing link in proximal-to-distal segmental sequencing. *Journal of Sports Sciences*, 18(4), 247-254.
- Maxwell, T. (1982). A cinematographic analysis of the volleyball spike of selected top-caliber female athletes. *Volleyball Technical Journal*, 7(1), 43-54.
- Meister, D. W., Ladd, A.L., Butler, E. E., Zhao, B., Rogers, A. P., Ray, C. J., & Rose, J. (2011) Rotational biomechanics of the elite golf swing: Benchmarks for amateurs. *Journal of Applied Biomechanics*, 27(3), 242-251.
- McTeigue, M., Lamb, S. R., & Mottram, R. (1994). Spine and hip motion analysis during the golf swing. In A. J. Cochran & M. R. Farrally (Eds.), *Science and golf II: Proceedings of the 1994 World Scientific Congress of Golf* (pp. 50-57). London, England: Taylor & Francis.

- Miyashita, K., Urabe, Y., Kobayashi, H., Yokoe, K., Koshida, S., Kawamura, M., & Ida, K. (2008a). Relationship between maximum shoulder external rotation angle during throwing and physical variables. *Journal of Sports Science & Medicine*, 7(1), 47-53.
- Miyashita, K., Urabe, Y., Kobayashi, H., Yokoe, K., Koshida, S., Kawamura, M., & Ida, K. (2008b). The role of shoulder maximum external rotation during throwing for elbow injury prevention in baseball players. *Journal of Sports Science & Medicine*, 7(2), 223-228.
- Morehouse, L. E., & Cooper, J. M. (1950). *Kinesiology*. St. Louis, Missouri: Mosby.
- Myers, J., Lephart, S., Tsai, Y.-s., Sell, T., Smoliga, J., & Jolly, J. (2008). The role of upper torso and pelvis rotation in driving performance during the golf swing. *Journal of Sports Sciences*, 26(2), 181-188.
- Nechita, F. (2009). Biomechanics in sport. *Bulletin of the Transilvania University of Braşov*, 2 (51), 135-138.
- Niesner, H. W. R., J. (1982). *Basic theory of stroke production*. Germany: German Badminton Federation.
- Ninos, J. C., Irrgang, J. J., Burdett, R., & Weiss, J. R. (1997). Electromyographic analysis of the squat performed in self-selected lower extremity neutral rotation and 30 of lower extremity turn-out from the self-selected neutral position. *Journal of Orthopaedic & Sports Physical Therapy*, 25(5), 307-315.
- Noonan, D. P., Mountney, P., Elson, D. S., Darzi, A., & Yang, G.-Z. (May, 2009). *A stereoscopic fibroscope for camera motion and 3D depth recovery during minimally invasive surgery*. Paper presented at the IEEE International Conference on Robotics and Automation (ICRA), Piscataway, USA.
- Osiński, W. (2003). *Anthropomotorics*. Poland: WF Poznań.
- Quintavalla, S. J. (2006). *Experimental determination of the effects of clubhead speed on driver launch conditions and the effects on drive distance for balls used by the PGA tour*. (Report No. 01). Washington, USA: USGA Technical Report.
- Papadopoulos, C., Emmanouilidou, M. & Prassas, S. (2000). *Kinematic analysis of the service stroke in tennis*. Oxford, England: Blackwell.
- Pink, M., Perry, J., & Jobe, F. W. (1993). Electromyographic analysis of the trunk in golfers. *The American Journal of Sports Medicine*, 21(3), 385-388.
- Poole, J. R. (1972). *A cinematographic analysis of the upper extremity movements of world class players executing two basic badminton strokes* (Unpublished doctoral dissertation). University of Oregon: School of Health, Physical Education, and Recreation.

- Putnam, C. A. (1991). A segment interaction analysis of proximal-to-distal sequential segment motion patterns. *Medicine and Science in Sports and Exercise*, 23(1), 130-144.
- Putnam, C. A. (1993). Sequential motions of body segments in striking and throwing skills: Descriptions and explanations. *Journal of Biomechanics*, 26, 125-135.
- Rambely, A. S., Abas, W. A. B. W., & Yusof, M. S. (2008). The analysis of the jumping smash in the game of badminton. In International Society of Biomechanics in Sports (Ed.). *Proceedings of International Symposium on biomechanics in sports conference (pp: 671- 674)*. Beijing, China: International Society of Biomechanics in Sports.
- Rasmussen, J., Kwan, M. M. S., Andersen, M. S., & de Zee, M. (2010, September). *Analysis of segment energy transfer using musculoskeletal models in a high speed badminton stroke*. Paper presented at the 9th International Symposium on Computer Methods in Biomechanics and Biomedical Engineering, Valencia, Spain.
- Reid, M., & Elliott, B. (2002). Tennis: The one - and two - handed backhands in tennis. *Sports Biomechanics*, 1(1), 47-68.
- Reilly, T., & Williams, M. (2003). *Science and soccer (2nd ed.)*. London, England: Routledge.
- Roach, N. T., & Lieberman, D. E. (2014). Upper body contributions to power generation during rapid, overhand throwing in humans. *The Journal of Experimental Biology*, 217(12), 2139-2149.
- Robinson, R. (1994, August). *A study of the correlation between swing characteristics and club head velocity*. Paper presented at the Science and Golf II: Proceedings of the 1994 World Scientific Congress of Golf, London, England.
- Roetert, P., & Groppe, J. L. (2001). *World-class tennis technique*. England: Human Kinetics Publisher.
- Rossi, J., Foissac, M., Baly, L., Vigouroux, L., & Grelot, L. (2010). Characterization of grip force during badminton strokes. *Procedia Engineering*, 2(2), 34-55.
- Sakurai, S., Ikegami, Y., & Yabe, K. (1989). A three-dimensional cinematographic analysis of badminton strokes. In L. Tsarouchas, J. Terauds, B. Gowitzke and L. Holt (Eds.), *Biomechanics in Sports V (pp. 357-363)*. Perth, Australia: Hellenic Sports Research Institute.
- Sakurai, S., & Ohtsuki, T. (2000). Muscle activity and accuracy of performance of the smash stroke in badminton with reference to skill and practice. *Journal of Sports Sciences*, 18(11), 901-914.

- Saladin, K. (2010). *Anatomy & Physiology: The Unity of Form and Function*. New York, USA: McGraw-Hill.
- Salim, M., Lim, H., Salim, M., & Baharuddin, M. (2010, December). *Motion analysis of arm movement during badminton smash*. Paper presented at the Biomedical Engineering and Sciences (IECBES), 2010 IEEE EMBS Conference on Kuala Lumpur, Malaysia.
- Shan, G., Visentin, P., Zhang, X., Hao, W., & Yu, D. (2015). Bicycle kick in soccer: Is the virtuosity systematically entrainable? *Science Bulletin*, 60(8), 819-821.
- Shan, G., Bohn, C., Dust, M., & Nicol, K. (2004). How can dynamic rigid-body modeling be helpful in motor learning? Learning performance through dynamic modeling. *Kinesiology*, 36(2), 182-191.
- Shan, G., & Westerhoff, P. (2005). Soccer: Full - body kinematic characteristics of the maximal instep soccer kick by male soccer players and parameters related to kick quality. *Sports Biomechanics*, 4(1), 59-72.
- Shan, G., & Zhang, X. (2011). From 2D leg kinematics to 3D full-body biomechanics-The past, present and future of scientific analysis of maximal instep kick in soccer. *BMC Sports Science, Medicine and Rehabilitation*, 3(1), 23.
- Shan, G. (2009). Influences of gender and experience on the maximal instep soccer kick. *European Journal of Sport Science*, 9(2), 107-114.
- Shan, G., & Bohn, C. (2003). Anthropometrical data and coefficients of regression related to gender and race. *Applied Ergonomics*, 34(4), 327-337.
- Shan, G., Zhang, X., Li, X., Hao, W., & Witte, K. (2011). Quantification of golfer-club interaction and club-type's affect on dynamic balance during a golf swing. *International Journal of Performance Analysis in Sport*, 11, 417-426.
- Sørensen, K., de Zee, M., & Rasmussen, J. (2010, July). *A biomechanical analysis of clear strokes in badminton executed by youth players of different skill levels*. Paper presented at the Congress of the International Society of Biomechanics, Islamabad, Pakistan.
- Sørensen, K., de Zee, M., & Rasmussen, J. (2011, July). *A biomechanical analysis of clear strokes in badminton executed by youth players of different skill levels*. Paper presented at the XXIII Congress of the International Society of Biomechanics, Brussels, Belgium.
- Sprigings, E., Marshall, R., Elliott, B., & Jennings, L. (1993). The effectiveness of upper limb rotations in producing racket-head speed in racket sports. *Journal of Biomechanics*, 26(3), 292-293.

- Springs, E., Marshall, R., Elliott, B., & Jennings, L. (1994). A three-dimensional kinematic method for determining the effectiveness of arm segment rotations in producing racket-head speed. *Journal of Biomechanics*, 27(3), 245-254.
- Steindler, A. (1970). *Kinesiology of the human body*. Springfield, Illinois: Charles C Thomas.
- Stigler, S. M. (1989). Francis Galton's account of the invention of correlation. *Statistical Science*, 4, 73-79.
- Strohmeier, S., Armstrong, C., Litvinsky, Y., Nooney, R., Moore, J., & Smith, K. (2009, Desember). *Intersegment Coordination Differences Between Beginning Performers Executing A Badminton Smash for Accuracy or Velocity*. Paper presented at 27th International Conference on Biomechanics in Sports, Limerick, Ireland.
- Takahashi, K., Elliott, B., & Noffal, G. (1996). The role of upper limb segment rotations in the development of spin in the tennis forehand. *Australian Journal of Science and Medicine in Sport*, 28(4), 106-113.
- Tang, H., Abe, K., Ae, M., & Katoh, K. (1993, February). *Three dimensional cinematographic analysis of the forearm movement during a badminton forehand smash*. Paper presented at the Proceedings of the 1st World Congress of Science and Racket Sports, London, England.
- Tang, H., Abe, K., Katoh, K., & Ae, M. (1995). Three-dimensional cinematographical analysis of the badminton forehand smash: Movements of the forearm and hand. In T. Reilly, M. Hughes and A. Lees (Eds.), *Science and Racket Sports (pp. 113-120)*, London, England: E & FN Spon.
- Tang, H. P., & Toyoshima, S. (1997, July). *Evaluation of smash technique from the viewpoint of conservation of angular momentum*. Paper presented at the 16th Congress of the International Society of Biomechanics, Tokyo, Japan.
- Taube, F. W. (1972). *An Electromyographic Analysis of Selected Muscles Performing the Soccer Instep Kick Following Levels of Physiological Stress* (Unpublished doctoral dissertation). University of Utah: College of Health, Physical Education, and Recreation.
- Teu, K. K., Kim, W., Tan, J., & Fuss, F. K. (2005). Using dual Euler angles for the analysis of arm movement during the badminton smash. *Sports Engineering*, 8(3), 171-178.
- Tong, G. (2004). *Mechanics analysis of a shuttlecock terminal velocity* (Unpublished master thesis). Taiwan, China: National Kaohsiung Normal University.

- Tsai, C.-L., Huang, C., Lin, D.-C., & Chang, S. S. (2000, June). *Biomechanical analysis of the upper extremity in three different badminton overhead strokes*. Paper presented at Proceedings of XVIII International Symposium on Biomechanics in Sports, Hong Kong, China.
- Tsai, C.-L., Huang, C., Lin, D., Chang, S., & Cheng, C. (2001, June). *Biomechanical analysis of the upper extremity between badminton smash and drop shot*. Paper presented at Proceedings of XVIII International Symposium on Biomechanics in Sports, Hong Kong, China.
- Tsai, C., Chang, S., & Huang, C. (1998, June). *Biomechanical analysis of differences in the badminton smash and jump smash between Taiwan elite and collegiate players*. Paper presented at Proceedings of XVIII International Symposium on Biomechanics in Sports, Hong Kong, China.
- Tsai, C.-L., Huang, K.-S., & Chang, S.-S. (2005, January). *Biomechanical analysis of EMG activity between badminton smash and drop shot*. Paper presented at the ISB XXth Congress–ASB 29th Annual Meeting, Cleveland, Ohio.
- Tsai, C.-L., Yang, C.-C., Lin, M.-S., Huang, K.-S., & Chang, S.-S. (2006). The EMG activity of the lower extremities in badminton smash stroke. *Journal of Biomechanics*, 39, 562-563.
- van den Tillaar, R., & Ettema, G. (2009). Is there a proximal-to-distal sequence in overarm throwing in team handball? *Journal of Sports Sciences*, 27(9), 949-955.
- van Gheluwe, B., & Hebbelinck, M. (1985). *The kinematics of the service movement in tennis: A threedimensional cinematographic approach*. Champaign, IL: Human Kinetics.
- Waddell, D. B., & Gowitzke, B. A. (2000, July). *Biomechanical principles applied to badminton power strokes*. Paper presented at the 18th International Society of Biomechanics in Sports Symposium, Hong Kong, China.
- Wang, J., & Moffit, J. (2009). Teaching badminton based on student skill levels. *Strategies*, 22(6), 14-18.
- Wąsik, J., & Shan, G. (2015). Kinematics of the turning kick- Measurements obtained in testing well-trained taekwon-do athletes. *Archives of Budo*, 11, 61-66.
- Watkins, R. G., Dennis, S., Dillin, W. H., Schnebel, B., Schneiderman, G., Jobe, F., Pink, M. (1989). Dynamic EMG analysis of torque transfer in professional baseball pitchers. *Spine*, 14(4), 404-408.
- Whittaker, E. T. (1952). *A Treatise on the Analytical dynamics of particles and rigid bodies*. Cambridge, England: University Press.

- Wilkinson, A. T., & Strkalj, G. (2005). Use of the race concept in anthropometry. *Applied Ergonomics*, 36(1), 121; author reply 122.
- Wright, T. W. (1898). *Elements of mechanics including kinematics, kinetics and statics, with applications*. New York, USA: D. Van Nostrand Company.
- Yap, C. (n.d.). Badminton-Fastest racket sport. Badminton Information. Retrieved from <http://www.badminton-information.com>
- Yang, N. (2013). Research of badminton forehand smash technology based on biomechanical analysis. *Journal of Chemical and Pharmaceutical Research*, 5(11), 172-177.
- Yontz, N. A. (2010). Determining the correlation between core performance and golf swing kinematics and kinetics (Electronic Thesis, Ohio State University). Retrieved from <https://etd.ohiolink.edu/>
- Young, J. (2014). Trunk contributions to baseball pitching velocity (Electronic thesis, Ohio State University). Retrieved from <https://etd.ohiolink.edu/>
- Yu, D., Yu, Y., Wilde, B., & Shan, G. (2012). Biomechanical characteristics of the axe kick in tae kwon-do. *Archives of Budo*, 8(4), 213-218.
- Zatsiorsky, V. M. (1998). *Kinematics of human motion*. Champaign, Illinois: Human Kinetics.
- Zhang, Y., Guo, J., & Chen, L. (1999). Discussion on skill of push kicking with full instep by simultaneity of myodynamic, myographic and video measurements in soccer players. *Journal of Tianjin Institution Physical Education*, 14(2), 50-53.
- Zhang, X., & Shan, G. (2014). Where do golf driver swings go wrong? Factors influencing driver swing consistency. *Scandinavian Journal of Medicine & Science in Sports*, 24(5), 749-757.
- Zhao, X. (2007). *Badmintonn: A course book in English-Chinese*. Xiangtan, China: Xiangtan University Publication.
- Zheng, N., Barrentine, S., Fleisig, G., & Andrews, J. (2008). Kinematic analysis of swing in pro and amateur golfers. *International Journal of Sports Medicine*, 29(6), 487-493.
- Zhu, Q. (2013a). Expertise of using striking techniques for power stroke in badminton^{1,2}. *Perceptual & Motor Skills*, 117(2), 427-441.
- Zhu, Q., Dapena, J., & Bingham, G. P. (2009). Learning to throw to maximum distances: Do changes in release angle and speed reflect affordances for throwing? *Human movement Science*, 28(6), 708-725.

Zhu, Q. (2013b). Perceiving the affordance of string tension for power strokes in badminton: Expertise allows effective use of all string tensions. *Journal of Sports Sciences*, 31(11), 1187-1196.

Appendix A:
Promotional Poster Sample

Badminton Smash in a 3D Motion Capture System

Are you an **EXPERT** or **NOVICE** badminton player?

40 MIN

Volunteers needed for a graduate research study in the Biomechanical Lab (PE 240) at **University of Lethbridge**



- ⇒ Want to know what a 3D Motion Capture System is?
- ⇒ Want to know how fast your Badminton Smash is?
- ⇒ Want to know how to improve your Badminton Smash?
- ⇒ Want to know what your Badminton Smash detailed looks like?



★ Please contact the researcher at zhao.zhang@uleth.ca for more information.

Thesis title: Full-body Kinematic Characteristics of the Badminton Forehand Overhead Smash and Parameters Related to Smash Quality

Researcher: zhao ZHANG (major: Kinesiology) Graduate Student under the supervision of Dr. Gongbing Shan.



Badminton Smash study

Appendix B: Invitation Letter

Dear _____

If you have not played badminton since Grade 10, or you are playing and practicing badminton at the provincial level, you are invited to participate in a research study performed by graduate student Zhao Zhang at the University of Lethbridge. The project uses 3-D motion capture technology to identify parameters that are most sensitive and prone to the quality of a badminton smash. The experiment takes about 40 minutes per person. The participants will be asked to wear a black garment made of stretchable material, which directly touches participant's skin and covers the upper and lower body; the garment will be washed between each participant use. Affixed to the garment will be 42 reflective markers (for motion capture, no identifying visual information will be captured), each with a diameter of 9mm. Before the test, each participant will be allowed to perform a sufficient number of warm-up smashes (i.e. individualized warm-up) to get used to the test environment. After the warm-up they will perform at least five smashes in a static position by hitting a suspended bird using only the arm with a racket. Next, the participant will perform at least five smashes from a dynamic position upon receiving underhand clears from the researcher. During each smash, the kinematic (3D motion) data will be captured in Biomechanics Lab (PE 240) at the U of L.

The dominant skill in badminton is the smash. The smash is a complicated movement that requires coordination of all major body segments. The smash plays a decisive role in the outcome of the game. Because of its complexity, the smash requires athletes' physical exertion (speed, power, flexibility and coordination), and precision. Therefore, increasing smash quality is always a challenge for all level players. The proposed project aims to investigate the factors influencing smash quality in order to supply pedagogical guidance for smash training. The study also aims to identify major factors that contribute to a better smash by measuring body segment velocities and accelerations, joint angles, range of motion of wrist, elbow, hip, knee, ankle, bird velocity and trajectory. Such research will yield insightful instructions on how to execute a good badminton smash, as these instructions will help players learn how to smash well.

In this proposed study, I will compare the smashes of both expert experienced and novice non-experienced players in order to identify kinematic parameters that are most sensitive and prone to smash control. The results will benefit all levels of badminton pedagogy by pinpointing hidden problem areas that require extra care and attention during a badminton smash. There are no anticipated risks associated with your participation.

To maximize the anonymity, participants will be assigned a code, and this code will be used instead of their names at all times. The signed consent form and the assigned code will be stored in a locked file cabinet in room PE239. Only the researcher will be able to access the personal information of the participants. All of the kinematic data will be securely stored in a password protected file (accessible only by researcher) on a

Biomechanical Lab computer in PE 240. The collected kinematic data will be stored for minimum of 5 years and maximum of 10 years for knowledge dissemination.

Further thesis development will use data measurements for research presentations and publications in the future. There will be no identifiable visual information collected during the test and the data will link to a code only (e.g. elbow extension of Subject 1). As a result, your identity will be kept confidential.

Your participation is totally voluntary and you can withdraw at any time including withdrawal during your experiment. Once you decide to withdraw from experiment, data that has been collected from you will be deleted immediately.

If you are interested to know how good your smash skill is and how fast you could hit the shuttlecock during a smash, I will supply you with the results of your trials (the video and photo containing your 3D motion analysis) after the data analysis is completed.

I would appreciate your participation very much! If you are interested, please confirm your wish to participate by replying, "Yes, I would like to participate in the badminton smash study." and I will send you the consent form and available testing time slots.

Thank you for your consideration!

A handwritten signature in cursive script, reading "Shang Zhao", enclosed in a thin rectangular border.

Appendix C:
PARTICIPANT (ADULT) CONSENT FORM
Full-body Kinematic Badminton Forehand Overhead Smash

You are being invited to participate in a study entitled “Full-body Kinematic Characteristics of the Badminton Forehand Overhead Smash and Parameters Related to Smash Quality” that is being conducted by Miss Zhao Zhang. Miss Zhao Zhang is a graduate student in the Faculty of Arts and Science, Kinesiology and Physical Education Department at the University of Lethbridge. Miss Zhao Zhang can be reached at (587) 968 2866 or at zhao.zhang@uleth.ca if you have further questions.

As a graduate student, I am required to conduct research as part of the requirements for a degree in Science Master Degree. It is being conducted under the supervision of Dr. Gongbing Shan. You may contact my supervisor at (403) 329 2683 or g.shan@uleth.ca.

The purpose of this research project is to investigate the factors influencing smash quality in order to supply pedagogical guidance for smash training. Research of this type is important because the dominant skill in badminton is the smash. The smash has complicated movements that require coordination of all major body segments. The smash plays a decisive role in the winning of the game. Because of its complexity, the smash requires athletes’ physical exertion (speed, power, flexibility and coordination), and precision. Therefore, increasing smash quality is a challenge for all level players. You are being asked to participate in this study because you are in either the novice group which represents the people who have not played badminton since Grade 10 or the expert group which is composed of people playing and practicing badminton at a provincial level.

The project uses 3-D motion capture technology to identify parameters that are most sensitive and prone to the quality of a badminton smash. The experiment takes about 40 minutes per person. The participants will be asked to wear a black garment made of stretchable material without participants’ clothing, which directly touches participant’s skin and covers the upper and lower body; the garment will be washed between each participant use. Affixed to the garment will be 42 reflective markers (for motion capture, no identifying visual information will be captured), each with a diameter of 9mm. Before the test, each participant will be allowed to perform a sufficient number of warm-up smashes (i.e. individualized warm-up) to get used to the test environment. After the warm-up they will perform at least five smashes in a static position by position by hitting a suspended bird using only the arm with a racket. Next, the participant will perform at least five smashes from a dynamic position upon receiving underhand clears from clears from the researcher. During each smash, the kinematic (3D motion) data will be captured in Biomechanics Lab (PE 240) at the University of Lethbridge. There are no anticipated risks to you from participating in this research.

The potential benefit of your participation in this study is an understanding of your own motor skill pattern. Furthermore, it will identify major factors that contribute to a better smash by measuring body segment velocities and accelerations, joint angles, range of motion of wrist, elbow, hip, knee, ankle, bird velocity and trajectory. Such research will yield insightful instructions on how to execute a good badminton smash, as these instructions will help players learn how to smash well.

Your participation in this research is completely voluntary. You may withdraw at any time without any consequences or any explanation. If you do withdraw from the study your data will be deleted immediately.

In terms of protecting your anonymity, once you have agreed to participate in this study you will be assigned a numerical code to protect your anonymity. The signed consent form and the assigned code will be stored in a locked file cabinet in room PE239. All your kinematic data collection for the video will be assigned to your code. This code will be used instead of your name at all times. In addition, your confidentiality and the confidentiality of the data will be protected by researcher, Miss Zhao Zhang. Only the researcher will be able to access the personal information of the participants. All of the data collected will be securely stored in a password protected file (accessible only by researcher) on a Biomechanical Lab computer on a PE 240. The collected data will be stored for minimum of 5 years and maximum of 10 years for knowledge dissemination. This research will be presented in a Master's thesis. The thesis will be used for public research presentations and publications in the future.

In addition to being able to contact the researcher or supervisor at the above contact information, you may verify the ethical approval of this study, or raise any concerns you might have, by contacting the Office of Research Ethics at the University of Lethbridge at (403)-329-2747 or research.services@uleth.ca.

Your signature below indicates that you understand the above conditions of participation in this study and that you have had the opportunity to have your questions answered by the researcher. Thank you very much for your consideration!

Name of Participant

Signature

Date

A copy of this consent will be left with you, and a copy will be taken by the researcher.

*Yes, I would like to receive the video and photo containing my 3D motion analysis.
My email address is: _____*

**Appendix D:
Table for All Participants Information**

Subject (Novice Group)	Gender F/M	Age (yrs.)	Height (m)	Weight (kg)	Training Period (yrs.)
1	F	35	1.60	58	0
2	M	22	1.75	70	0
3	F	24	1.65	51	0
4	F	21	1.66	57	0
5	M	24	1.80	76	0
6	F	22	1.67	55	0
7	F	24	1.78	68	0
8	M	20	1.70	55	0
9	F	30	1.69	56	0
10	M	21	1.78	75	0
Mean ± DS		24.3±4.7	1.71±0.07	62.05±9.24	0
Subject (Skilled Group)	Gender F/M	Age (yrs.)	Height (m)	Weight (kg)	Training Period (yrs.)
1	F	24	1.71	68	6
2	M	20	1.73	61	8
3	M	20	1.70	89	5
4	M	26	1.73	73	16
5	M	22	1.85	62	7
6	M	20	1.74	82	6
7	M	24	1.89	74	5
8	M	28	1.76	69	7
9	M	26	1.78	70	5
10	M	21	1.78	68	6
11	M	20	1.82	75	5
12	M	23	1.78	73	9
13	M	27	1.77	66	4
14	M	24	1.73	72	4
Mean ± DS		23.2±2.8	1.77±0.05	71.56±7.73	6.6±3.1