KINEMATIC ANALYSIS OF FOREHAND DROP SHOT AND LONG SHOT SERVICES IN TABLE TENNIS

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ABSTRACT

Table tennis is one of the most widely played sports in the world. A frequent hand movement is compulsory to execute stroke than other limbs, especially the projection of racket and ball speeds, which can help to improve players' performance. Until now, research on table tennis serving is limited. Service was assumed important in table tennis because the effective serve may allow the serving player to have advantage and control over the game. The 3D dynamic analysis is the appropriate method to analyze a sport activity such as table tennis. Therefore, the aim of research was to determine the kinematic involved in arm segment rotations towards horizontal ball and racket head velocities during forehand service in table tennis. Yamaguchi's kinematic model is one of methods to analyze arm segment motion. However, the equations in Yamaguchi's model were not completed since only developed the model until proximal end of segment. Furthermore, the value of specific positions at arm segment in the model remained unknown. Thus, the present study has improved the Yamaguchi's kinematic model by adding some parameters (calculation of velocity until COM of segments and obtained the value of specific positions at arm segment) to complete the model and can be used to analyze table tennis serving motion. Twenty six participants were selected to participate in this research. The study captured radiography images of 10 participants to obtain the value of positions at arm segment. Furthermore, 16 collegiate table tennis players were selected to perform forehand drop shot and long shot services. Five infrared cameras operating at 250 Hz were used to record the table tennis serving motion. Radial deviation angular velocity was significantly correlated with racket velocity ($r_s = 0.638$, $P < 0.05$) and ball velocity during drop shot service ($r_s = 0.647$, $P < 0.05$). Racket velocity at impact exhibited a significant correlation with radial deviation ($r = 0.803$, $P < 0.05$) and wrist palmar flexion angular velocities ($r = 0.737$, $P < 0.05$)

during long shot service. The shoulder flexion and shoulder internal rotation velocities were significantly different between long shot and drop shot services (p = 0.001, p = 0.005). The amplitude of the graph during long shot service (Figure 4.6) was less sharp compared to the graph during drop shot service particularly in shoulder internal rotation, elbow flexion and wrist palmar flexion which revealed that players played both services with the same posture at different speed. Furthermore, the change in shoulder flexion and shoulder internal rotation at impact will distinguished between drop shot and long shot services. Moreover, it was concluded that increasing radial deviation will increase racket and ball velocities at impact during drop shot service. Increasing the radial deviation and wrist palmar flexion will increase racket head velocity at impact during long shot service. However, the ball velocity at impact could not be influenced by the arm segment rotations and racket speed during long shot service. Focusing on the recommendations above during training may allow the players to gain advantage over the game.

ABSTRAK

Permainan ping pong merupakan salah satu sukan yang terkenal di dunia. Pergerakan tangan yang pantas diperlukan untuk memukul bola supaya dapat menghasilkan kelajuan pada raket dan bola. Namun begitu, kajian mendapati analisis berkaitan servis dalam sukan ping pong sangat terhad. Servis dalam sukan ping pong merupakan sesuatu teknik yang penting kerana servis yang baik dapat menguasai sesuatu perlawanan. Analisis 3D dinamik adalah suatu kaedah yg sesuai untuk mengkaji pergerakan tangan terutamanya dalam sukan ping pong.Oleh itu, kajian ini bertujuan untuk mencari kaitan di antara kinematik tangan dengan kelajuan raket dan bola ketika impak bagi servis pukulan depan berjarak dekat dan jauh di dalam sukan ping pong. Model kinematik Yamaguchi merupakan salah satu kaedah untuk mengkaji pergerakan tangan. Walaubagaimanapun, persamaan-persamaan di dalam model kinematik Yamaguchi masih belum sempurna kerana model ini hanya dibangunkan sehingga ke akhir proksimal segmen. Selain itu, nilai tertentu pada posisi tangan masih tidak diketahui sehingga kini. Oleh itu, kajian ini telah menambahbaikan model kinematik tangan dengan menambahkan beberapa parameter (pengiraan kelajuan sehingga pusat jisim segmen tangan dan mendapatkan nilai pada posisi tangan) supaya dapat menyempurnakan model ini sekaligus dapat digunakan untuk mengkaji pergerakan servis dalam sukan ping pong. Seramai 26 orang peserta dipilih untuk menyertai kajian ini. Kajian ini telah memilih seramai 10 orang peserta untuk mendapatkan imej radiografi tangan. Tambahan pula, seramai 16 orang pemain kolej telah dipilih untuk melakukan servis pukulan depan berjarak dekat dan jauh. Sebanyak 5 kamera inframerah beroperasi pada 250 Hz telah digunakan untuk merakam pergerakan servis dalam sukan ping pong. Kelajuan putaran pada abduksi pergelangan tangan didapati mempunyai kolerasi signifikan yang positif dengan kelajuan bola (r_s = 0.647, P < 0.05)

dan raket ($r_s = 0.638$, $P < 0.05$)ketika melakukan servis pukulan depan berjarak dekat. Kelajuan putaran pada abduksi pergelangan tangan ($r = 0.803$, $P < 0.05$) dan fleksi pergelangan tangan ($r = 0.737$, $P < 0.05$) didapati mempunyai kolerasi signifikan yang positif dengan kelajuan raket ketika melakukan servis pukulan depan berjarak jauh. Kelajuan pada fleksi bahu dan putaran dalam bahu didapati sangat berbeza di antara servis pukulan depan berjarak dekat dengan berjarak jauh ($p = 0.001$, $p = 0.005$). Tambahan pula, amplitud pada graf ketika servis pukulan depan berjarak jauh didapati kurang tajam apabila dibandingkan dengan servis pukulan jarak dekat terutamanya bagi graf putaran dalam bahu, fleksi siku dan fleksi pergelangan tangan. Selain itu, perubahan kelajuan pada fleksi bahu dan putaran dalam bahu ketika impak dapat membezakan di antara servis pukulan depan berjarak dekat dengan pukulan berjarak jauh. Tambahan pula, menambahkan kelajuan pada abduksi pergelangan tangan dapat menambahkan kelajuan pada bola dan raket ketika impak bagi servis pukulan depan berjarak dekat. Manakala, menambahkan kelajuan pada abduksi dan fleksi pergelangan tangan dapat meningkatkan kelajuan raket ketika impak bagi servis pukulan depan berjarak jauh. Namun begitu, kelajuan bola tidak dipengaruhi oleh kelajuan raket dan putaran pada segmen tangan ketika impak bagi servis pukulan depan berjarak jauh. Cadangan-cadangan di atas dapat menambahbaikan prestasi pemain ping pong dalam sesuatu perlawanan.

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LIST OF SYMBOLS AND ABBREVIATIONS

TTAM	:	Table Tennis Association Malaysia
ITTF	:	International Table Tennis Federation
3D	:	3-dimensional
ETTA	:	English Table Tennis Association
GRF	:	Ground reaction force
ANOVA	:	Analysis of variance
N/A	:	Not applicable
DOF	:	Degree of freedom
EMG	:	Electromyography
COM	:	Center of mass
N	:	Reference frame, upper trunk
$\tilde{n}_x$	:	Reference frame, n was defined as setting x-axis point anteriorly
$\tilde{n}_z$	:	Reference frame, n was defined as setting z-axis vertically downward
$\tilde{n}_y$	:	Reference frame, n was defined as setting y-axis perpendicular to x- and z- axes
l_A	:	Length of humerus
l_C	:	Length of radius
A^*	:	COM humerus
B^*	:	COM ulna
C^*	:	COM radius
C_0	:	Proximal end of radius
B_0	:	Proximal end of ulna

A_0 : proximal end of humerus

D_0 : proximal end of hand

C_1 : distal end of radius

B_1 : Distal end of ulna

A : Humerus

B : ulna

C : Radius

D : Hand

$q_i (i = 1, 2, 3, ..., 7, \varphi)$: Angles that rotate around the arm segment

$\vec{p}$: Certain position at upper extremity

D' : The second rotation of wrist (hand) joint

v : Joints velocity

ω : Joints angular velocity

a : Joints acceleration

α : joints angular acceleration

D^* : COM Hand

UM : University of Malaya

UMMC : University Malaya Medical Center

AP : Anterior-posterior

δ : Width of humerus

l_B : Length of ulna

r : Length from B_0 to C_0 during elbow flexion at 90°

l_{CB} : Length from C_0 to B_1

φ : angle between the center of the concave proximal end of radius and the distal end of ulna

$\hat{a}_1, \hat{a}_2$, and $\hat{a}_3$	:	The axes of rotation at shoulder joint
ρ_A	:	Length from proximal end of humerus until COM humerus
ρ_B	:	Length until proximal end of ulna until COM ulna
ρ_C	:	Length until proximal end of radius until COM radius
ρ_D	:	Length until proximal end of hand until COM hand
AXIS	:	Two forearm models were used to define a priori two kinematic chains
ISB	:	International Society of Biomechanics

LIST OF APPENDICES

CHAPTER 1: INTRODUCTION

This chapter will briefly discuss on table tennis equipment, techniques and regulations to play. Furthermore, dynamic model of human motion will be explained particularly the relation between the dynamic model and analysis of table tennis movement. The Yamaguchi's kinematic model of arm segment will be described which later on will be utilized greatly in this research. After that, the aim of research will be clarified as a result after the discussion on the research gap (problem statements). Finally, the significance of the study and the correlation among chapters will be explained.

1.1 Background of Table Tennis

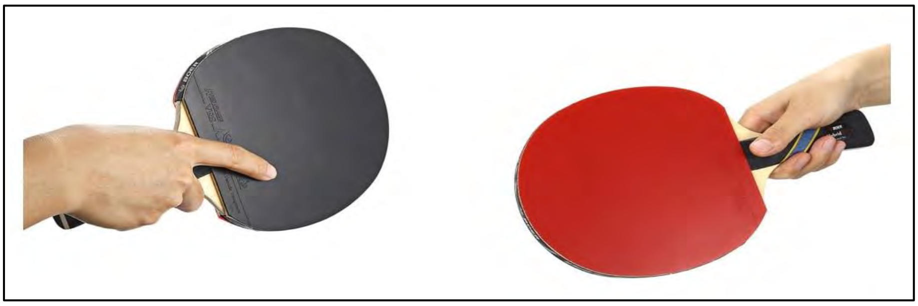
Table tennis is categorized as a racket sport (Figure 1.1). The differences between table tennis and other racket sports like squash and badminton are the shape, materials, color and size of both rackets and balls.

Figure 1.1: Equipment required to play in table tennis game reproduced from en.wikipedia.org

As mentioned in Heaton (2009), the diameter of the spherical ball is 40 mm and weighs at 2.7 g, which are only allowed in the game. In general, the ball that is used in a game is white or yellow in color. The table is set at 2.7 m long, 1.5 m wide and must be 0.7 m high above the ground (Figure 1.2). The net should be 15.2 cm high above the table. There are two ways to hold the racket, which are shake-hand grip and penhold grip (Figure 1.3). Shake-hand grip is executed with the thumb and index fingers only while the other three fingers are removed from the racket handle. Meanwhile, the penhold grip is executed as though you are holding a chopstick.

Figure 1.2: Table Tennis that allowed in the game reproduced from en.wikipedia.org

a)



b)

Figure 1.3: Types of grip in table tennis a) shake-hands grip b) penhold grip reproduced from sportten.com

Any sports clothing can be worn to play the game, although loose-fitting clothing is important to allow freedom of motion during games. Furthermore, the main clothing color should be different from the ball. A good selection of sport footwear will allowed better performance in the game. Good selection of sport footwear including good support around the heel and instep, anti-slipping and injury, and flexible.

Figure 1.4 showed the environment in table tennis tournament. Table tennis can be played singles (two players) or doubles (four players). The service rules require a server to throw the ball upward at least 16 cm before the server strikes the ball to the table and bouncing twice before being received by the opponent. The player can win a point if the opponent failed to strike the received ball, let the ball bounce twice before hitting it, touch the net or hit the ball twice. The first player who scores 11 points will win the game.

a) b)

Figure 1.4: a) Singles (two players during match) b) Doubles (four players during match) reproduced from tabletennisspot.com and zimbio.com

Racket angles are also important in table tennis, in which different angles will produce various strokes and different amount of spin (Heaton, 2009). There are three basic racket angles, which are neutral, open and closed (Figure 1.5). The racket angle is described as neutral when the head of the racket is held in the vertical position (Heaton, 2009). When the hitting surface is angled upwards, then the racket angle is described as open and will produce backspin (Hodges, 1993). The racket angle is described as closed when the hitting surface is angled downwards and this technique will produce topspin (Hilton & Eaton, 1985).

a) b) c)

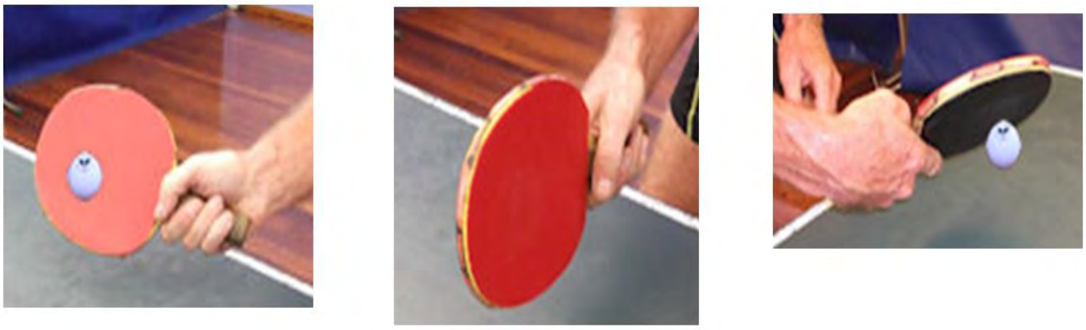


Figure 1.5: Different racket angles a) open b) neutral c) close reproduced from allabouttabletennis.com

1.2 Introduction in Dynamic model of Human Motion in Sports

The 3D dynamic analysis is the appropriate method to analyze a sport activity (Lloyd, Alderson, & Elliot, 2000) and clinical activity (Sancho-Bru, Mora, León, Pérez-González, Iserte & Morales, 2014; Western, Ketteringham, Neild, Hyde, Jones & Davies-Smith, 2013). Although the 2D dynamic analysis is adequate to understand the mechanical transform in human motion, the 3D dynamic analysis is more accurate as it approaches human motion reality (Lloyd, Alderson, & Elliot, 2000). However, it is difficult to perform the 3D analysis during matches because of factors like anatomy landmarks identification for constructing the 3D kinematic model, clothing that covers the arm segment and calibration of experimental area (Lloyd, Alderson, & Elliot, 2000). Therefore, it was recommended to implement a 3D analysis in the laboratory with simulation match conditions (Lloyd, Alderson, & Elliot, 2000).

The combination of skeletal rigid body modeling and the soft tissue continuum dynamic analysis may become an obstacle for a simple control of simulation (Maurel & Thalmann, 1999). A rigid body dynamic analysis that is not influenced by continuum dynamic analysis would be more suitable for real-time control (Maurel & Thalmann, 1999). This means that the rigid body and soft tissues are considered as a similar rigid body motion with a negligible soft tissue deformation (Maurel & Thalmann, 1999).

Dynamic models of human motion are available for selection and can be used for biomechanical analysis purposes. The dynamic models can be reached through databases, such as Web of Science, ScienceDirect and Taylor & Francis Online. The software packages, such as MATLAB (MATLAB, The MathWorks, Inc., Natick, MA), SIMM (SIMM, Musculographics Inc., IL, USA, Delp and Loan, 1995) and AUTOLEV (OnLine Dynamics) can be used to make the calculation easier. However, researchers used different methods in dynamic analysis, depending on purposes and software packages available.

Several studies that utilized dynamic model to analyze table tennis movement were Iino and Kojima (2016a), Iino and Kojima (2016b), Lee and Xie (2004a) and Iino, Mori and Kojima (2008). Other studies such as Tanabe and Ito (2007) used the dynamic model to study on tennis service movement while Lloyd, Alderson and Elliott (2000) utilized the dynamic model to analyze the cricket bowling delivery.

1.3 Yamaguchi's kinematic model of arm segment

In recent years, dynamic model proving to be beneficial to various multibody dynamic systems specifically in the analysis of human motion. Yamaguchi (2006) is one of methods to analyze arm segment motion. A lot of studies have utilized upper limb model to analyze body movement (Bankosz & Winiarski, 2018; Lanzoni, Bartomei, Michele & Fantozzi, 2018). Chan and Moran (2006) developed a model of a primate arm. Furthermore, they used software package AUTOLEV to develop musculoskeletal dynamics model which based on Kane's method. Kane's method same as Lagrange's and Newton–Euler's methods are methods used to solve dynamic problems. Several studies used Newton-Euler method such as Ayusawa, Ikegami and Nakamura (2014) and Aslanov, Kruglov and Yudintsev (2011).

Yamaguchi (2006) used Kapandji (1982) and Kane's method to develop seven DOF (degree of freedom) arm segment kinematic models. Study on the upper limb physiology (Kapandji, 1982) was utilized in the development of 3D kinematics model of the arm segment. Kane's method used vector product to allow 3D analysis on body movement. Vector dot and cross products were preferably used than the derivation and integration to obtain acceleration and velocity. Table of direction cosines is important to develop the present model. The table of direction cosines in the present study was widely used, mostly in the robotic and human motion field (Kane & Levinson, 1985; Shah, Saha & Dutt, 2013; Jazar, 2010) to describe the direction of the vector in coordinate axes (Yamaguchi, 2006). The kinematic model of the upper extremity consisted of the trunk, humerus, ulna, radius and hand. The seven DOF were shoulder adduction/abduction, shoulder flexion/extension, shoulder external/internal rotation, elbow flexion/extension, forearm supination/pronation, ulnar/radial deviation, and wrist dorsi /palmar flexion. The motion of the bones and joints were accumulated in the Yamaguchi's model to attain human motion reality at the upper extremity, mainly at the forearm supination/pronation (Yamaguchi, 2006). AUTOLEV is a symbolic language based on the Kane's method (Chan & Moran, 2006; Kane & Levinson, 1985) which was used to develop an algorithm for dynamical equations of motion and generate a forward dynamic model of the arm segment.

1.4 Problem Statement

In Malaysia, badminton, squash, football and hockey are preferred compare to table tennis. Badminton and football have always been a topic in social media and advertisements, which could cause table tennis to lose effectiveness amongst sponsors. A sponsor plays an important role in increasing players' performance. Several improvements were implemented to increase the Malaysian table tennis players' performance by sponsors, such as players were to undergo an intensive training session in China (International Table Tennis Federation, 2017), increase in tournaments (Utusan Online, 2003) and allowing the youth players to witness themselves in world tournaments to gain experiences (Astro Arena, 2017). Moreover, the Journal of Sports Sciences published a special issue on April, 2017 in regard to table tennis since the global competitiveness of the sport was violated (Taylor & Francis, 2017). With this, they wished that the sport future is unharmed and effective.

Most papers elaborated on the psychology and techniques of playing the game. Approximately 70% (n = 251) of the papers have dwelt in table tennis players' psychology and playing techniques. 10% of papers discussed in biomechanics or sport science and another 20% of papers deliberated on sport history, injuries and software packages. However, adapting knowledge on biomechanics of body movement can give better results to players and the sport itself. Studying the techniques and movement data of skilled players can determine potential success or otherwise. Players may find that discussion on force, acceleration, torques and movement momentum are difficult to understand. Biomechanists can help coaches improve players' movements by sharing their knowledge about the field. Therefore, this analysis can be useful whereby it can indirectly help players to win a match. Biomechanics is the study of body movements by considering mathematics, physics and biology as the disciplines or areas of knowledge that can help to solve and understand a phenomenon (Carr, 1997; Winter, 2009).

There were recent research in biomechanical of table tennis such as Iino, Mori and Kojima (2007), Iino and Kojima (2008), Iino and Kojima (2011), Iino and Kojima (2016a), Iino and Kojima (2016b), Lee and Xie (2004a) and Wang, Zhou, Li, and Li (2008). Generally, they studied the contribution of joint rotation movements of skilled players in strokes/rally games. They emphasized on upper limb rotations to analyze players' movement in their studies.

Trained players could twist hand efficiently during table tennis strokes as compared to intermediate players (Hao et al., 2010). Elbow extension and wrist dorsiflexion could contribute significant difference in racket velocity between backspin and topspin in table tennis backhand strokes (Iino, Mori, & Kojima, 2008). Furthermore, elbow and shoulder angles are important to increase ball speed in rally games among elite table tennis players (Lee and Xie, 2004). Sufficient use of lower trunk axial rotation and shoulder internal rotation could accelerate the racket during table tennis forehand stroke in minimum time (Iino and Kojima, 2009; Iino and Kojima, 2011). Late timing of axial rotation of the upper trunk and upward thrust of the shoulder could improve players' performance during table tennis backhand stroke (Iino and Kojima, 2016).

Until now, research on table tennis serving is limited. A study on the comparison between drop shot and long shot table tennis services performance was conducted by Wang et al. (2008). Since the velocity of ball, racket and arm segments were almost the same between drop shot and long shot services, it was concluded that the service performance was moderate (Wang et al., 2008). Service was assumed important in table tennis because the effective serve may allow the serving player to have advantage and control over the game (Lanzoni, Michele, & Merni, 2014). Chinese table tennis players are always concerned with service or the first three strokes (Hilton & Eaton, 1985; Hsu, 2010). The Chinese players frequently won because of the powerful first three strokes (Cai, Hua, & Tang, 2001). These facts have given benefits to players to organize good strategies during training. However, the mechanical knowledge on how they served is important to hit the ball with the right postures. To our knowledge, there is limited study that had emphasized on kinematic contributions to the table tennis service.

Observations from previous studies found that the served ball mostly landed at the center and near the net (Lanzoni, Michele, & Merni, 2014; Hilton & Eaton, 1985; Ghoneim & Salem, 2010). In fact, over 75% of balls served by Asian and European players landed at the center/side and near the net (Lanzoni, Michele, & Merni, 2014). Thus, it is presumed that the quality of a served ball requires landing the ball near the net. Since the drop shot service is one of the best strokes, examining the service kinematics could enhance the players' performance. However, to authors' best knowledge, the study on this matter is very limited.

Nevertheless, variation in service was needed to increase capability of players in controlling the games (Hodges, 1993). The kinematic differences between various services have not been studied in detail. The contributions of body segment rotations to the ball impact during different services remain unclear. It was suggested that the long shot service could be performed after several times performing drop shot service to increase difficulty on the opponent in returning the service caused by the surprise factor (Hilton & Eaton, 1985). To hide the technique of service from opponents, serving is done by assuming similar posture for different services but should adjust the racket angle and contact point on ball or racket just before the impact (Heaton, 2009). This would allow change between drop shot and long shot services in the brief seconds. The position and distance from the table at which a player will executes the service will also be observed by the opponent as this can determine the distance of landed ball, spin and speed of ball, and the intended type of service (Heaton, 2009; Hodges, 1993). If different services are executed in the same position and postures, the technique of services can be concealed from the opponent. The sudden change may catch the opponent unaware of the changing speed of the ball and the location of landed ball. These situations will yield an advantage to the server and give the opponent less time to recover for the next stroke. However, to the authors' best knowledge, there was limited study that analyzed the mechanical differences between different types of service. With these knowledge, the players may anticipate his opponent's service and gain advantage over the game.

To execute a biomechanical analysis of table tennis strokes requires knowledge in dynamic model of body movement. Previous studies showed that most of them used software packages to analyze body movements (Sancho-Bru et al., 2014; Lloyd, Alderson, & Elliot, 2000, Iino and Kojima, 2016b). However, to replicate simulation from previous studies will be difficult due to financial problem and not publicly accessible for some researchers (Saul, Hub, Goehler, Vidt, Daly, Velisar & Murray, 2014; Sancho-Bru et al., 2014). Therefore, researchers always have to find other alternatives to analyze body movements.

1.5 Aim and Objectives

The overall aim of this study is to determine the kinematic involved in arm segment rotations towards horizontal ball and racket head velocities during forehand service in table tennis, in which these findings can improve players' performance.

To achieve the aim, four objectives have been recognized which are:

1. To improve and validate the existence of 3D kinematic model of arm segment (Yamaguchi's kinematic model).
2. To determine the contributions of arm segment rotations towards the horizontal ball and racket head velocities during table tennis forehand drop shot and long shot services at impact.
3. To compare the kinematic involved between the two types of services (drop shot vs. long shot) in table tennis.

1.6 Significance of Study

Many research discussed on upper limb movement in table tennis, including Lee and Xie (2004a), Iino, Mori and Kojima (2008), Iino and Kojima (2009), Iino and Kojima (2011) and Iino and Kojima (2016a). A frequent hand movement is compulsory to execute stroke than other limbs; thus, the arm segment is assumed to have an influence on table tennis performance, especially the projection of racket and ball speeds, which can help to improve players' performance (Hodges, 1993). Furthermore, the arm segment dynamic model such as Yamaguchi's kinematic model of arm segment is useful to confront problems in human motion, such as analyzing and preventing injury of the human arm. Additionally, the model can be utilized to improve athletes' performance. Investigation on the correct posture and joint movement while playing games will help to improve wrong actions and reduce injuries (Chang, Jung, & Tsung, 2010).

1.7 Correlation among Chapters

Chapter 1 discusses on the study background, problem statement, objectives and significance. This chapter will briefly discuss on table tennis equipment, techniques and regulations to play. Furthermore, dynamic model of human motion will be explained particularly the relation between the dynamic model and analysis of table tennis movement. The Yamaguchi's kinematic model of arm segment will be described which later on will be utilized greatly in this research to analyze table tennis movement. After that, the aim of research will be clarified as a result after the discussion on the research gap (problem statements). Finally, the significance of the study and the correlation among chapters will be explained.

Chapter 2 is on literature review which reports on the general information about table tennis, overview of the 3D dynamic arm segment model and the previous studies on biomechanical analysis on strokes in table tennis. The review was organized based on the study objectives. The information from the literature review assisted the author to organize the study methodology, predict the findings and verify the results with previous studies. Topics relevant to table tennis biomechanics, such as forehand stroke, backhand stroke and ball and racket aerodynamics are discussed later. Meanwhile, topics related to 3D dynamic model of upper limb, including upper limb model with muscles, upper limb model without muscles, software packages related to the upper limb motion are reviewed afterwards.

Chapter 3 discusses the research methodology. The ethical clearance application by the author's institution was described in this chapter. This chapter also discusses the experimental procedure to analyze body movement and methods to improve the existing 3D arm segment kinematic model along with its algorithm (Yamaguchi's model). An experiment of table tennis serving motion was conducted to obtain the kinematic data for validation of the improved model. Finally, the application of the improved model to the sport biomechanics, specifically during the table tennis serving was described. This stage discussed on the demographic of the selected participants in this study, experimental procedures and statistical analysis that were used to achieve the objectives of the study. Then the results will be analyzed and discussed after the final stage.

Chapter 4 discusses the results and the discussion on the findings. These findings were used to fulfill the objectives of the study. The improved model and its algorithm were developed after adding some parameters and validated. The table tennis kinematics were discussed to find the relation and contributions to the improvement in table tennis.

Chapter 5 discusses the conclusions and recommendations for future research. The conclusions were made after obtaining the findings which to fulfill the aim and objectives of the research. Several recommendations were discussed for future research. By introducing other methods and append other parameters, the players can anticipate their opponents' movement during games and gain control over the games.

Figure 1.6 showed the process to complete this study.

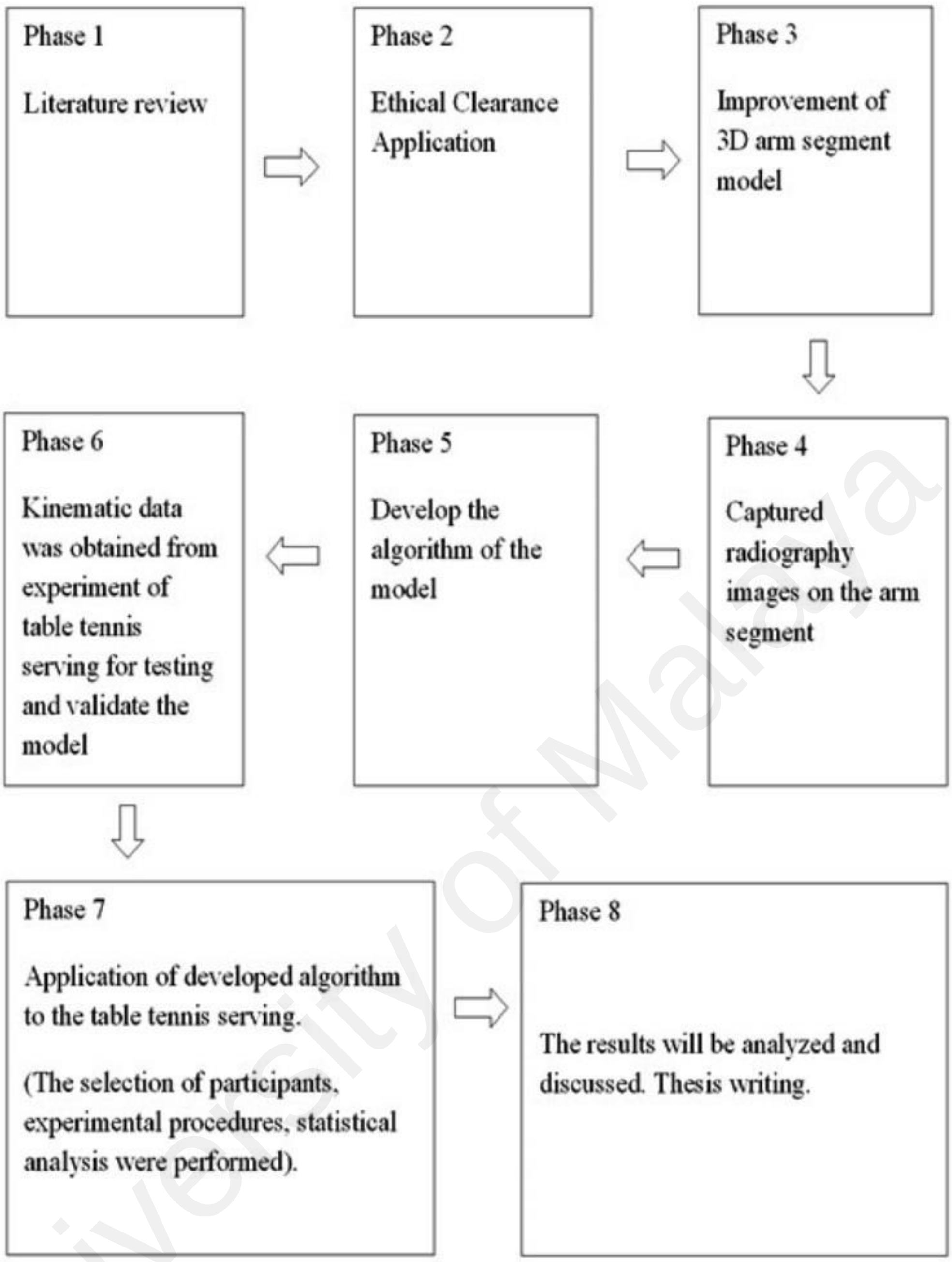


Figure 1.6: The flowchart of overall study

CHAPTER 2: LITERATURE REVIEW

This chapter delivers a crucial review on areas related to biomechanical analysis of table tennis and 3D dynamic model of the upper limb. The review was organized based on the study objectives. The information from the literature review assisted the author to organize the study methodology, predict the findings and verify the results with previous studies. Topics relevant to table tennis biomechanics, such as forehand stroke, backhand stroke, other strokes, and ball and racket aerodynamics are discussed later. Meanwhile, topics related to 3D dynamic model of upper limb, including upper limb model with muscles, upper limb model without muscles, software packages related to the upper limb motion are reviewed afterwards. Finally, a conclusion is made to provide a summary of information on the latest findings and contributions from previous studies to the author and readers.

2.1 History in Table Tennis

Table tennis was adapted from lawn tennis which could be played on a dining table. It was stated from Hodges (1993) that the sport was invented in the 1890s. Ping pong was the other name for table tennis, which was named from the sound of the ball made, and Whiff-Waff was named from the sound of the racket motion (Heaton, 2009; Hodges, 1993).

In 1902, a Japanese professor introduced table tennis game to his students in Japan (Lee, 1991). Meanwhile, a British businessman named Edward Shires, introduced this game to Vienna and the Budapest residents (Lee, 1991). It was believed that the sport became renowned after it was introduced to several countries in the world (Lee, 1991).

England produced a lot of champions in the early days of the sport (Heaton, 2009). Later in 1927, an English Table Tennis Association (ETTA) and International Table Tennis Federation (ITTF) were officially formed at the same time the First World Championships were held (Hammersley-Parker & Eaton, 1985; Lee, 1991). The notable European table tennis players, included Fred Perry who won the World Singles Champion in 1929, Di Rowe who won European Team title and Double Title, John Hilton who won the European Championships in 1980 and Jill Parker who won the European Singles title in 1976 (Heaton, 2009; Hilton & Eaton, 1985).

In early 1960s, Asian players started to take over the game from the European players (Hodges, 1993). Until now, the Chinese players are still dominating the game (Hodges, 1993. One of the Chinese notable players was Chang Tse Tung, who won the World Table Tennis Championships in 1963 and 1965 (Heaton, 2009). Nowadays, remarkable Chinese players, include Fan Zhen Dong who won Men's single World Cup in 2016 (International Table Tennis Federation, 2016), Xu Xin who was nominated as the second ranked player in the world, as of September 2018 (International Table Tennis Federation, 2018), Chen Meng who won Women's Single titles 2017 in Qatar (International Table Tennis Federation, 2018), and Zhu Yu Ling who won Women's World Cup, Ontario in 2017 (Wikipedia, 2017).

2.2 Development of Table Tennis in Malaysia

In 1952, a table tennis club known as Table Tennis Association Malaya was established in Malaysia (Lee, 1991). However, the name of the club was changed to Table Tennis Association Malaysia (TTAM) in 1964 (Lee, 1991). Since it was established, a lot of people started to play table tennis as a recreational activity (Lee, 1991). Until today, most of the national and advanced table tennis players consist of Chinese players (Lee, 1991).

It was the first time that a team consisting of three male players who joined an international tournament, Table Tennis World Championships, Japan in 1972 (Lee, 1991). It was reported that the Malaysian table tennis team finished at 25th place out of 39 teams which participated in the tournament (Lee, 1991). In 1972, TTAM was one of the founders that established the Asian Table Tennis Union. Since then, Malaysia has become one of the important roles in Asian table tennis game development (Lee, 1991). In 1979, a representative from Malaysia, Datuk Michael Chen was appointed as one of International Table Tennis Federation (ITTF) Council Members (Lee, 1991). Meanwhile, in 1983, a representative from Malaysia named Yap Yong Yih was appointed as one of ITTF Council Members (Lee, 1991).

Since 1980, Malaysia has sent players to Japan, South Korea and China to undergo intensive training sessions (Lee, 1991). It was known that the three countries were leaders in the world's table tennis game (Lee, 1991). Today, several famous national table tennis players are Leong Chee Feng, Ashraf Haiqal Rizal and Shakirin Ibrahim. At the 2015 SEA Games, Malaysia won one silver and three bronze in table tennis games (Seng, 2017).

2.3 Types of Racket

Racket, ball, net and table are the required equipment to play table tennis. The characteristics of ball, net and table that must be approved by ITTF was discussed in Chapter 1. However, there are various types of racket which could give different speed, spin and control (Hodges, 1993). A beginner player is suggested to buy a racket which gives control and slow speed. With this, the beginners can easily understand and play the game. However, some opinions suggested a beginner to select a racket that is suitable to play at high level (Hilton & Eaton, 1985). Table tennis game is about speed, therefore, a player should adopt this situation and the skill will be developed after repeated trainings (Hodges, 1993).

Figure 2.1 showed the racket characteristics which consists of blade, rubber and sponge (Hilton & Eaton, 1985). Blade is the racket without its rubber. Blade must be made 85% from the wood (Heaton, 2009). Some players added carbon fiber to their blade to increase its speed (Hodges, 1993). Blade can be divided into five types which are defensive blade (slow), all round blade (medium), offensive blade (fast), carbon blade (very fast) and soft wood (Heaton, 2009; Hodges, 1993). The surface of the blade must be flat and rigid, regardless of any size, shape or weight. Most skilled players select and stick to the blade that fits on his/her play style and replace the rubber and sponge when the surface can no longer grip or spin (Hilton & Eaton, 1985).

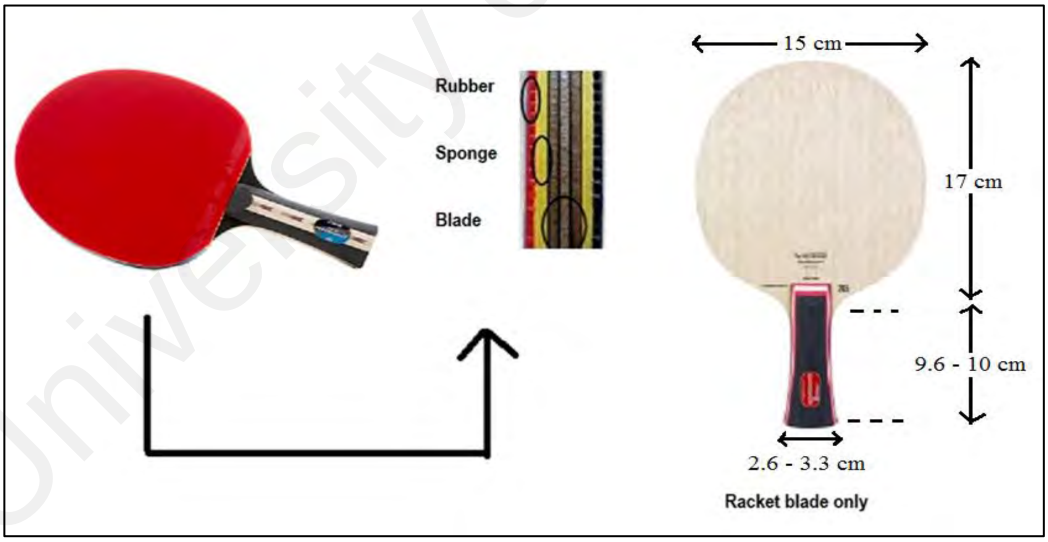


Figure 2.1: The table tennis racket

The blade is often enclosed with rubber which must have a matt finish and colored in red on one side and black on the other (Heaton, 2009). There are various types of rubber and not all consist a sponge attached to the rubber during manufacture

(Hodges, 1993). However, a player must use rubber that is approved by ITTF (Heaton, 2009; Hilton & Eaton, 1985). Rubber can be categorized as long pimples, short pimples, reversed rubber and anti-spin rubber (Hammersley-Parker & Eaton, 1985). Players use long pimples to defend, anti-spin rubber to kill spin and give control, reversed rubber to give fast speed and short pimples to produce the desired speed and control (Hodges, 1993; Hilton & Eaton, 1985).

2.4 The stroke Cycle

Figure 2.2 showed four phases in a table tennis game, which are ready position, backswing and preparation, forward swing and contact and follow through (Hodges, 1993). The ready position is defined as a neutral position, in which it is a ready position to play all possible strokes (Heaton, 2009). The player is in a position to start playing the game or waiting to return a ball from his/her opponent (Heaton, 2009). Backswing and preparation phase is a phase where a player starts to swing his/her racket arm from the back and be ready to strike the ball (Hodges, 1993). Forward swing and contact phase is a phase where a player swings his/her racket arm forward to make contact with the ball (Hodges, 1993). Finally, the follow through phase is a phase where a player moves his/her body to complete the stroke and return to the ready position phase (Heaton, 2009).

Figure 2.2: The stroke cycle in table tennis which reproduced from sydneytabletennis.net

2.5 Strokes

To start a game in table tennis, a service has to be used (Hammersley-Parker & Eaton, 1985). The service rules require a player to throw a ball vertically upward at least 16 cm before it can be struck on the way down (Heaton, 2009). Service in table tennis is an important stroke that could determine whether a player could control the game or otherwise (Lanzoni, Michele, & Merni, 2014). There are two basic services in table tennis, which are forehand and backhand services (Figure 2.3). All services and strokes can be played as long shot or drop shot strokes (Hodges, 1993).

a) b)

Figure 2.3: The basic services. a) forehand service b) backhand service reproduced from myactivesg.com

Figure 2.4 showed the location of the first bounce for drop shot service which should be near the net of the server's table side, while for long shot service it should be between the end of the server's table side to the middle of the server's table side (Hilton & Eaton, 1985; Heaton, 2009). The third bounce for drop shot service must be located near the middle of the opponent's table side. Meanwhile, there was no third bounce for long shot service, which was out of the table area (Heaton, 2009).

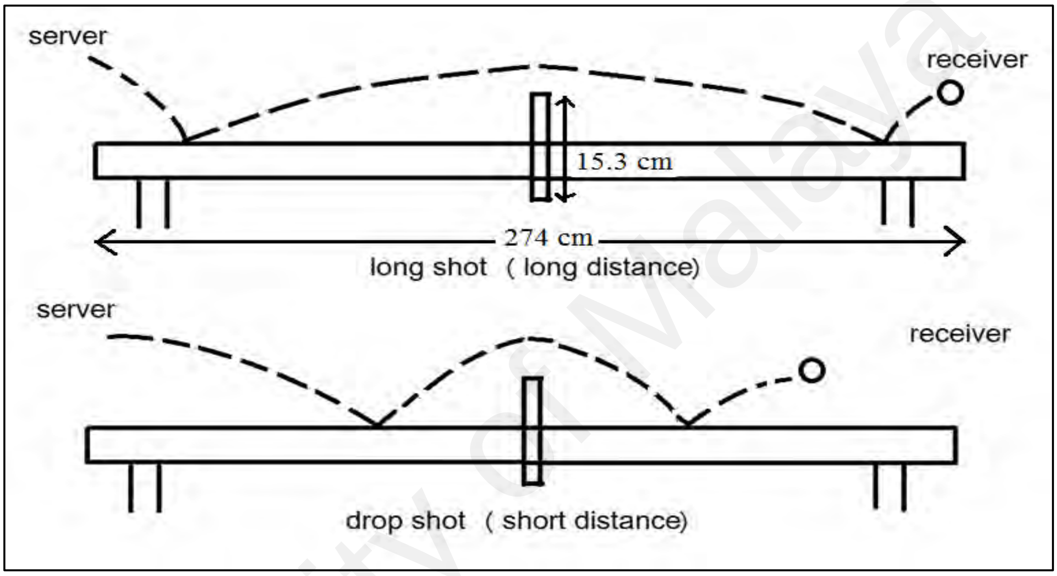


Figure 2.4: Different position of ball bounces affects length of serves. The figure was adapted from Heaton (2009)

Long shot service is often being played to obscure the opponents after a few times implementing drop shot service in the games (Hilton & Eaton, 1985). Heaton (2009) mentioned that the difficulty caused by a surprise factor in returning the service could exceed more than 50%.

However, the drop shot service was revealed to be more powerful as compared to long shot service (Hodges, 1993; Lanzoni, Michele, & Merni, 2014). Furthermore, Hilton and Eaton (1985) and Hodges (1993) indicated that drop shot service was the best and effective service in table tennis. Observations from previous studies found that the served ball mostly landed at the center and near the net (Lanzoni, Michele, & Merni, 2014; Hilton & Eaton, 1985; Ghoneim & Salem, 2010). In fact, over 75% of balls served by Asian and European players landed at the center/side and near the net (Lanzoni, Michele, & Merni, 2014).

Nevertheless, variation in service was needed to increase players' capability in controlling the games (Heaton, 2009; Hodges, 1993). Heaton (2009) stated that skilled players constantly performed different services with the same postures but could instantly (spontaneously) change the racket angle before the impact. A service can be varied by changing the point of contact on the ball, changing the angle of the bat on contact with the ball, changing the height of the toss, and disguising the follow through (Hilton & Eaton, 1985).

Figure 2.5 showed the basic stroke in table tennis. The served ball will be hit back by an opponent with four ways of basic strokes, which are forehand push, backhand push, forehand drive and backhand drive (Heaton, 2009). The service return is the second important in table tennis game after the service because a good return by a receiver gives high chances to the receiver to control the rally (Hilton & Eaton, 1985). Push strokes are used to control, when the receiving ball is low, and play in short distance (Hodges, 1993). A player use a push stroke to prevent an opponent from taking control of the game or to force an error (Heaton, 2009). Control is obtained by playing the stroke close to the body and using the wrist and elbow (Heaton, 2009). Drive strokes are produced by using a closed racket and hence produce topspin (Hodges, 1993). This stroke is developed to play fast and hard (Heaton, 2009).

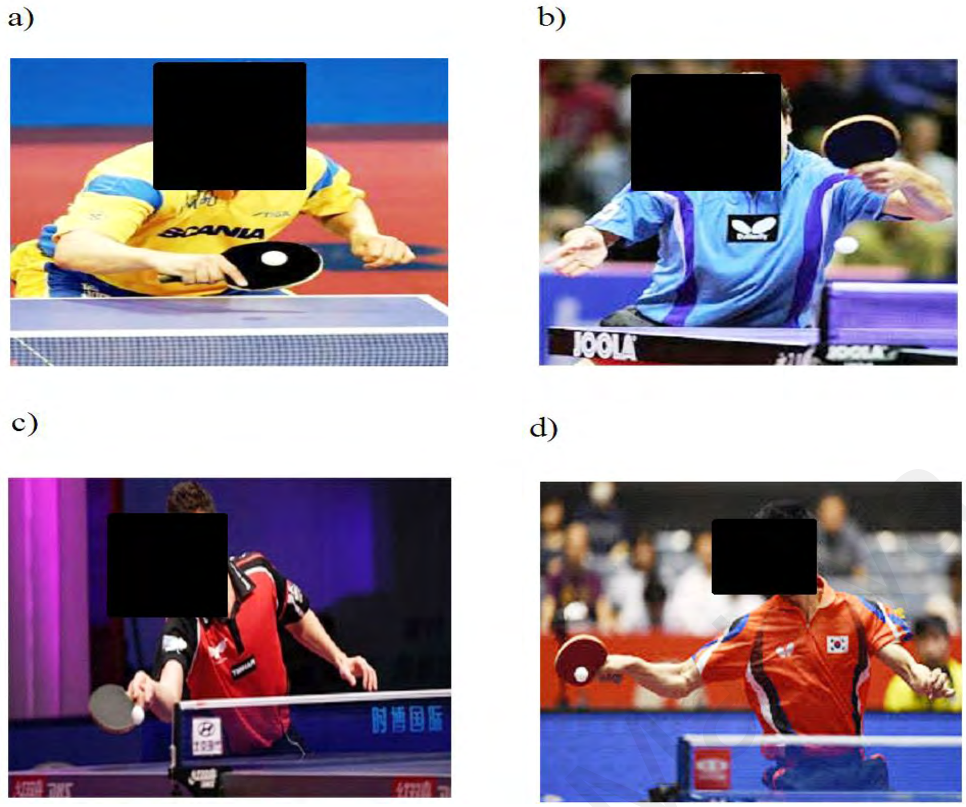


Figure 2.5: The basic strokes. a) backhand push (open racket) b) backhand drive (closed racket) c) forehand push (open racket) d) forehand drive (closed racket) reproduced from experttabletennis.com

When playing any strokes, a player should adapt suitable postures for different line of play (Heaton, 2009). Figure 2.6 showed the three major lines of play which are across the diagonal, down the line and into the middle. The body movement, footwork, direction of racket, racket angle or contact ball on racket are assumed differed when playing the same stroke but different lines of play (Hilton & Eaton, 1985).

a) b) c)

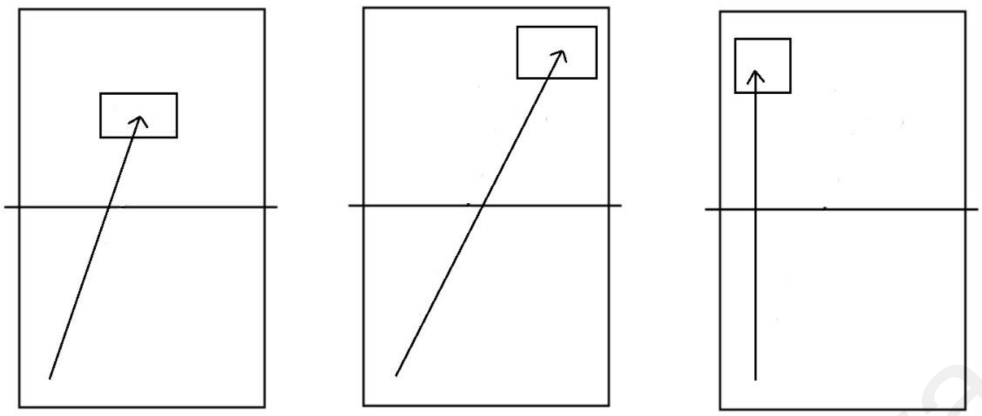


Figure 2.6: Three types of line of play. a) into the middle b) across the diagonal c) down the line. The figure was adapted from Heaton (2009)

The advanced strokes or services are developed from the basic forehand and backhand strokes (Hodges, 1993). However, different lengths of swing, racket angle and stroke speed will develop different advanced strokes (Hilton & Eaton, 1985). Examples of advanced strokes are chop, float, block, forehand counter-spin and flick return (Heaton, 2009).

2.6 Methodology for Systematic Review

Existing articles were mainly searched by using the following databases: Google Scholar, ScienceDirect, International Journal of Table Tennis Sciences, Taylor & Francis Online, and Web of Science. Figure 2.7 showed the flowchart of systematic review in table tennis. The keyword used was table tennis, which produced 251 related journals. At this stage, all related journals to table tennis appeared in the search engines, such as players psychology, injuries, health, history, the development of table tennis equipment and software tools, techniques in table tennis, ball and body movement. At this stage, articles discussed on other racket sports and non-English articles were excluded. Then, 218 articles were screened for title and abstract. The "table tennis" keyword was combined with other keywords such as "movement", "performance", "forehand stroke", "backhand stroke", "stroke", "service", "biomechanics", "upper limb" and "contribution of rotation" so that the inclusion criteria which were technique, ball movements and players movements/posture during playing were included in the selected articles. The exclusion criterion for selected articles was studies that involved in player's psychology during games, tactic, table tennis equipment and software tools, health, history and injuries. Later, 34 articles were assessed for eligibility. Then, 4 articles were removed from the review because it was duplicated from the other. Finally, 30 selected articles were included for review. The content of the articles which were related to the contributions of ball and players' movement during table tennis games were considered at this stage. The selected articles were divided into 6 groups, which were "strokes and techniques in table tennis", "analysis of body movement for forehand stroke", "analysis of body movement for backhand stroke", "other analysis on body movement of strokes", "ball movement" and "system used and statistical analysis". These articles were analyzed based on methodology, research equipment and contributions to table tennis. These selected articles will become substantial references for future research work on the biomechanical analysis of table tennis.

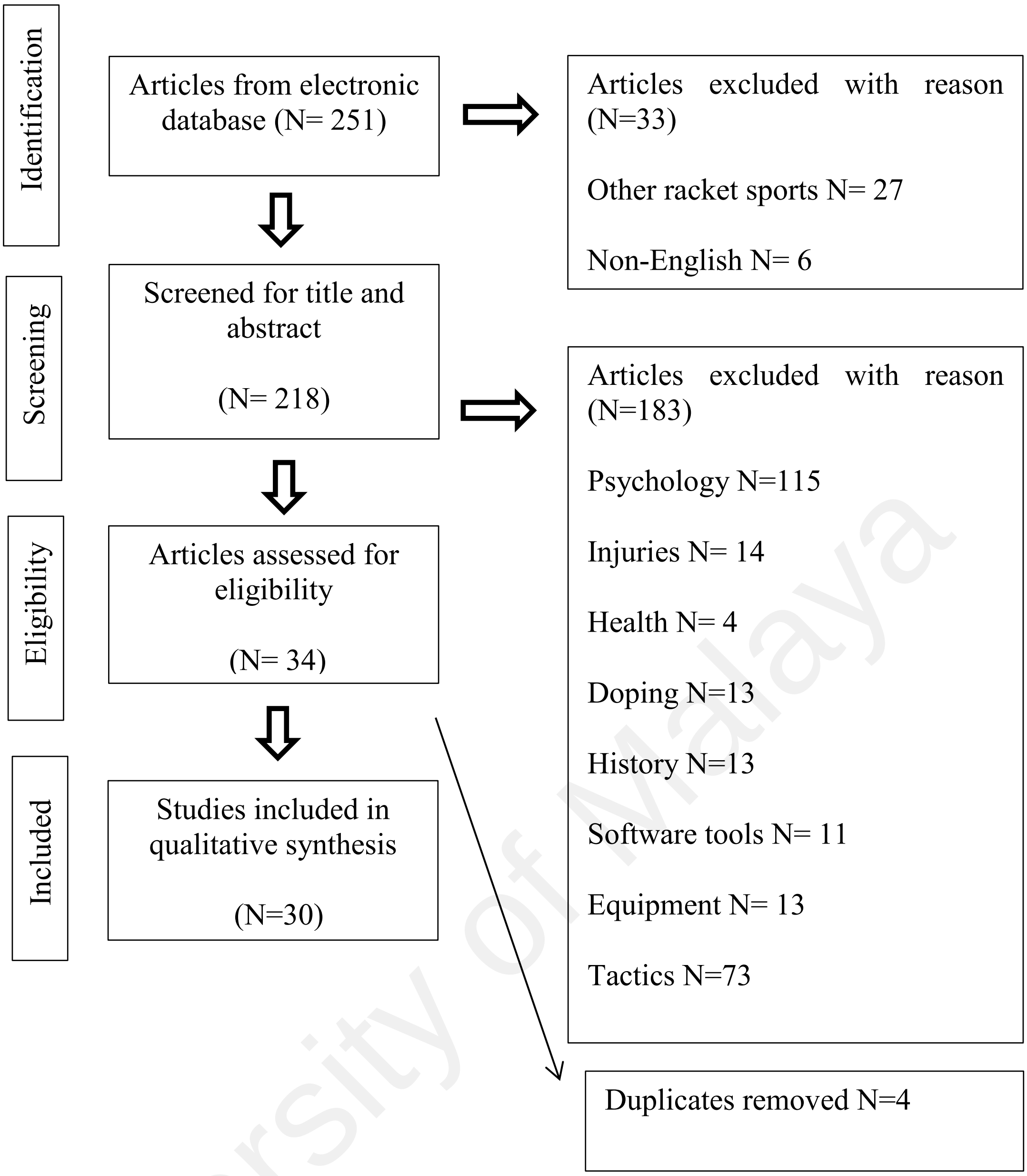


Figure 2.7: The flow chart of systematic review in table tennis

2.7 Review from Previous Articles

2.7.1 Strokes and Techniques in Table Tennis

Several authors concluded that the skilled players always pay more attention on the first three strokes (Cai, Hua & Tang, 2001; Hsu, 2010). Chinese players always compete and succeed on the first three strokes which encouraged the other players to adopt their technique (Lee & Xie, 2004a). Cai, Hua, and Tang (2001) found that winning percentage by using serve and attack technique for Chinese players was 66.95 % while

Sweden players was 58.12 %. Zhang, Liu, Hu, and Liu (2013) also found that Chinese players were better than other players for serve and attack technique. They found that Chinese male and female elite table tennis players were “excellent” for all techniques, except for male players which were rated as “good” for the first and third strokes. However, other elite players were rated as “general” for all techniques. They concluded that the Chinese players’ techniques were better than other players.

Most players played forehand topspin which was believed to be the most successful stroke (Ghoneim & Salem, 2010; Lanzoni, Michele & Merni, 2014; Iino, Mori & Kojima, 2008). Furthermore, Lanzoni, Michele, and Merni (2014) found that the highest percentage of stroke used in the game was forehand topspin (19.5 %, n = 720). Besides, Ghoneim and Salem (2010) found that forehand smash is more efficient than backhand smash. Forehand smash allows the body to produce more energy due to the technique body position as compared to backhand smash.

Another suggested technique is shadow practice, which means that a player exercises the stroke techniques without a ball to enhance his/her performance level during training. Flores, Bercades, and Florendo (2010) proved that shadow practice can improve the skill of beginners in backhand drive stroke. Two different groups were formed; a control group and an experimental group. The control group is practiced by executing the backhand strokes in combination with multi-ball practice. The experimental group performed the shadow practice with a combination of multi-ball practice. The number of balls that landed at the designated area and cleared the optimum height instructed by the authors was counted and became the participant’s score. The number of balls in the control and experimental groups was 64.5±20.59 and 67.2±17.8 in the pre-test, 81±14.25 and 81±10.37 in the post-test and 78.86±10.88 and 83.6±13.01 in the retention test, respectively. The results showed that a large difference in the number of balls in the pre- and post-tests was observed, indicating that both groups performed backhand drive stroke successfully. Nevertheless, there were no significant difference between the post and retention test for both groups which means the players retained their performance. It was recommended to practice this technique to improve the backhand stroke performance for the beginners.

2.7.2 Analysis of Body Movement for forehand stroke

Many studies were conducted to determine the different techniques between winning and losing players (Ando, Ae, Yuuki, Hagihara & Kuraki, 1992; Hao, Tian, Hao & Song, 2010; Hsu, 2010; Kasai & Mori, 1992; Lee & Xie, 2004a; Zhao, Lu, Jaquess & Zhou, 2018). Most importantly, to be a winner, one must understand the opponent's tactic and strategy as well as always be prepared to control the game (Hao et al., 2010). Moreover, it was said that skilled players can twist their hands quickly and efficiently during strokes than other players (Hao et al., 2010; Kasai & Mori, 1992). Zhao et al. (2018) discovered that both regional and college players were superior to novices in the capability (accuracy) to predict ball trajectory using kinematic information, but no difference was discovered between college-level and regional-level players. No capability difference between college and regional level players during prediction of ball trajectory may cause of existence of a baseline level of motor experience for successful anticipation, from which further experience provides no additional assistances. For overall accuracy in the mixed-cues assignment, a significant main effect was found [$F(2, 68) = 8.446$, $p = 0.001$, $\eta 2 = 0.199$]. Further analysis exhibited that the college players ($p = 0.002$) and the regional players ($p = 0.002$) had a higher overall accuracy than the novices, while no difference was detected between the two experienced groups ($p = 1.000$).

Lanzoni, Bartomei, Michele and Fantozzi (2018) stated that played down the line and cross-court in forehand topspin will contributed to different body rotations kinematics. It was revealed that more flexed right knee and elbow angles were measured at the moment of maximum velocity (MMV) of the racket in down the line than in cross-court. The MMV of elbow and MMV of right knee angles were significant different in down the line and cross-court (p = 0.015, effect size = 1.37; p = 0.001, effect size = 2.34). A higher inclination of the racket at the MMV was found in down the line than cross-court. The racket inclination and elbow flexion may be linked to the direction of the shot (Lanzoni, 2018).

Iino and Kojima (2009) aimed to study the kinematics of table tennis forehand topspin drives. The contribution of lower trunk axial rotation was significantly higher for the advanced players as compared to the intermediate players. The contribution of lower trunk axial rotation to the racket speed of forehand drive was 3.8 m/s (against light backspin) and 3.5 m/s (against heavy backspin) by advanced players. The contribution of lower trunk axial rotation to the racket speed of forehand drive was 1.8 m/s (against light backspin) and 1.7 m/s (against heavy backspin) by intermediate players. Other than lower trunk axial rotation, shoulder flexion, shoulder internal rotation and upper trunk rotation were the major contributors to the racket speed at ball impact during forehand drive. Moreover, postures during strokes are mostly generated by muscles at hip and lower trunk (Iino & Kojima, 2009). As conclusion, an adequate use of the lower trunk axial rotation is suggested to accelerate the racket in minimum time.

Iino and Kojima (2011) studied the importance of energy in producing higher racket speed during forehand topspin drive. They found that the shoulder internal rotation torque was significantly higher for the advanced players as compared to the intermediate players. The advanced players generated 0.58±0.13 and 0.61±0.1 Nm/kg for shoulder internal rotation torque against light and heavy backspin, respectively. The intermediate players generated 0.37±0.1 and 0.39±0.11 Nm/kg for shoulder internal rotation torque against light and heavy backspin, respectively. The large value of shoulder internal rotation torque of advanced players generated energy that was transferred from the trunk to the upper arm at a higher rate than the intermediate players. The energy transfer (6.6±2.1 and 7.0±1.6 W/kg against light and heavy backspin, respectively) generated by advanced players accelerated the racket at ball impact. It was found that 76% of the increase in the mechanical energy of the racket arm from the beginning of pelvic forward rotation until ball contact was due to energy transfer from the upper trunk. They concluded that increasing energy transfer is one of the ideas for intermediate players to accelerate the racket speed at ball impact during forehand topspin drive.

Kasai, Mori, and Watanabe (1996) found that extending the elbow joint can produce accurate forehand smash strokes. Moreover, skilled players always brought the racket near the front body after ball contact (Yoshida, Iimoto & Ando, 1996). During contact phase, the skilled players used smaller variance of arm segment angular velocity than non-skilled players during forehand stroke (Yoshida, Iimoto & Ando, 1996). Moreover, Yoshida, Iimoto, and Ando (1996) found that skilled players changed their torque which was generated by the legs at contact. However, there was not enough data to support the above findings.

The determiner to hit the ball and at the same time control the amount of the ball rotation is varied between racket speed, racket face angle, racket path direction and impact point height (Iino & Kojima, 2009). Therefore, they concluded players have to adjust their arm movement during forehand strokes against heavy and light backspin.

Lubrica, Florendo, Revano, and Agulo (2013) analyzed the body movement of advanced and beginner players during forehand drive. The movement of elbow and wrist joint of advanced players during the stroke were constant and otherwise for beginner players based on the horizontal motion of graph. As recorded in the video, beginner players were practically without a body twist while producing forehand stroke. Moreover, based on the graph of vertical motion, the beginners obtained power to swing from the arm, which was not similar to advanced players who assembled the power from the inner body to execute the forehand drive.

A paper discussed the analysis of ground reaction force (GRF) in 3D direction during forehand attack and forehand loop drive strokes. Zhang, Zhu, Li, Xiao, and Zhang (2013) found the maximum GRF values of right foot during forehand attack and loop drive strokes were 272.44 ± 21.15 N and 226.67 ± 19.55 N in the vertical direction, respectively. The maximum GRF values of left foot during forehand attack and loop drive strokes were 303.35 ± 33.30 N and 207.97 ± 27.20 N in the vertical direction, respectively. The maximum GRF values of right foot during forehand attack and loop drive strokes were 40.45 ± 2.45 N and 63.78 ± 7.56 N in the horizontal direction, respectively. The maximum GRF values of left foot during forehand attack and loop drive strokes were 9.39 ± 2.37 N and 41.54 ± 5.70 N in the horizontal direction, respectively. The maximum GRF values of right foot during forehand attack and loop drive strokes were 36.88 ± 2.98 N and 59.89 ± 7.05 N in the fore-aft direction, respectively. The maximum GRF values of left foot during forehand attack and loop drive strokes were 52.44 ± 7.89 N and 23.11 ± 2.46 N in the fore-aft direction, respectively. The GRF value in the vertical direction was higher than horizontal and fore-aft directions. The maximum GRF value during loop drive stroke was higher than forehand attack stroke in the horizontal and fore-aft directions. As a result, the forehand stroke movement should be given more attention to push off in the vertical direction while the forehand loop drive movement should be given more attention to push off in the horizontal and fore-aft directions to improve body postures of those strokes. Moreover, the authors and Yoshida, Iimoto, and Ando (1996) concluded that ground reaction of force is always shifted from left to right and vice versa in order to get balance while playing.

2.7.3 Analysis of Body Movement for Backhand Stroke

Iino, Mori, and Kojima (2008) conducted a study on the analysis of backhand stroke contributions towards the racket tip velocity during contact. They found that the elbow extension, wrist dorsiflexion and shoulder external rotation were the main contributors to the forward velocity of the racket tip. Furthermore, the whole players in the research were playing in a similar way in both backhand strokes, based on the similar data value. The speed of elbow extension to the forward velocity of racket tip was 4.3 ± 1.8 m/s for backhand against topspin and 3.9 ± 1.6 m/s for backhand against backspin. The speed of shoulder external rotation was 2.9 ± 1.3 m/s for backhand against topspin and 2.5 ± 1.0 m/s for backhand against backspin. Meanwhile, the speed of wrist dorsiflexion was 4.1 ± 0.7 m/s for backhand against topspin and 3.8 ± 0.9 m/s for backhand against backspin. Results showed that the contributions of elbow extension towards racket tip velocities were -2.4 ± 0.4 m/s for backhand against topspin and -1.4 ± 0.4 m/s for backhand against backspin. Meanwhile, the contributions of wrist dorsiflexion towards racket tip velocities were 0.1 ± 0.8 m/s for backhand against topspin and 1.1 ± 0.8 m/s for backhand against backspin. The findings showed that the significant difference in racket upward velocity upon impact was mainly caused by the different contributions of elbow extension and wrist dorsiflexion. It probably occurred because the differences were in the upper limb configuration rather than the magnitudes of the angular velocities.

The forehand topspin stroke against topspin ball requires a substantial hip and trunk rotation, whereas the backhand topspin against topspin ball needs the least hip and trunk rotation (Seemiller & Hollowchak, 1997). The backhand stroke was assumed to rely more on the relatively small muscles around the shoulder, elbow and wrist joints as compared to forehand stroke (Iino & Kojima, 2016a). Thus, a study by Iino and Kojima (2016a) analyzed the effect of the racket mass and the rate of strokes on the kinetics and kinematics of the trunk and racket arm during table tennis topspin backhand. The participants were asked to perform backhand topspin against topspin balls projected at 35 ball/min and 75 ball/min by using three different mass of rackets: 153.3 g, 176 g, and 201.5 g. The racket mass did not significantly affect all the trunk and racket arm kinetics and kinematics, excluding the wrist dorsiflexion torque, which was significantly higher for the low ball frequency as compared to the high ball frequency. The peak of wrist dorsiflexion torque was 4.6-5.4 Nm. The racket speed at contact was 5-7% lower for the high ball frequency compared to the low ball frequency. It probably occurred because pelvis and upper trunk axial rotations tended to be more limited for the high ball frequency. From the results, it was suggested that the trunk rotation significantly contributes to the racket speed in the backhand stroke when adequate time is allowed for the players to execute it. The racket speed at ball impact was higher for the low ball frequency condition, and may prove as useful in considering the game tactics. For players who have trouble in dealing with the high ball speed of an opponent's offensive shot, playing near to the table is recommended as a good strategy to overcome it.

Iino and Kojima (2016b) again analyzed backhand stroke kinematics and kinetics in order to understand how the mechanical energy is generated and transferred in the racket arm during the stroke. The mechanical energy of the racket arm obtained during forward swing (65% and 75% against topspin and backspin, respectively) was due to energy transfer from the trunk. The shoulder joint force directed to the right, which peaked just before contact, transferred extra energy to the racket. This energy transfer entailed significant shoulder upward velocity. It was recommended to encourage players to lower the trunk and racket and then thrust the upper body upward substantially to produce high racket speed during backhand topspin against topspin and backspin balls.

2.7.4 Other Analysis on Body Movement of Strokes

Kasai, Mori, and Watanabe (1996) found that the elbow rotation speed of an elite player before impact was 20 m/s. Wang et al., (2008) found that the speed of the shoulder, elbow, and wrist joints were gradually enhanced; similar to biomechanics theory.

The angles of the elbow and shoulder joint varied, depending on the style of play and athlete's techniques (Lee & Xie, 2004a). Some players preferred to keep their arms close to their bodies when hitting a ball, whereas some did not. As an example, one of the participants adopted a small underarm angle at 38°, whereas another used a wide underarm angle at 80° during ball impact. Furthermore, Kasai, Mori, and Watanabe (1996) and Lee and Xie (2004a) found that the elbow joint angle were the factors that determined the ball speed with a minimum factor from the shoulder angle.

A frequently used shoulder rotation indicated that the player played the high loop strokes during game (Lee & Xie, 2004a). As an example, the shoulder joint angle's player increased 50 % and elbow angle decreased 30 % before ball contact. Moreover, a player who played at the lowest height with low speed at ball contact indicated good control in high loop stroke (Lee & Xie, 2004a; Wu, Qin, Xu & Xi, 1992). An example from the findings in Lee and Xie (2004a) showed that a good high loop stroke player played at 0.09 m of ball contact height from the table ground with the lowest speed, 12.6 m/s among players in the study.

Barczyk-Pawelec, Bankosz, and Derlish (2012) analyzed the relationship between body posture, asymmetries and training experience among table tennis players. Most of the participants, 25 out of 40 players who played table tennis, were in the kyphotic body posture group. There was statistically significant correlation (r = 0.902, P = 0.05) between training experience and asymmetry of the inclination of the shoulder line angle. It may result from one-sided work, the negative influence of very intensive and continuous work of shoulder muscles of the active limb with less work of the other limb.

2.7.5 Ball Movement

A player must not neglect the biomechanical principles of ball movement, including the angle of hitting the ball, forces, speed, and spin to enhance his or her performance. Iino, Mori, and Kojima (2008) and Iino and Kojima (2009) found that the mean of ball speed before impact was between 3.0 to 4.7 m/s. Yoshida, Sugiyama and Murakoshi (2010) found that the speed of service ball was 4 m/s. Wang et al. (2008) found that the ball speed after impact was 4.98 m/s and 4.76 m/s during long shot and drop shot services. Meanwhile, Iino and Kojima (2009), Iino, Mori, and Kojima (2008) and Ando et al. (1992) found that the range of ball speed after impact was between 16.7 – 21.6 m/s.

The range of ball spin varied between 26 to 37 rev/s (Iino & Kojima, 2009; Iino, Mori, & Kojima, 2008; Lee & Xie, 2004a; Wang et al., 2008). Furthermore, the range of ball spin for light ball was between 11 rev/s to 12.5 rev/s (Lee & Xie, 2004a; Iino & Kojima, 2009). Meanwhile, Wu et al. (1992) found the mean of ball spin was 134.9 rev/s during forehand loop and 55.6 rev/s during heavy chop strokes.

Lee and Xie (2004b) analyzed the rotation of the flight ball. They found that the ball spin at impact was reduced after bouncing twice. It reduced more than 40% after bouncing twice for backspin ball. Other types of spin ball were reduced in the range of 10% to 30% after second bounce. The results partly supported findings reported by Wang et al. (2008). They found that the ball spin at impact was reduced after bouncing twice during long shot and drop shot services (Wang et al., 2008). The authors found that the ball spin of long shot and drop shot services were reduced to 5.1% and 6.7% after second bounce, respectively (Wang et al., 2008).

Xie and Qin (2001) found that the reduction in spin was less in topspin balls as compared to backspin balls. Furthermore, they found that the ball speed was reduced to 29% after apart from the racket and the air resistance on ball spin was only 3% to 4%. Therefore, it was assumed that the air resistance can be neglected and the force that might reduce the ball rotation was friction (Xie & Qin, 2001). Furthermore, friction was one of the factors that generated the ball rotation (Tsuji & Kimura, 2013). As a result, backspin ball gained more friction from the table as compared to other spin balls (Lee & Xie, 2004b; Xie & Qin, 2001).

According to Kei, Yukihiko, Zhang, Yang, and Shinji (2010), players should hit the ball at a higher position to have more chances in winning games. Most of the skilled players hit the balls between 0.24 and 0.36 m from the table ground to the net.

The served ball frequently landed at the center and near the net as one of the strategies to control the game (Ghoneim & salem, 2010; Lanzoni, Michele & Merni, 2014). Lanzoni, Michele, and Merni (2014) found that half of the served balls were landed near the net.

2.7.6 System used and Statistical Analysis

Iino and Kojima (2009) used five high speed cameras operating at 200 Hz to record forehand topspin motion in their study. Twenty-one two-way repeated measures analysis of variance (ANOVA) tests were executed to assess the effects of ball spin and performance level on the dependent variables: the racket kinematic parameters at impact, the ball speed after impact, and contributions of joint rotations and segment.

Iino and Kojima (2011) used five high speed cameras operating at 200 Hz to record forehand topspin drive same as in Iino and Kojima (2009). They utilized inverse dynamic formula to analyse the data. Two-way repeated measure ANOVA was performed to test the effects of performance level and ball spin on the forehand topspin kinetics.

Furthermore, Lubrica et al. (2013) used a regular digital video camera to record the table tennis forehand drive movement. They used low cost motion analysis software to analyze the movement.

Zhang, Zhu, Li, Xiao, and Zhang (2013) used two force platforms to analyze the forehand stroke. They used Kistler data analysis software (Kistler, Amherst, NY, USA) to produce related data. The t-test for independent samples was used to conduct statistics analysis on forehand stroke motion.

Iino, Mori, and Kojima (2008) used two cine cameras operating at 100 Hz to record backhand stroke. Two-tailed paired t-tests were used to compare between backhand against topspin and backhand against backspin kinematics.

The table tennis topspin backhand motion was recorded by motion capture system using eight infrared cameras (MX-T10, Vicon Motion Systems, Oxford, UK) operating at 250 Hz in Iino and Kojima (2016a). The joint torques of the racket arm were obtained by using inverse dynamics. Two-way repeated measures ANOVA were used to test the effect of the ball frequency and racket mass on the following dependent variables: the racket speed at ball impact, the angle of inclination of the racket tip path, the racket face angle at impact, the trajectory length of the racket tip during the racket forward movement, the maximum pelvis axial rotational velocity, the pelvis axial rotational velocity at impact, the upper trunk axial rotational velocity relative to the pelvis at impact, the joint angular velocities of the shoulder, elbow and wrist joints at impact and the peak joint torque components of the shoulder, elbow and wrist joints.

Iino and Kojima (2016b) used Eight Vicon cameras operating at 250 Hz were used to record the motion of backhand topspin against topspin and backspin balls. A two tailed, paired t-test was used to compare the kinematic and kinetic of the backhand stroke against topspin and backspin balls.

Lee and Xie (2004b) used a high-speed video camera operating at 200 Hz and video cassette recorder to record the table tennis service motion. The recording was converted from Analog to Digital format via the Peak Motus analysis system (Peak Performance Inc., USA).

Lee and Xie (2004a) used six high-speed video cameras operating at 200 Hz and video cassette recorders to record the table tennis match in Sea Games 2001. The recording was converted from Analog to Digital format via the Peak Motus analysis system.

Wang et al. (2008) used a high-speed video camera (Baslen Asbozfc) operating at 200 Hz and two video cameras operating at 50 Hz to record table tennis service in the final of Women's World Cup 2007. Table 2.1 and Table 2.2 showed the research methodologies of the recent studies.

Table 2.1: Implementation of the experiment and research methodologies of the recent studies

Research	Purpose of journal	Experiment	System	Tools	Method of Analysis
Yang et al. (2010)	Analyzed the routes of ball in table tennis game	Analyzed the routes of the ball in table tennis game	N/A	Video camera, ball, table tennis	schedule of landed ball on opponent's side of table
Lee et al. (2004b)	Analyzed the spin of the ball that produced by Singapore elite table tennis players	Analyzed variation of ball spin that produced by players	Peak Motus motion analysis software	Video camera, high speed camera, table tennis,bet, ball	Mechanical formula
Kei et al. (2010)	Examined and analyzed the skills of different players during rally in table tennis game	Analyzed the movement of table tennis ball during the game	The lasers units of the measuring system	Infrared laser, video camera, computer, ball	Physics formula and statistical analysis
Pradas et al. (2011)	Evaluated the power of leg extensor musles among table tennis players	Analyzed the jumping force manifestation in table tennis	Jump computer Newtest Powertimer (Oulu, Finland	Weight bars, plastic bars protection, box, scale, stadiometer	Medical formula, statistical analysis
Wang, et al. (2008)	Analyzed the serve techniques that produce by elite table tenis player, Yinning Zhang	Analyzed the serve motion in table tennis	3D-SignalTEC v10c analysis system	High speed video camera, video camera	Mechanical formula, statistical analysis

Table 2.1, continued

Iino and Kojima (2009)	Determined whether the kinematic topspin forehands that produced by different players can affect the performance level and ball spin	Analyzed the topspin forehands that produce by advanced and intermediate players	Frame-DIAS II (DKH Co., Ltd, Tokyo, Japan)	High speed camera, table tennis, ball, bet, ball machine	Physics formula, statistical analysis, dynamic model
Lanzoni et al. (2014)	Analyzed the relationship of footwork, strokes and efficacy of players during matches	Analyzed the techniques produce by table tennis players during matches	Kinovea software	Video recorded from television	Statistical analysis, analysis of the contingency table about footwork/strokes and footwork/efficacy
Flores et al. (2010)	Evaluated shadow practice techniques in learning backhand drive among beginner players	Examined the performance of beginner players using shadow practice in learning backhand drive	N/A	Table tennis, string, net, trainer ball, ball, basket	Consistency and accuracy formula, Statistical analysis
Lee & Xie (2004a)	Compared and analyzed techniques that produce by elite players during tournament	Analyzed techniques produced by table tennis players during game	Peak Motus motion analysis system	High speed video camera, video camera, racket, ball, table tennis	Physics formula, statistical analysis
Iino, Mori and Kojima (2008)	Analyzed the contributions of arm segment to the velocity of racket and ball at impact	Analyzed the backhand drive against topspin and backspin produced by advanced and collegiate players	Film motion analyzer (NAC Image Technology, Inc)	High speed video camera, ball, bet, table tennis, ball machine	Physics formula, statistical analysis, dynamic modelling

Table 2.1, continued

Hao et al. (2010)	Analyzed the tactic and techniques that produced by international players during tournament	Analyzed the techniques produced by table tennis players	N/A	Video, document review	Scoring rate formula
Iino and Kojima (2011)	Investigated the importance of energy transfer and generation in order to increase racket speed	Analyzed the topspin forehand drive against light and heavy backspin produced by advanced and intermediate players	Frame-DIAS II motion analysis system (DKH Co., Ltd, Tokyo, Japan)	High-speed video camera, ball machine, bet, table tennis, ball	Physics formula, statistical analysis
Iino and Kojima (2016a)	Analyzed the racket mass and rate of strokes on kinematic and kinetics in table tennis backhand	Analyzed the motion of backhand against topspin and backspin balls	Vicon Motion System	Infrared cameras, high speed cameras, ball machine, ball, racket, table tennis	Dynamic model, inverse dynamic, statistical analysis,
Iino and Kojima (2016b)	Analyzed the mechanical energy generation and transfer in the racket arm during table tennis backhand	Analyzed the motion of backhand stroke	Vicon Motion System	Infrared cameras, high speed cameras, ball machine, ball, racket, table tennis	Dynamic model, inverse dynamic, statistical analysis
Otcheva and Drianovski (2002)	Comparative analysis of final players in international match of table tennis players	Analyzed the techniques produced by table tennis players	N/A	Video tape	Consistency and accuracy formula, statistical analysis

Table 2.1, continued

Cai, Hua, and Tang (2001)	Comparative analysis of China and Sweeden players	Analyzed the techniques produced by table tennis players	N/A	Video tape, document review	Scoring rate formula, statistical analysis
Barczyk-Pawelec el al. (2012)	Assessed the correlations between body posture types, asymmetries and training experience among table tennis players	Assessed the body posture types	N/A	CQ Electronic	Photogrammetric method, Statistical analysis
Lubrica et al. (2013)	Analysis of forehand drive stroke motion	Analyzed the forehand drive stroke motion	MATLAB	Ball, racket, table tennis, video cameras,	Statistical Analysis
Zhang, Liu, Hu, and Liu (2013)	Evaluation of elite table tennis players' technique effectiveness	Evaluated the elite table tennis players' technique effectiveness	N/A	Videos, internet videos	Indices of technique effectiveness evaluation, scoring rate formula, usage rate formula
Ghoneim & Salem (2010)	Evaluation of advanced table tennis players' technique during international tournament	Evaluated the advanced table tennis players' technique effectiveness	N/A	Videos	Efficiency rate formula, statistical analysis
Zhang, Zhu, Li, Xiao & Zhang (2013)	Analysis of GRF during forehand attack and forehand loop drive strokes	Analyzed the GRF in 3D direction during forehand attack and forehand loop drive strokes	KISTLER force-plate system	force platform, racket, ball, table tennis	Physics formula, statistical analysis

Table 2.1, continued

Wu et al. (1992)	Biomechanical analysis of table tennis stroke	Analyzed the table tennis strokes motion	N/A	Ball, Table Tennis robot, racket	Mechanical formula
Kasai, Mori & Watanabe (1996)	Analysis of elbow joint during forehand strokes	Analyzed the elbow joint motion during forehand strokes	N/A	Video cassette recorder, electric oscillography, ball, racket	Physics formula
Yoshida, Iimoto & Ando (1996)	Analysis of forehand topspin stroke in table tennis	Analyzed the forehand topspin stroke motion	N/A	High speed video tape recorder, accelerator, ball, racket	Physics formula
Ando et al. (1992)	Analysis of forehand topspin kinematics	Analyzed the forehand topspin motion	N/A	High speed video tape cameras, ball, racket	Physics formula

*N/A = not applicable / not enough information

Table 2.2: Participants demographic in recent studies

Research	Total participants	Gender	Ranking
Yang et al. (2010)	1	Male	Advanced player
Lee et al. (2004b)	5	N/A	Elite players
Pradas et al. (2011)	5	Male	Elite players
Ando et al. (1992)	2	Male	Elite players
Yoshida et al. (2010)	1	Male	Elite players
Wang et al. (2008)	3	Female	Elite players
Iino, Mori and Kojima (2008)	11	Male	Advanced players
Zhang, Zhu, Li, Xiao and Zhang (2013)	10	N/A	Elite players
Iino & Kojima (2009)	17	Male	Collegiate (advanced and intermediate) players
Iino & Kojima (2011)	17	Male	Collegiate (advanced and intermediate) players
Lee et al. (2004a)	4	Male	Elite players
Kei et al. (2010)	8	Male	Collegiate (advanced and intermediate) players
Flores et al. (2010)	12	N/A	Beginner
Barczyk-Pawelec et al. (2012)	83	N/A	Beginner and intermediate players
Iino & Kojima (2016a)	8	Male	Advanced players
Iino & Kojima (2016b)	10	Male	Advanced players
Lubrica et al. (2013)	2	N/A	Beginner and collegiate players
Wu et al. (1992)	24	N/A	Elite players
Kasai, Mori & Watanabe (1996)	4	male	Elite and collegiate players
Zhao et al. (2018)	7	male	Advanced players

Table 2.2, continued

Lanzoni et al. (2018)	75	N/A	All ranked players
Yoshida, Iimoto & Ando (1996)	6	N/A	Elite, advanced and beginner players
Ando et al. (1992)	2	male	Elte players

*N/A= not applicable / not enough information

2.8 Summary for Review Articles in Table Tennis

The tools and equipment used to perform the experiments were different between studies, depending on their purposes. Previously, a video tape recorder was one of the tools utilized in the experimental procedures (Table 2.1). Today, researchers use high speed and infrared cameras to record body movement (Table 2.1). They utilize various types of system to analyze human movement (Table 2.1). However, researchers who analyzed players' tactic and techniques used video recording from the previous matches to gather and evaluate data (Table 2.1).

In general, the basic methods to analyze data were quite similar between previous studies (Table 2.1). They used physics, statistical and mechanical formula to analyze data. However, different mechanical formulas and statistical analysis were used, depending on the study objectives. Some used other alternative ways to maximize and make the results accurate, such as dynamic models which were reported in Iino, Mori and Kojima (2008) and Iino and Kojima (2016b). However, researchers used scoring rate, efficiency, accuracy and usage rate formula to evaluate the effectiveness of a player's technique (Table 2.1).

Sometimes the results were varied for the same problem amongst research. Probably, different participants and research methodology are factors that influence the variation in findings (Table 2.1, Table 2.2).

Most of the selected participants in the studies were male and elite players (Table 2.2). Elite players are good examples in improving athlete performance. However, some studies used intermediate and beginner players as their participants to determine the differences in techniques and postures of different levels of players (Ando et al., 1992; Hao et al., 2010; Iino & Kojima, 2009). Research on various techniques, different rank of players, and movement of players can determine efficient ways to execute good strokes.

Knowledge of player's tactic and technique is important to analyze the body movement. For instance, forehand stroke is said to be the most powerful and fastest stroke (Ghoneim & Salem, 2010). Because of that, there were many studies which discussed forehand stroke as compared to backhand stroke (Iino & Kojima, 2009; Iino & Kojima, 2011; Zhang, Zhu, Li, Xiao, & Zhang, 2013).

Many studies discussed on upper limb movement in table tennis, including Lee and Xie (2004a), Iino and Kojima (2009) and Iino and Kojima (2011). A frequent hand movement is compulsory to execute stroke rather than other limbs. By employing research on body segments kinetic and kinematic, coaches can be alerted on the importance of biomechanics in preventing incorrect playing postures. Incorrect playing postures can lead to injury (Chang, Jung & Thung, 2010). Therefore, serious or light injuries can be minimized or prevented.

Understanding the biomechanical principles of table tennis ball movement can help coaches to strengthen their athletes' performance in matches. Balls do not land on the table randomly. The ball lands at a particular area because of certain factors, such as friction, air resistance, the intended stroke, swing of the racket or gravity (Tsuji & Kimura, 2013; Heaton, 2009; Xie & Qin, 2001). Studying and further analyzing the ball movement can help players to improve their strokes so that the ball lands at their preferred area.

2.9 Introduction of Dynamic Model of Upper Limb

There are two methods to calculate the body segment orientation which are "traditional joint centers method" and "marker based method" (Gordon & Dapena, 2013). The traditional joint centers method uses shoulder, elbow and wrist joint centres to calculate the upper arm twist orientation (Gordon & Dapena, 2013). This method was widely used in throwing and tennis serving (Bahamonde, 2000; Gordon & Dapena, 2006). The marker based method utilizes skin-mounted markers which usually produce two problems, which are small error in the location of markers and the method is not required to follow the underlying bone motion (Gordon & Dapena, 2013). The small error in the position of markers may produce a large error in twist orientation (Gordon & Dapena, 2013).

The global optimization method, which can be found in Vicon software (Oxford Metrics Ltd., Oxford, UK), provides realistic joint kinematics by using skin-markers method but not necessarily accurate (Fohanno, Lacouture & Colloud, 2013). It is due to the existence of soft tissue between markers and bones which generates noise on the markers' 3D coordinates (Fohanno, Lacouture & Colloud, 2013). The noise which usually known as soft tissue artefact has mainly affected the human movement analysis (Fohanno, Lacouture & Colloud, 2013). Several studies have improved the 3D analysis regarding this matter such as Fohanno, Lacouture and Colloud (2013) and Sholukha, Bonnechere, Salvia, Moiseev, Rooze and Van Sint Jan (2013).

Muscles forces may be obtained from the optimization analysis of joint and torques forces (Maurel & Thalmann, 1999). Then, the muscle forces will be used in the continuum dynamic analysis to determine the simulation of soft tissue deformation (Maurel & Thalmann, 1999). Furthermore, torque that is developed by muscle will cause rotation to a joint (Yu, Ackland & Pandy, 2011). Torque applied by a muscle is similar to the muscle's force multiplied by the moment arm of the muscle (Yu, Ackland & Pandy, 2011). The dynamic coupling occurred when a torque at a joint can induce acceleration at all other joints due to muscle-force imparting from segment to another segment through joint contact forces (Yu, Ackland & Pandy, 2011). Nevertheless, the role of individual muscles experimentally could be difficult to assess because of the muscles' complex arrangements and the coordination of a large number of muscles during a movement.

It could be difficult to replicate the simulation work of others because some were not publicly available (Saul et al., 2014). Furthermore, the financial cost on the model and technical expense needed for gaining an expert to run the complex model could be the factors for not using other models (Saul et al., 2014). However, to develop a self-complex model on the upper limb requires knowledge from previous studies; thus, the next deliberation will be discussed on various methods that were developed by previous studies on 3D dynamic model of the upper limb.

2.10 Methodology for Systematic Review on Dynamic model of Upper Limb

Previous articles were mainly searched by using the following databases: Google Scholar, ScienceDirect, SAGE, Taylor & Francis Online, and Web of Science. Figure 2.8 showed the flow chart of systematic review in 3D dynamic model of upper limb. The main keyword used was "dynamic model". At this stage, non-English articles and articles discussed on other fields, such as multibody dynamic, chemistry, zoology and electrical field were excluded. Then, 386 articles were screened by title and abstract. The "dynamic model" keyword was combined or changed with other keywords, such as "kinematic model", "kinetic model", "upper limb", "arm segment", "upper extremity", "muscles", "computational model", "musculoskeletal model" and "biomechanics model" so that the inclusion criteria which were 3D biomechanics model of upper limb/upper extremity were included in the selected articles. The exclusion criterion for selected articles was studies that were involved in mechanics analysis related to 3D dynamic model of the upper limb, 2D dynamic model of body movement and 3D dynamic model of the lower limb. Afterwards, 51 articles were assessed for eligibility. Then, four articles were removed from the review because they were duplicated from the others. Finally, 47 selected articles were included for the review. Only articles which were discussed on 3D biomechanics model of the upper limb were considered at this stage. They were divided into three groups, which were "3D dynamic model of the upper limb without involving muscles", "3D musculoskeletal model of the upper limb for clinical problems" and "other 3D musculoskeletal models of the upper limb". These articles were analyzed based on the methodology and equipment of the study and their contributions to the 3D dynamic model of the upper limb. These selected articles will become substantial references for future research work on biomechanical model of the upper limb.

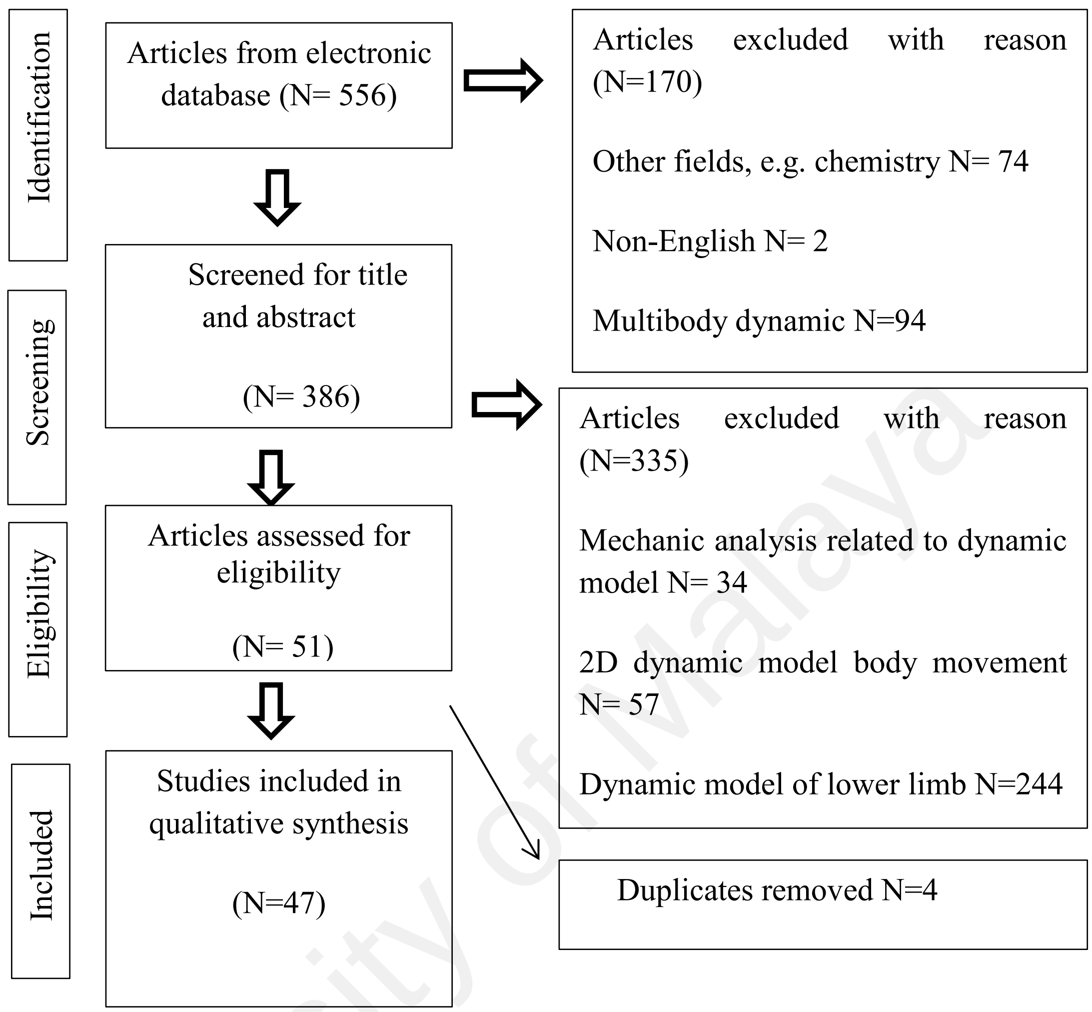


Figure 2.8: The flow chart of systematic review in 3D dynamic model of upper limb

2.11 Review on Previous Articles

2.11.1 3D Dynamic Model of Upper Limb without Muscles Involvement

Yamaguchi (2006) used Kapandji (1982) and Kane's method to develop seven DOF (degree of freedom) arm segment kinematic models. Study on the upper limb physiology (Kapandji, 1982) was utilized in the development of 3D kinematics model of the arm segment. Kane's method used vector product to allow 3D analysis on body movement. Vector dot and cross products were preferably used than the derivation and integration to obtain acceleration and velocity. Table of direction cosines is important to develop the present model. The table of direction cosines in the present study was widely used, mostly in the robotic and human motion field (Kane & Levinson, 1985; Shah, Saha & Dutt, 2013; Jazar, 2010) to describe the direction of the vector in coordinate axes (Yamaguchi, 2006). The kinematic model of the upper extremity consisted of the trunk, humerus, ulna, radius and hand. The seven DOF were shoulder adduction/abduction, shoulder flexion/extension, shoulder external/internal rotation, elbow flexion/extension, forearm supination/pronation, ulnar/radial deviation, and wrist dorsi /palmar flexion. The motion of the bones and joints were accumulated in the Yamaguchi's model to attain human motion reality at the upper extremity, mainly at the forearm supination/pronation (Yamaguchi, 2006). AUTOLEV (OnLine Dynamics) is a symbolic language based on the Kane's method (Chan & Moran, 2006; Kane & Levinson, 1985) which was used to develop an algorithm for dynamical equations of motion and generate a forward dynamic model of the arm segment.

It was claimed that the calculation of the upper arm orientation about its own longitudinal axis (twist orientation) was difficult (Gordon & Dapena, 2013). The upper arm orientation is defined as twist orientation of the humerus which is covered with a soft tissue that blocks it from view. Hence, it is determined by indirect methods which lead errors in twist orientation, and subsequently in other kinetic and kinematic parameters. Gordon and Dapena (2009) aimed to find the orientation of the upper arm about its longitudinal axis during dynamic motions. They used nine tennis players as the participants. In the experiment the participants were asked to extend both elbows. The movements were recorded by using four cameras which operated at 50 Hz. It was claimed that the mediolateral axis will not change during elbow extension if the upper arm holds a perfectly static position. "The basis for the new method is that at any angle in the flexion/extension range of an individual's elbow, it is possible to define a true mediolateral axis and also a surrogate mediolateral axis perpendicular to the plane containing the shoulder, elbow and wrist joints". The recording data were used to calculate the provisional upper arm reference frame, elbow joint center, corrected upper arm reference frame, surrogate upper arm reference frame and correction angle for false twist rotation. The model was limited since the deformation of elbow joints during dynamic actions was negligible. To verify the developed model, they used a physical model to simulate the static upper arm condition. Since the upper arm of the physical model was clamped to a table, the twist orientation remained constant, which was close to 0° through the recording; thus, the findings had verified the developed model.

A previous study developed a 3D kinematic model of arm segment to determine the effectiveness of the segment rotations in producing speed of racket head (Springings, Marshall, Elliott & Jennings, 1994). They developed a system of vector equations for 3D arm segment rotations that used selected displacements as inputs. To validate the model, values of the racket head speed obtained from a motion analysis system and previous studies were compared. The racket head speed was measured by summing all of the individual arm segment contributions to racket speed commencing from the forward swing phase and ending at ball impact during tennis serve. This model was widely used in the related studies (Iino & Kojima, 2009; Iino & Kojima, 2011; Tanabe & Ito, 2007).

Chkze, Gutierrez, Marcelino and Dimnet (1996) developed a model of the upper limb by using robotic techniques. They described the movement of the upper limb internal structure from external markers trajectories. Another study that used a robotic technique was by Kodek and Munih (2003). They aimed to quantify wrist, elbow and shoulder dynamic and static torques in elbow extension-flexion movements. A subject was asked to keep calm while resting the arm on handle of a position-controlled antrophometric 6-DOF industrial robot (Yaskawa© MOTOMAN sk6) to keep his muscle relaxed. The movement of the arm was recorded by 3D tracking system Optorak© operating at 50 Hz. Sixth order Butterworth filter at 8 Hz was used to remove the noise contribution. Software package MATLAB was used to process the data from the system. Velocity and acceleration data from the robot were applied to the matrices to describe the dynamic components in the upper extremity movements.

Meanwhile, Dehghani and Moosavian (2014) developed a compact model of continuum robotic arms. It was assumed that an arm consisted of a backbone made of elastic rods. They approached the Jacobian and Cosserat rod theory to develop the model.

Previous studies (Iino & Kojima, 2016a; Iino & Kojima, 2016b; Koike & Hashiguchi, 2014) used a software package named Vicon motion analysis system to find the kinematic and kinetic data of body segment. Vicon BodyBuilder software (Oxford Metrics Ltd, Oxford, UK) was an alternative method to develop a 3D kinematic model of the upper limb to analyze the kinematic of cricket bowling movement (Lloyd, Alderson & Elliott, 2000). A sixth camera, Vicon MX operating at 50 Hz, was used to record the full delivery motions. The results showed that the participant (elite player) did not follow the law of throwing in cricket based on the kinematic quantities from the trials.

Another study, (Sholukha et al., 2013) used Vicon motion analysis (marker-based motion) and Microsoft Kinect system (markerless single camera hardware) to develop a model-based method that allowed the combination of accurate joint kinematic information with collected motion analysis data. This paper extended previous model-based approach from Marin, Hoang, Aufaure and Ho Ba tao (2010), Nicolas, Multon, Berillon and Marchal (2007) and Poppe (2007) that combined the validated joint kinematics with limb segment positions. The results showed that the model, based Vicon system and Microsoft Kinect, led to physiologically acceptable human kinematics.

Fohanno, Lacouture and Colloud (2013) developed a model on forearm, personalized by means of a functional approach for the axes of rotation of the forearm, implemented in a kinematic chain (AXIS model) and compared it with the global optimization method (ISB model). AXIS model was defined as two forearm models which were used to define a priori two kinematic chains. Model of the forearm segment was selected based on frequently used in daily life, which was claimed from previous studies. The difference between ISB model and AXIS model was only at the forearm model level with respect to the supination-pronation and extension-flexion function axes. The findings showed that the model had improved the hand and forearm posture. "The reduction in marker residuals for these segments ranged between 23% and 60 %. The contribution of pronation-supination, in terms of joint amplitudes, was increased by 15% during specific task" (Fohanno, Lacouture & Colloud, 2013).

2.11.2 3D Musculoskeletal Model of Upper Limb for Clinical Problems

Western et al. (2013) analyzed the upper limb tremor. It was claimed that previous models were not effective for tremor sufferers. The kinematic data from tremor movement were recorded from an Xbus kit (Xsens Technologies, P.O. Box 559, 7500 AN Enschede, The Netherlands), comprising five MTx sensors and an Xbus master which was operating at 50 Hz. The system was used to record the orientations of five body segments (torso, shoulder, upper arm, lower arm and hand). The kinematic was combined with inverse dynamics model by using SimMechanics (SimMechanics, The MathWorks, Inc., Natick, MA) to estimate the torques applied at individual joints during tremor movements. They examined the sensitivity of the torque estimates and the cross-correlation analysis by introducing reasonable errors to the estimates. It was concluded that the methods used to analyze the tremor movements can be applied in clinical area.

Another model in clinical field was reported in a study by Slavens, Sturm and Harris (2010). This study developed a 3D upper extremity model to quantify joint dynamics of paediatric crutch-assisted gait. The latest upper extremity inverse dynamic models from previous studies were not suitable to analyze the paediatric myelomeningocele groups because of some previous models had simplified the anatomical DOF at the upper extremity (Slavens, Sturm and Harris, 2010). This model was based on the previous studies, including Nyugen and Baker (2004) and Requejo, Wahl, Bontrager, Newsam, Gronley, Mulroy and Perry (2005). This model consisted of thorax, upper arm, forearm, hand and Lofstand crutches. The model was applied and evaluated to a paediatric crutch-assisted gait participant. Forces and joint motions were greater during swing through gait than reciprocal gait. Upper limb pathology, such as shoulder arthritis, may occur due to long term usage of swing through gait. It was because of high compression forces at the joints.

Riener and Straube (1997) developed an inverse dynamic model of the upper limb by 9 DOF with limitation 1 DOF at forearm. The forearm pronation-supination was not included in the study because of limitation in the study and the rotary moment occurred at the forearm was very small as compared to other DOF. From the findings, it was found that the model could distinguish normal and abnormal limb movements by using arm tracking movements. The model could be an effective tool for motion analysis in patients with cerebellar disorders.

2.11.3 Others 3D Musculoskeletal Model of Upper Limb

Maurel and Thalmann (1999) developed a human upper limb model to allow the simulation of human motion. They constructed a topological model, which was a combination of a concept of biomechanical model and its 3D construction of musculoskeletal system. Then, the inverse dynamic was developed to allow the interactive generation of motion sequences. Afterwards, the optimization analysis was developed to distribute the resulting joint efforts on the muscles. Then, the finite element was performed to compute the deformation of the soft tissues. Finally, the model will be validated before considering it as a successful simulation. Yet, the validation part in the study was not performed. The hand motion was negligible during the development of the model. The Euler angles method was utilized to determine the 3D orientation of a coordinate system. Most of the muscles were modeled as single polylines.

Lemay and Crago (1996) modeled an upper extremity as a skeleton of the upper arm connected by joints and is moved by activated the Hill-type model of muscles. The study covered forearm and wrist movements for simulation. The model of the study was implemented by Automatic Dynamic Analysis of Mechanical Systems (ADAMS, Mechanical Dynamics Inc.). This software package solves and analyzes the forces and movements of 3D mechanical systems by the Lagrangian equations approach and predictor corrector methods of numerical integration. From the analysis, it was found that the model could predict well the direction of the muscle actions. The study developed a dynamic model of upper extremity propelled by muscles without solving the equations of motion. Another study adopted Hill Type muscle model was by Ambrosio, Quental, Pilarczyk, Folgado and Monteiro (2011). They developed a musculoskeletal model of the upper limb with three different complexity levels.

Charlton and Johnson (2001) developed an upper limb model with a method that was related to the definition of moving coordinate systems in which the path of a wrapped muscle does not move. To build the model, they assumed that no other forces acted between the muscles and bone surface. The model was developed by using a software package SIMM (SIMM, Musculographics Inc., IL, USA, Delp and Loan, 1995). Another study that used a software package called SIMM was done by Ramsay, Hunter and Gonzalez (2009). They developed a geometrical musculoskeletal model of elbow and wrist joints to calculate muscle moment arm. Software package SIMM was used to create geometrical model of an arm.

Chan and Moran (2006) developed a 3D musculoskeletal model of primate arm. This model translated coordinate of markers on arm into joint angles, joint torques and musculotendon length. The software package SIMM was used to optimize joint locations and bone orientations so that it could replicate the kinematic of the original arm. The arm model consisted of five segments which were the upper arm, ulna, radius, hand and torso (reference frame). The movement of the primate arm was analyzed by using an optoelectronic motion capture system (Optotrak3020, Northern Digital) which operated at 100 Hz. The resulting bone-based attitude matrices were used to generate joint rotation matrices for the upper extremity segment. Muscle anthropometry and muscle mechanics of bones and joints from previous studies (Swindler & Erwin, 1986, Cheng & Scott 2000; Graham & Scott, 2003) were added to make the model accurate. The dynamic of musculoskeletal primate arm was developed by using the software package AUTOLEV 3.4 (OnLine Dynamics). The model allowed researchers to measure accurately the arm movement parameters such as muscle lengths and joint torques of a primate arm.

Saul et al. (2014) developed a benchmarking application to evaluate the common simulation system, which were electromyography (EMG) and optimization-based to identify the muscle activation inputs for dynamic simulation. The optimization-based was influenced by a dynamic system that is being controlled while EMG is independent of the computational model and platform. A simulation results across platforms was developed by using SIMM–Dynamics Pipeline–SD/Fast (SIMM version 4.2.1; Dynamics Pipeline, version 3.3, Musculographics Inc., Santa Rosa, CA, USA; SD/Fast version B.2.8, PTC, Needham, MA, USA) and OpenSim software packages (version 2.4, Stanford University, Stanford, CA, USA).

Pennestri, Stefanelli, Valentini and Vita (2007) developed a musculoskeletal model of the upper limb which consisted of humerus, ulna, radius and hand. The human joints have physical limits which reduce the range link of motion. Thus, they had overcome these problems with ergonomics index method. The problem of muscular activations was resolved using the optimization method. The model was validated after comparing previous studies with the results from the turn of a steering wheel movement.

Yu, Ackland and Pandy (2011) determined the contributions of the individual muscles of the shoulder to glenohumeral joint motion during abduction and quantify the effect of elbow flexion on shoulder muscle function during arm elevation. A musculoskeletal model of the upper limb was used to find the contributions of muscle sub-regions and 18 main muscles of the shoulder towards glenohumeral motion during abduction. Previous studies (Wu et al., 2005; Bey, Kline, Zauel, Lock & Kolowich, 2008) were used as references to define the rotation sequences for glenohumeral joint. The dynamic musculoskeletal upper limb model was calculated by using SD/Fast (Symbolic Dynamic, Inc., Mountain View, CA, USA). It was found that the shoulder and elbow joints function greatly affected the muscle function. “When the elbow was extended, the middle and anterior deltoid and supraspinatus were the greatest contributors to angular acceleration of the shoulder abduction. When the elbow was flexed at 90˚, the anterior deltoid and subscapularis were the greatest contributors to angular acceleration in abduction". The dependence of elbow joint position and shoulder muscle function was described by the presence of dynamic coupling in musculoskeletal system.

Rankin and Neptune (2012) developed an upper extremity model to estimate the musculotendon lengths and moment arms by utilizing regression equations. This method was adopted from Menegaldo, de Toledo Fleury and Weber (2004), who developed a lower extremity model. Wrapping surface algorithms method was used to develop the model.

Naaim, El Habachi, Moissenet, Dumas and Chèze (2014) developed a kinematic upper limb model, including soft tissue artefacts using multibody optimization. They adopted the method by Duprey et al. (2010), which developed a model for the lower limb. Multibody optimization described the limb as a kinematic chain composed of rigid segments linked by mechanical joints. The upper limb model consisted of six rigid segments which were thorax, scapula, humerus, radius, ulna and hand. The shoulder complex consisted of two joints which were scapulothoracic joint and glenohumeral joint. Pennestri's model was used to develop a forearm model which consisted of humeroulnar joint, humeroradial joint and radioulnar joint (Pennestri el al., 2007). A 100Hz optoelectronic tracking system (Qualysis AB, Gothenburg, Sweden) was used to record a subject standing in the anatomical reference position form. Data analysis and multibody optimization was performed by using MATLAB. It was found that the movement of scapula seemed less important without using multibody optimization.

Sancho-Bru et al. (2014) analyzed human grasp by using previous biomechanical model of hand. The equilibrium of the grasped object was added to the model for the analysis. Furthermore, a grasping posture generation algorithm was combined into the model. They verified that the modified model (human grasp model) from data of a subject who acted by grasping two cylinders of different diameters and weights. They found that some of the existing grasp model did not work well with the validated 3D hand model during the simulation of grasping of an object.

2.12 Summary for Review Articles in Dynamic Model of Upper Limb

Today, a dynamic model of the upper limb becomes an essential tool to analyze human motion. It is widely used in sports activity and clinical problem such as crutch-assisted gait and tennis. There were various studies which presented a dynamic model of the upper limb with different methods and purposes. However, it is recommended for researchers to select references related to self-research problems and software packages that were available.

Based on previous studies, at least a software package was used to develop a model of the upper limb (Naaim et al., 2014; Saul et al., 2014; Yamaguchi, 2006). Rigid mathematical calculations and large size data will affect the selection of various software packages. Motion analysis systems, such as Vicon and Qualysis, were used to obtain kinematic data of human motion (Kodek & Munih, 2003; Naaim et al., 2014). Mathematical calculations and dynamic model were further used to obtain the kinematic and kinetic joints to complete the model (Chan & Moran, 2006; Naaim et al., 2014).

Generally, developing a musculoskeletal model is more difficult than developing a dynamic model without involving muscles. Rigid calculations and a software package related to muscles are needed to create a musculoskeletal model. Software package

SIMM is usually used to create musculoskeletal model. However, the complexity to develop musculoskeletal model could disturb the real-time control (Maurel & Thalmann, 1999).

It was found that at least a reference from previous studies was added to the current model that was developed by the researchers. Some of them would test and validate the previous model before adding to the current model that they developed. Therefore, it is assumed that previous studies will be the guidelines for a researcher who wishes to develop a validated dynamic model of the upper limb.

The review was based on the latest studies in 3D dynamic model of the upper limb and biomechanical of table tennis strokes. The methodology of the research and the findings from the previous studies were reported in the discussion section in this chapter. It will be the guidelines for researchers to solve related problems in this area. Although the purposes of the study were the same with certain previous studies, a variety of methods can be used to solve the matter, and thus it may yield slightly different findings amongst the studies. The previous studies showed that there were limited research in biomechanical field of table tennis strokes, specifically service. Seldom people emphasize on the importance of biomechanics while playing table tennis. More than a development in science, analyzing players' movements can help players to perform better in the games.

CHAPTER 3: METHODOLOGY

To facilitate the objectives of the study, this section had seven main parts to perform. The first part briefed on the systematic literature review about the biomechanical analysis of table tennis and the 3D dynamic model of the upper body. The second part described on the ethical clearance application by the author’s institution. The third part detailed on the improvement of 3D arm segment kinematic model from Yamaguchi (2006). Then, the study captured radiography images of volunteered participants on the right handed arm segment to find certain positions at the arm segment. The certain position at arm segment can be referred in Yamaguchi (2006). These values were important to solve velocity and acceleration equations of arm segment model. The fifth part detailed on step to develop an algorithm in MATLAB which was applied from Yamaguchi’s kinematic model. An experiment of table tennis serving motion was conducted to obtain the kinematic data for validation in the sixth part. The kinematic quantities (joints angle) from the experiment were applied to the developed algorithm to produce the rest of the kinematic data. The kinematic quantities were compared with previous studies and validated. The final phase described on the application of the developed algorithm to the sport biomechanics, specifically during the table tennis serving. This stage discussed on the demographic of the selected participants in this study, experimental procedures and statistical analysis that were used to achieve the objectives of the study. Then the results will be analyzed and discussed after the final stage.

3.1 Method on Literature Review

The literature review was performed by manually searching the internet since 2012. Existing articles were searched by using the following databases: Google, ScienceDirect, International Journal of Table Tennis Sciences, Taylor & Francis Online, Web of Science, and other databases in University of Malaya Library online. Detailed information of the stage can be found in Chapter 2.

3.2 Ethical Clearance

As required by the university, any research involving humans must obtain an ethical clearance from the ethic committee. This is to confirm that the study was performed according to the law and regulations involving human research volunteers. Therefore, the study was approved by the University of Malaya Research Ethics Committee for research on table tennis stroke (Ethics no: UM. TNC 2/RC/H&E/UMREC) and Medical Ethics Committee University Malaya Medical Center for research on radiography images (Ethics no: 20159-1625). The ethical clearance statement, consent form and participation information sheet can be referred in the Appendix section.

3.3 The Improvement of Existence 3D Kinematic Model Of 3-Linked Segments of Arm Segment

Yamaguchi (2006) used Kapandji (1982) and Kane's method to develop a 3D arm segment kinematic model. Knowledge of physiology of the upper limb from Kapandji (1982) was used for reference on positions at arm segment. Kane's method applies vector-based that allows the development of a 3D dynamic model (Kane & Levinson, 1985).

Vector dot and cross products are preferably used than derivation and integration to obtain acceleration and velocity. The table of direction cosines is important to develop the present model. The table of direction cosines in the present study has been widely used, mostly in the robotic and human motion field (Jazar, 2010; Kane & Levinson, 1985; Shah, Saha & Dutt, 2013) to describe the direction of the vector in coordinate axes (Yamaguchi, 2006). The motions of the bones and joints are accumulated together in Yamaguchi's model to replicate the reality of human motion at the arm segment mainly for the forearm supination/pronation (Yamaguchi, 2006). Figure 3.1 illustrates the kinematic model of the right-handed arm segment, where the reference frame N is the trunk, A is the humerus, B is the ulna, C is the radius and D is the hand. The segmental coordinate systems were defined by setting x-axes each of rigid reference frame point anteriorly, the y-axes point to the right, and the z-axes point inferiorly.

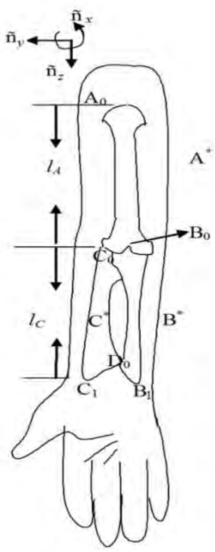


Figure 3.1: The 7 degree of freedom arm segment model adapted from Yamaguchi (2006). $\tilde{n}_x$ **= reference frame, *n* was defined as setting *x*-axis point anteriorly;** $\tilde{n}_z$ **= reference frame, *n* was defined as setting *z*-axis vertically downward;** $\tilde{n}_y$ **= reference frame, *n* was defined as setting *y*-axis perpendicular to *x*- and *z*- axes;** l_A **= length of humerus;** l_C **= length of radius;** A^* **= COM (center of mass) humerus;** B^* **= COM ulna;** C^* **= COM radius;** C_0 **= proximal end of radius;** B_0 **= proximal end of ulna;** A_0 **= proximal end of humerus;** D_0 **= proximal end of hand;** C_1 **= distal end of radius;** B_1 **= distal end of ulna**

The angles that rotate around the arm segment revolve around the shoulder adduction, shoulder flexion, shoulder external rotation, elbow flexion, forearm supination, wrist adduction and wrist dorsiflexion. These seven angles represent the 7 DOF at the arm segment. The equations (3.0) – (3.14) are part of the Yamaguchi's kinematic model of arm segment that utilized in the present study (Yamaguchi, 2006). The notational convention of equations (3.0) – (3.14) in Yamaguchi's model can be referred in Table 3.1.

The angular velocity from trunk to humerus. There is 3 degree of freedom (DOF) at shoulder joint.

$$^{N}\vec{\omega}^{A} = {}^{N}\vec{\omega}^{A'} + {}^{A'}\vec{\omega}^{A''} + {}^{A''}\vec{\omega}^{A} \tag{3.0}$$

Angular velocity from trunk to ulna

$$^{N}\vec{\omega}^{B} = {}^{N}\vec{\omega}^{A} + {}^{A}\vec{\omega}^{B} \tag{3.1}$$

Angular velocity from trunk to radius

$$^{N}\vec{\omega}^{C} = {}^{N}\vec{\omega}^{B} + {}^{B}\vec{\omega}^{C} \tag{3.2}$$

Angular velocity from trunk to hand. There is 2 DOF at wrist joint.

$$^{N}\vec{\omega}^{D} = {}^{N}\vec{\omega}^{C} + {}^{C}\vec{\omega}^{D'} + {}^{D'}\vec{\omega}^{D} \tag{3.3}$$

The velocity from trunk to the proximal end of ulna

$$^{N}\vec{v}^{B_0} = {}^{N}\vec{v}^{A_0} + {}^{N}\vec{\omega}^{A} \times \vec{p}^{A_0B_0} \tag{3.4}$$

which $\vec{p}$ is the certain position at upper extremity.

The velocity from trunk to the proximal end of radius

$$^{N}\vec{v}^{C_0} = {}^{N}\vec{v}^{B_0} + {}^{N}\vec{\omega}^{A} \times \vec{p}^{B_0A} + {}^{A}\vec{v}^{C_0} \tag{3.5}$$

The velocity from trunk to the proximal end of hand

$$^{N}\vec{v}^{D_0} = {}^{N}\vec{v}^{C_0} + {}^{N}\vec{\omega}^{C} \times \vec{p}^{C_0D_0} \tag{3.6}$$

Angular acceleration of humerus

$$^{N}\vec{\alpha}^{A} = \frac{d\left({}^{N}\vec{\omega}^{A}\right)}{dt} \tag{3.7}$$

Angular acceleration of ulna

$$^{N}\vec{\alpha}^{B} = \frac{d\left({}^{N}\vec{\omega}^{B}\right)}{dt} \tag{3.8}$$

Angular acceleration of radius

$$ {}^{N}\vec{\alpha}^{C} = \frac{d\left({}^{N}\vec{\omega}^{C}\right)}{dt} \tag{3.9} $$

Angular acceleration of hand

$$ {}^{N}\vec{\alpha}^{D} = \frac{d\left({}^{N}\vec{\omega}^{D}\right)}{dt} \tag{3.10} $$

Acceleration from trunk to proximal end of humerus

$$ {}^{N}\vec{a}^{A_0} = 0 \tag{3.11} $$

Acceleration from trunk to the proximal end of ulna

$$ {}^{N}\vec{a}^{B_0} = {}^{N}\vec{a}^{A_0} + {}^{N}\vec{\omega}^{A} \times \left({}^{N}\vec{\omega}^{A} \times \vec{p}^{A_0 B_0}\right) + {}^{N}\vec{\alpha}^{A} \times \vec{p}^{A_0 B_0} \tag{3.12} $$

Acceleration from trunk to the proximal end of radius

$$ {}^{N}\vec{a}^{C_0} = \left({}^{N}\vec{a}^{B_0} + {}^{N}\vec{\omega}^{A} \times \left({}^{N}\vec{\omega}^{A} \times \vec{p}^{B_0 A}\right) + {}^{N}\vec{\alpha}^{A} \times \vec{p}^{B_0 A}\right) + {}^{A}\vec{a}^{C_0} + 2\,{}^{N}\vec{\omega}^{A} \times {}^{A}\vec{v}^{C_0} \tag{3.13} $$

Acceleration from trunk to the proximal end of hand

$$ {}^{N}\vec{a}^{D_0} = {}^{N}\vec{a}^{C_0} + {}^{N}\vec{\omega}^{C} \times \left({}^{N}\vec{\omega}^{C} \times \vec{p}^{C_0 D_0}\right) + {}^{N}\vec{\alpha}^{C} \times \vec{p}^{C_0 D_0} \tag{3.14} $$

Table 3.1: The notational convention of equations (3.0) – (3.14) in Yamaguchi's model

The notational convention used in the Yamaguchi's model	
N	reference frame, trunk
A	humerus
B	ulna
C	radius
D	hand
D'	the second rotation of wrist (hand) joint
A_0	proximal end of humerus
B_0	proximal end of ulna
C_0	proximal end of radius
D_0	proximal end of hand
v	joints velocity
ω	joints angular velocity
a	joints acceleration
α	joints angular acceleration
$\vec{p}$	certain position at upper extremity
A^*	COM of humerus
B^*	COM of ulna
C^*	COM of radius
D^*	COM of hand

To obtain velocity and acceleration of a segment, it is required to calculate at the center of segment (Yamaguchi, 2006). However, to date, Yamaguchi (2006) only developed velocity and acceleration at proximal end of segments. Therefore, this study extended the Yamaguchi's model to get the velocity and acceleration of arm segment.

3.4 Methods to obtain Value of Positions, $\vec{p}$ at Upper Extremity

This study captured radiography images of volunteered participants on the right arm segment to obtain the value of positions at arm segment. The certain positions at arm segment can be referred in Yamaguchi (2006). The value of positions was necessary to complete the model and can be applied to related areas. The participants were 10 random male, healthy body with mean age of 21.00 ± 0.89 y, mean height of 1.70 ±

0.24 m and mean weight of 64.70 ± 6.84 kg. The participants were briefed on the experimental procedures after which they provided consent form. The selection of the participants was considered based on weight and height of 20 random athletes (badminton and table tennis male players) at the University of Malaya (UM), Malaysia. The mean height and weight of athletes were 1.68 ± 0.58 m and 63.08 ± 8.72 kg, respectively. The summary of the demographic of the participants can be referred in Table 3.2.

Table 3.2: Demographics of participants involved for radiography images

Demographics of participants	
Age	21.00 ± 0.89 y
Sex	Male
Height	1.70 ± 0.24 m
Weight	64.70 ± 6.84 kg
Broken bone	Not applicable/ healthy body
Type of profession	College student

The radiographers helped to capture the radiography images on the right handed arm segment of the participants at x-ray room, department of Biomedical Imaging, University Malaya Medical Center (UMMC), Malaysia. The radiographers helped to capture the radiography images (Figure 3.2) on the volunteers at the right radius ulna anterior-posterior (AP) and lateral, and right humerus AP and lateral. They were required not to wear metal on their body while committing the procedure. The nomenclature and description of positions at arm segment obtained from radiography images are explained in Figure 3.3 and Table 3.3.

a) Right radius ulna (AP view)

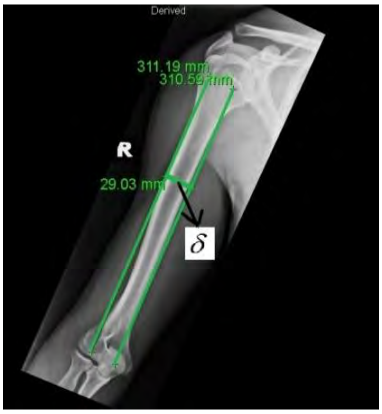
b) Right radius ulna (lateral view)

c) Right humerus (AP view)

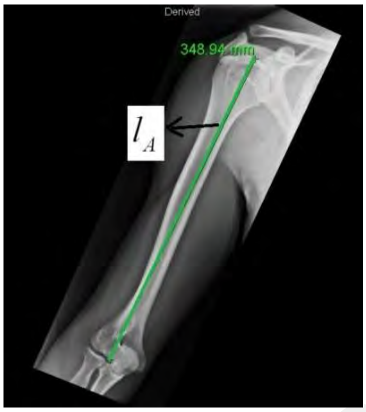
d) Right humerus (lateral view)

Figure 3.2: The procedures to capture radiography images of arm segment required in the study

a) Position δ



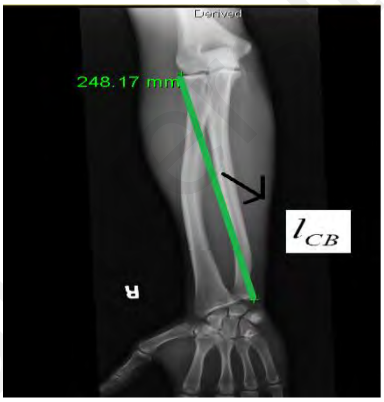
b) Position l_A



c) Position l_B / l_C

d) Position r

e) Position l_{CB}



f) Position φ

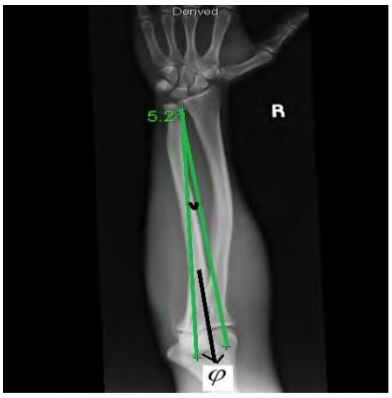


Figure 3.3: The description and value of positions at arm segment obtained from radiography images

Table 3.3: The nomenclature of positions at arm segment in Yamaguchi's model

Nomenclature of positions at arm segment in Yamaguchi's model	
δ	width of humerus
l_A	length of humerus
l_B	length of ulna
l_C	length of radius
B_0	proximal end of ulna
C_0	proximal end of radius
B_1	distal end of ulna
r	length from B_0 to C_0 during elbow flexion at 90°
l_{CB}	length from C_0 to B_1
φ	angle between the center of the concave proximal end of radius and the distal end of ulna

There are several methods that can be used to determine the length of proximal end to the COM of segments which can be obtained from Winter (2009), de Leva (1996) and Clauser, McConville, and Young (1969). The positions at arm segment developed by Yamaguchi (2006) were described from or at the proximal end of segment. Therefore, it was decided to use the de Leva (1996) method which was more suitable to find the COM segments' length in this study. This method (Figure 3.4) calculated the COM from the proximal end of segment. It was assumed that the hand and racket moved as a single segment (Iino and Kojima, 2009; Rambely, 2008). Therefore, P_D (COM of hand) was calculated from the proximal end of wrist joint to the COM of racket (Rambely, 2008).

The results were compared with the previous studies (Winter, 2009; de Leva, 1996) to ensure that the method to calculate the length of segments by using radiography images was correct.

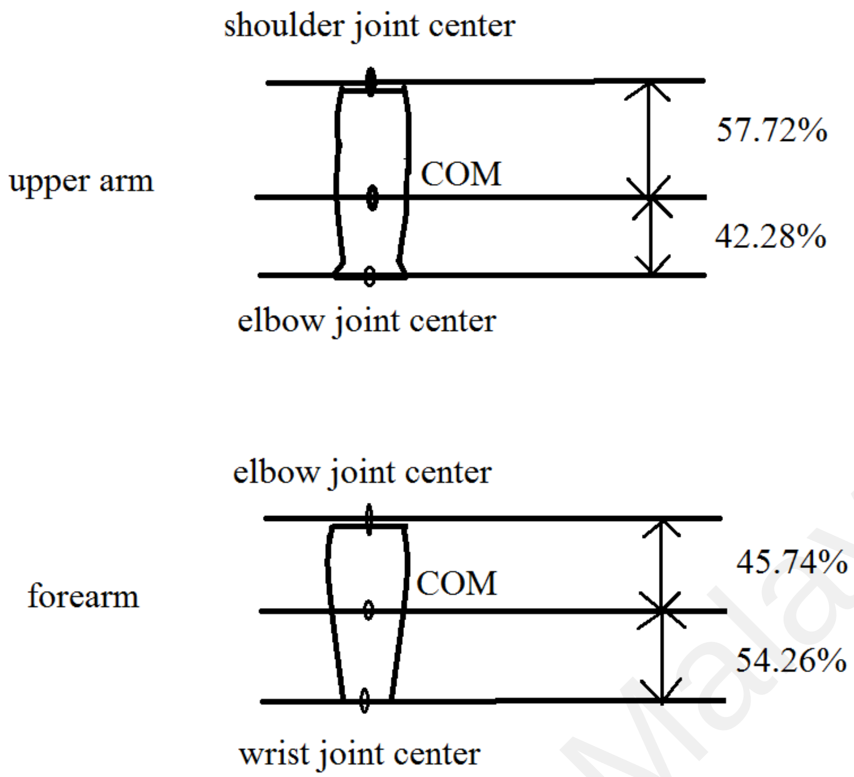


Figure 3.4: Method to calculate the length of COM of segment adapted from de Leva (1996)

3.5 Algorithm for Yamaguchi's 3D kinematic model of arm segment

The equations of Yamaguchi's arm segment model will connect one frame to other reference frames, thereby making the situation complex. The calculations were simple but generated a long equation. Therefore, an algorithm in any software packages was essential to develop the model. MATLAB was selected in the study because of its credibility to perform calculations that involve large amount of data. Figure 3.5 shows the process of developing the algorithm based on the arm segment kinematic model (Yamaguchi, 2006).

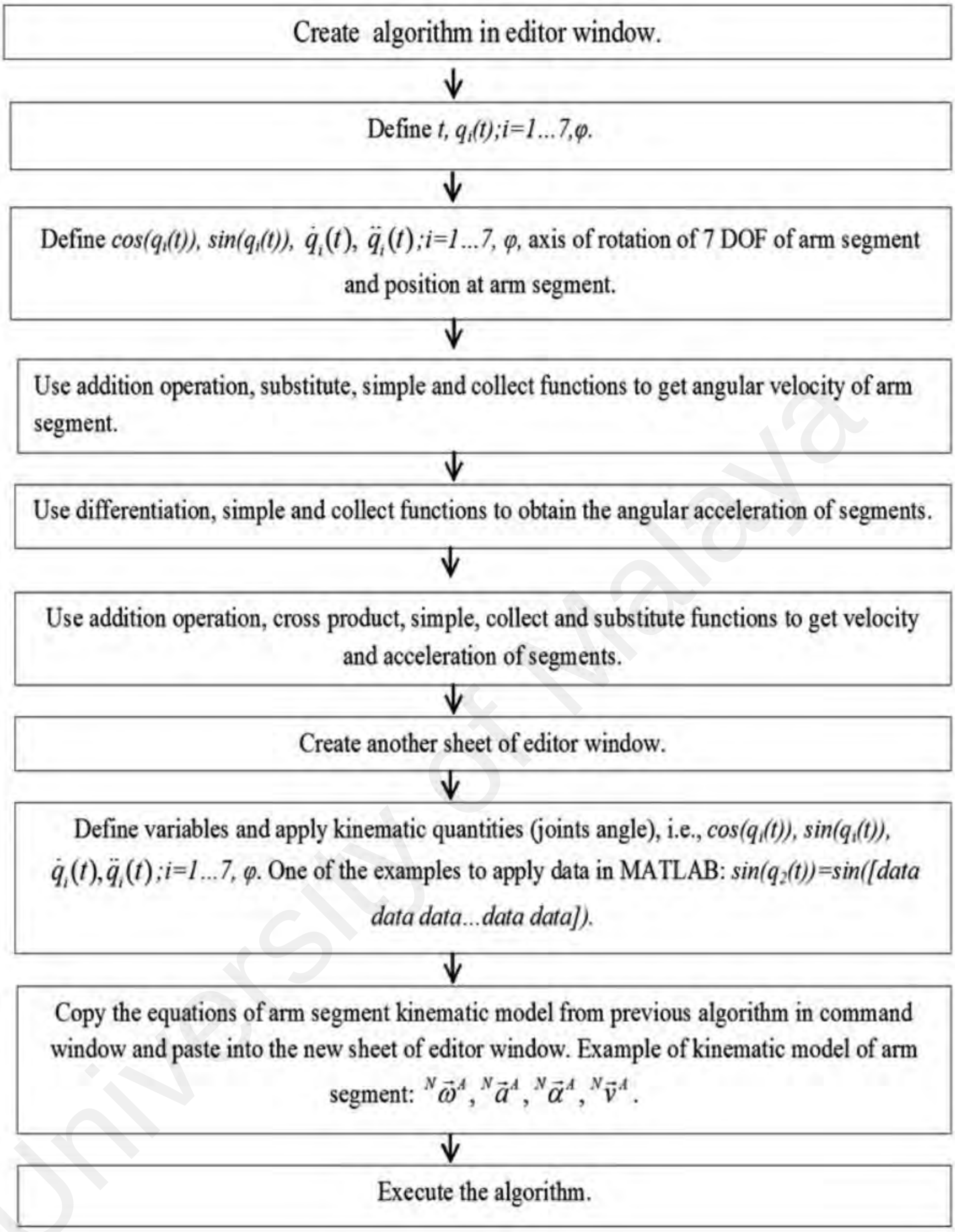


Figure 3.5: The algorithm in MATLAB for kinematic model of arm segment

Firstly, this study defined $q_i(t);i=1...7$, φ, where q is the angle of arm segment joints that changes with time (t). φ is defined as the angle between the center of the concave proximal end of radius and the distal end of ulna (Yamaguchi, 2006). Then, the differentiation of the function $q_i(t);i=1\ldots7$, φ and positions that were developed in the Yamaguchi arm segment kinematic model were defined in the algorithm with symbols (Figure 3.6).

```
%the positions from Yamaguchi model were defined
syms lA del lCB lC2 lC3 lD1 lD2 lD3 pA pB pC pD
%q1(t)
h=q1
q1_of_t=sym('q1(t)')
h1=subs(h,q1,q1_of_t)
%differentiate q1(t),differentiate twice q1(t)
diff_q1t=diff(h1,t)
diff_q1t2=diff(diff_q1t,t)
%cos(q1(t))
c1=cos(h1)
diff_c1_of_t=diff(c1,t)
%sin(q1(t))
s1=sin(q1_of_t)
diff_s1_of_t=diff(s1,t)
```

Figure 3.6: Positions, $q_i(t);i=1\ldots7$, φ, and differentiation of $q_i(t);i=1\ldots7$, φ defined in MATLAB

Next, the MATLAB was used to calculate the angular velocity from trunk to humerus. The table of direction cosines (refer to Yamaguchi, 2006) was substituted into the axes of rotation at shoulder joint. To substitute them, the substitute function was used in MATLAB. Based on the calculation in Yamaguchi's arm segment kinematic model, functions like addition, simple and collect were used to solve the equation. The simple function was used to simplify the equation and the collect function was alternatively used to arrange the terms of the axis of rotation orderly in the present equation.

Other angular velocity of arm segment can be calculated using the same function as above (Figure 3.7). To generate other angular velocity of the arm segment, previous equation of angular velocity of arm segment was called and merged into the new equation of angular velocity. The axes of rotation at previous equation were substituted with the table of direction cosines at the present equation so that the terms of axes of rotation were the same in the present equation. The differentiation function was used to obtain the angular acceleration of arm segment (Figure 3.7).

```
%Angular velocity N to B (Angular velocity trunk to ulna)
syms b1 b2 b3
NwBa=NwA+(diff_q4t*b2)
NwBb=collect(NwBa,{a1,a2,a3})

NwBc=subs(NwBb,{a1,a2,a3},{c4*b1+s4*b3,b2,-s4*b1+c4*b3})
NwBd=simple(NwBc)
NwB=collect(NwBd,{b1,b2,b3})


%angular acceleration N to A (angular velocity trunk to humerus)
diff_NwA1=diff(NwA,t)
diff_NwA=collect(simple(diff_NwA1),{a1,a2,a3})
```

Figure 3.7: Examples of segment angular velocity and angular acceleration calculated

Furthermore, the cross product function was utilized in the velocity and acceleration calculation (Figure 3.8). The position and the angular velocity of arm segment were transformed into the matrix form before executing the cross product function. The substitution, addition, simple and collect functions were also used to obtain the velocity and acceleration of arm segment (Figure 3.8).

```
%velocity N to B0 (velocity trunk to proximal end of ulna)
matrixNwA=[s3*diff_q2t+c2*c3*diff_q1t c3*diff_q2t-c2*s3*diff_q1t s2*diff_q1t+diff_q3t]
matrixpA0B0=[0 0 lA]
NvB0a=cross(matrixNwA,matrixpA0B0)
NvB0b=simple((lA*(c3*diff_q2t - c2*s3*diff_q1t))*a1-(lA*(s3*diff_q2t+c2*c3*diff_q1t))*a2)
NvB0=collect(NvB0b,{a1,a2})
```

Figure 3.8: Example of segment velocity calculated and written in MATLAB

The algorithm created in the MATLAB followed the equations from the improved model. When all above steps were executed, the algorithm of the kinematic equations can be obtained. A new sheet of "editor window" was created to allow the analysis of a wide range of data. The rest of kinematic quantities can be obtained from MATLAB after applying the joints angle of arm segment into the sheet. To create the algorithm, the positions, angles of arm segment rotations and its values were defined in the new "editor window" (Figure 3.9).

```
c4=cosd([67.439 65.488  64.071  63.393  63.505  ...])  % cos (q4(t))


%Below is the certain position at upper extremity (refer Yamaguchi (2006));
 lA=[0.34];
del=[0.024];
  r=[0.021];
lCB=[0.255];
```

Figure 3.9: Positions, angles of arm segment rotations and its values were defined in the new "editor window"

Then, the model algorithm obtained from the "command window" sheet earlier was copy and paste into the new "editor window" (Figure 3.10).

```
NwA_a1=(s3.*diff_q2t + c2.*c3.*diff_q1t)  % angular velocity  from N to A at axis '1'
NwA_a2=(c3.*diff_q2t - c2.*s3.*diff_q1t)  % angular velocity  from N to A at axis '2'
NwA_a3=(s2.*diff_q1t + diff_q3t)  % angular velocity  from N to A at axis '3'
```

Figure 3.10: Example of model algorithm (equation of angular velocity from trunk to humerus) obtained from the "command window" sheet earlier was copy and paste into the new "editor window"

The rest of kinematic data of the arm segment can be obtained by applying the preceding algorithm. Full algorithm can be referred in "Appendix" section.

3.6 Validation of the Improved Model

A study was conducted on the table tennis service to verify the aforementioned algorithm. 10 out of 55 collegiate male table tennis players were selected as participants in the present study (Figure 3.11). Others were out of contact, did not volunteer to participate and pull out of the study. The participants' mean age, height, and weight were 21.50 ± 1.27 y, 1.68 ± 0.56 m, and 62.75 ± 10.20 kg, respectively. They were right-handed and shake-hand grip. Four of them were advanced players, whom had a minimum of 5 years playing experience and had qualified to participate in National level tournaments. Other participants were categorized as intermediate players since they had not qualified to participate in National level tournaments. The summary of the demographic of the participants can be referred in Table 3.4.They were briefed about the experimental procedures. Later, they provided the consent form before participating in the study.

Table 3.4: Demographics of participants involved for the validation of improved model

Demographic of participants	
Age	21.50 ± 1.27 y
Sex	Male
Height	1.68 ± 0.56 m
Weight	62.75 ± 10.20 kg
Experience playing game	5.90 ± 0.32 y
Ranking players	6 intermediate players; 4 advanced players
Participation in tournaments	Intermediate players: college tournaments; Advanced players: college, club and national tournaments
Dominant hand (right handed)	Yes to all players
Type of grip	Shake hand grip

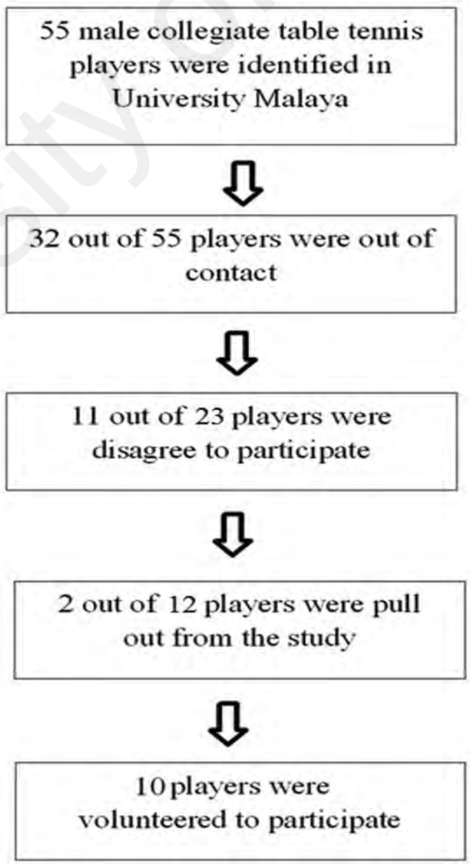


Figure 3.11: The process to obtain volunteered participants

The participants were asked to wear short pant or swimming trunk during recording. The short pant or swimming trunk was used in the study to ensure markers were stick at the right position on the body during recording. The equipment (ball, racket and table) used in the experimental procedures were approved by ITTF. In this study, 40 mm white ball and blue table were selected in this study. There are various types of racket which give different speed and control (Heaton, 2009). Therefore, the participants were asked to use the provided racket so that there was no factor from the racket that can contribute to different speed of ball and racket at impact. The inverted rubber on both sides of the racket was used in this study, which was adopted from Iino, Mori, and Kojima (2008).

Observations from previous studies found that high speed or infrared cameras operating at the range of 100 - 300 Hz were used to analyze sports activities such as cricket, golf and strokes in racket sports (Bingul, Aydin, Bulgan, Gelen, & Ozbek, 2016; Rusydi, Huda, Rusydi, Sucipto & Sasaki, 2016; Shorter, Nealon, Smith, & Lauder, 2011; Song, Beard, & Ustinova, 2015). It was stated that at least 100 Hz cameras were adequate to record sports activities (Barlett, 2007; Payton & Bartlett, 2007). Hence, in this study, five synchronized infrared cameras (Vicon MX T40-S, Oxford, UK) operating at 250 Hz were used to record the table tennis serving motion. Five cameras system which used in the present study was supported by Ackland, Elliott and Bloomfield (2009), Iino and Kojima (2009) and Iino and Kojima (2011). Two cameras were in front of the participant, one at the lateral side and the other two cameras were positioned behind the participant. The setting of the cameras and system were performed by the Vicon engineers and University of Malaya technicians. The experimental procedures were started with calibrating the area of experimental procedure. This action must be performed to make sure the cameras can identified the markers that attached on the participants, racket and the ball during recordings. After that, the global Cartesian system will be defined in the system. The z-axis of the global right handed Cartesian coordinate system was defined vertically upward, x-axis was defined along the projecting of racket velocity and y-axis was set perpendicular to the *x*- and *z*-axes. . The summary of the characteristics of experimental tools can be referred in Table 3.5.

Table 3.5: Characteristics of experimental tools for validation of the improved model

Characteristics of experimental tools	
Ball	40 mm white ball; Brand Nittaku
Racket	Inverter rubber on both sides; Length handle 10 cm; Width handle 3 cm; Length blade 17 cm; Width blade 15 cm; Brand Butterfly
Net	Length 15.30 cm; Brand Butterfly
Table	Length table 274 cm; Width table 152 cm; Height table 76 cm; Brand Butterfly
Clothes	Short pant/swimming trunk
Area ball landed for long shot service	1/6 of table area; Opponent side; At the edge of table
Area ball landed for drop shot service	1/4 of table area; Opponent side; At the middle of table
System	Vicon MX T40-S, Oxford, UK
Cameras	5 Vicon infrared cameras; 250 Hz
Filter	Woltring filter

Each participant was required to perform forehand service. They were to hit the ball freely, whether at long or short distance. Recording for each participant was repeated until five successful trials. A successful trial was based on the participant's feedback on his subjective judgement on the intended stroke, the smoothness of swing and the quality of ball flight. The players' judgement for each stroke was adopted from Iino and Kojima (2009). Ball spin is important in table tennis, however it could be difficult to calculate it without a suitable equipment. In this study, the participants were asked to define their ball spin, whether it was low or high spin right after the execution of successful services.

Participants were asked to wear 17 markers on the upper limb based on Vicon upper limb template. The markers were attached at both anterior superior iliac spine, both posterior superior iliac spine, clavicle, sternum, 7th cervical vertebrae, 10th thoracic vertebrae, right back, both acromio-clavicular joint, right upper arm between elbow and shoulder markers, lateral epicondyle approaching right elbow joint, right lower arm between the wrist and elbow markers, right wrist joint (thumb and little finger side) and just below the head of the second metacarpal at the right wrist. A marker was attached at the head of the racket and some reflective tapes were attached at the ball without changing its weight (0.9 % heavier than the original weight).

The Vicon motion analysis was further used for digitization. Gaps were filled for missing markers in certain frames during this process. Only several frames for each trial that missing some markers during this process. As suggested by the Vicon system, pattern fill or spline fill can be performed for missing markers. This procedure was supported by Alexander and Schwameder (2016). The Woltring filter was used to cut off the frequency and automatically smoothen the coordinate data. This procedure was supported by Yu, Shao, Baker and Gu (2018). The relative axis was more appropriate than global axis for use in the present study since the study analyzed arm movement. Hence, the kinematic quantities (joints angle) from the Vicon motion analysis system were applied to the 3D arm segment kinematic model. The rest of kinematic data were obtained from the Yamaguchi's model (Yamaguchi, 2006). The three linked segmental models were upper arm, lower arm and hand with racket, which were adopted from Yamaguchi (2006). Hand and racket were assumed to move as a single segment during serving (Iino & Kojima, 2009). The segmental coordinate system of each rigid body reference frame was defined as setting x-axes point anteriorly, z-axes vertically downward and y-axes perpendicular to x- and z- axes (refer to Yamaguchi, 2006). However, the horizontal ball and racket head velocities were obtained directly from the system.

The arm segment angles (7 DOF at arm segments) were identified after the digitization process. The authors identified the arm segment angles after performing preliminary experimental procedures.

The kinematic of arm segments, horizontal ball and racket head velocities were compared with previous studies that had conducted research in table tennis serving and stroke (Iino & Kojima, 2009; Wang et al., 2008; Yoshida, Sugiyama, & Murakoshi, 2010) to validate the improved model.

The overall methodology process to validate the improve model was interpreted in the Figure 3.12.

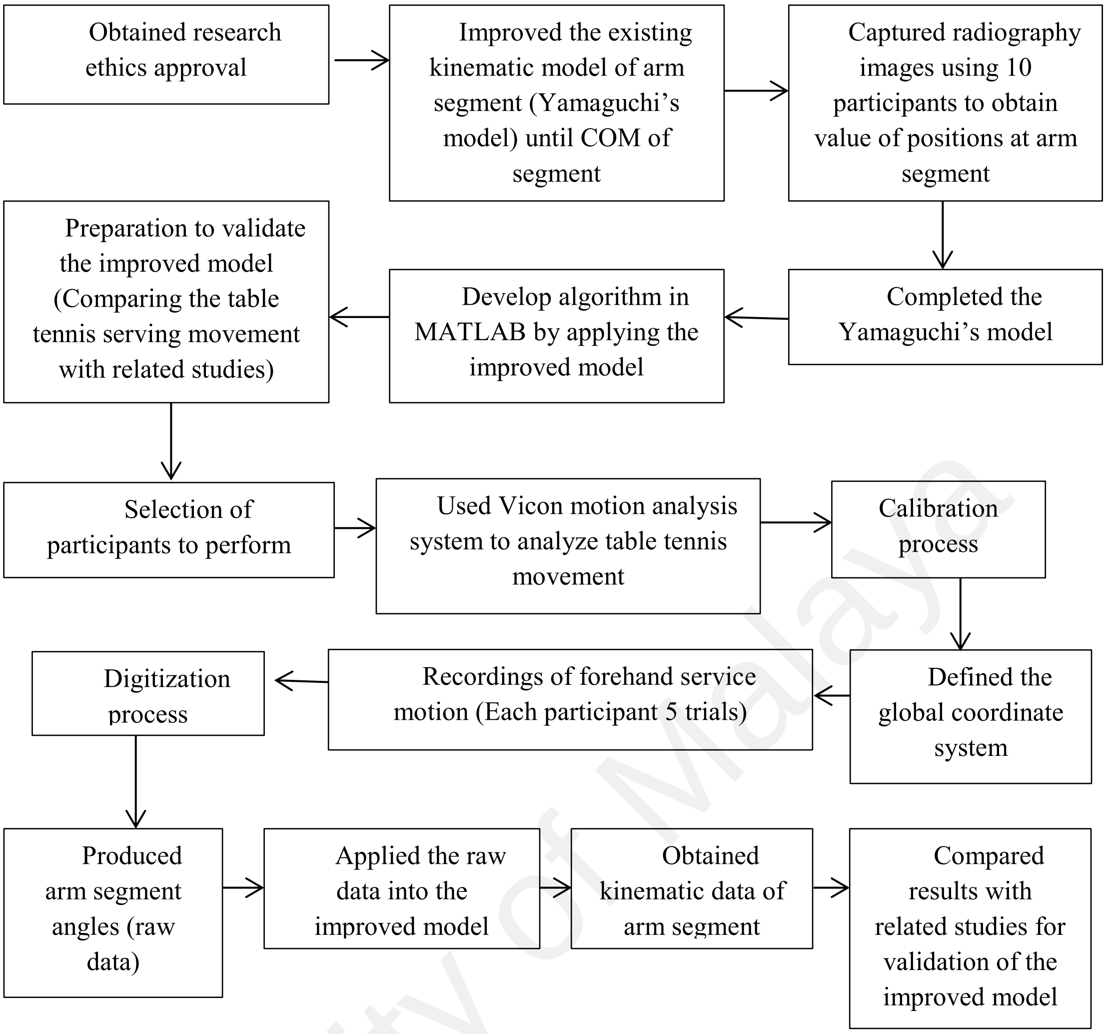


Figure 3.12: The methodology process to validate the improved model

3.7 Study Cases in Table Tennis Service

In general, the experimental procedures to validate the developed algorithm and study cases in table tennis service were similar, except for the quantity of participants, different intended services and statistical analysis.

3.7.1 Participants

A total of 16 out of 75 male collegiate players volunteered to participate in the current study (Figure 3.13). Others were out of contact, did not volunteer to participate and pull out of the study. However, a participant was pulled out from the experimental procedure during long shot service. Therefore, results for long shot service analysis only considered data from fifteen participants. Five of them were advanced players, whom had a minimum of 5 years playing experience and had qualified to participate in National level tournaments. Other participants were categorized as intermediate players since they had not qualified to participate in National level tournaments. Their average age, height and weight were 21.50 ± 1.27 y, 1.68 ± 0.56 m, and 61.59 ± 0.60 kg, respectively. They were briefed on the experimental procedures of this study, after which they provided written informed consent forms. The summary of the demographic of the participants can be referred in Table 3.6. All participants were right-handed and shake-hand grip table tennis players.

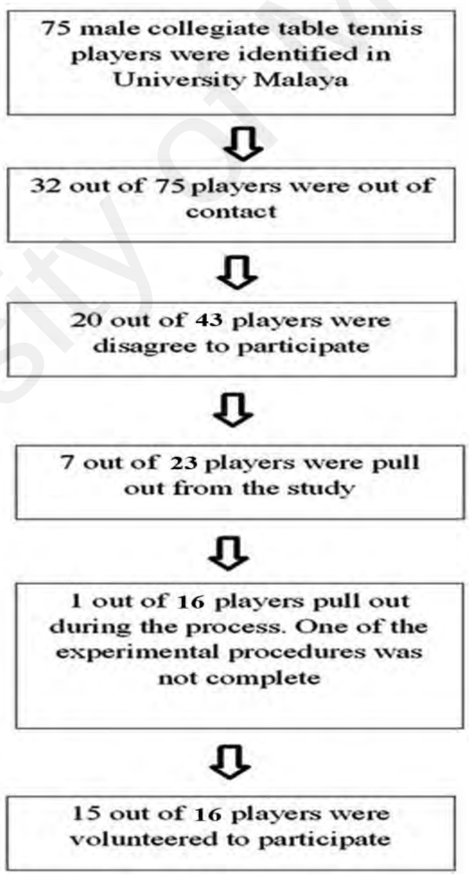


Figure 3.13: The process to obtain participants for study cases in table tennis service

Table 3.6: Demographics of participants involved for analysis of table tennis serving movement

Demographics of participants	
Age	21.50 ± 1.27 y
Sex	Male
Height	1.68 ± 0.56 m
Weight	61.59 ± 0.60 kg
Experience playing game	5.94 ± 0.54 y
Ranking players	11 intermediate players; 5 advanced players
Participation in tournaments	Intermediate players: college tournaments; Advanced players: college, club and national tournaments
Dominant hand (right handed)	Yes to all players
Type of grip	Shake hand grip

3.7.2 Experimental Procedures

The participants were asked to wear short pant or swimming trunk during recording. The equipment (ball, racket and table) used in the experimental procedures were approved by ITTF. In this study, 40 mm white ball and blue table were selected in this study. There are various types of racket, which gave different speeds and control (Heaton, 2009). Therefore, the participants were asked to use the provided racket so that there was no factor from the racket that can contribute to different speeds of ball and racket at impact. The inverted rubber on both side of racket was used in this study which was adopted from Iino, Mori, and Kojima (2008). The summary of the characteristics of experimental tools can be referred in Table 3.7.

Table 3.7: Characteristics of experimental tools in case studies of table tennis

Characteristics of experimental tools	
Ball	40 mm white ball; Brand Nittaku
Racket	Inverter rubber on both sides; Length handle 10 cm; Width handle 3 cm; Length blade 17 cm; Width blade 15 cm; Brand Butterfly
Net	Length 15.30 cm; Brand Butterfly
Table	Length table 274 cm; Width table 152 cm; Height table 76 cm; Brand Butterfly
Clothes	Short pant/swimming trunk
Area ball landed for long shot service	1/6 of table area; Opponent side; At the edge of table
Area ball landed for drop shot service	1/4 of table area; Opponent side; At the middle of table
System	Vicon MX T40-S, Oxford, UK
Cameras	5 Vicon infrared cameras; 250 Hz
Filter	Woltring filter

Five synchronized infrared cameras (Vicon MX T40-S, Oxford, UK) operating at 250 Hz were used to record the movement of participants performing forehand long shot and drop shot table tennis services. Five cameras system which used in the present study was supported by Ackland, Elliott and Bloomfield (2009), Iino and Kojima (2009) and Iino and Kojima (2011). Two cameras were positioned at the back of a participant, one at the lateral side and the other two cameras were in front of the participant. Figure 3.14 showed the experimental setup in this study. The setting of the cameras and system were performed by the Vicon engineers and Universiti Malaya technicians. The experimental procedures were started with calibrating the area of experimental procedure. This action must be performed to make sure the cameras can identified the markers that attached on the participants, racket and the ball during recordings. After that, the global Cartesian system will be defined in the system. The z-axis of the global right handed Cartesian coordinate system was defined vertically upward, x-axis was defined along the projecting of racket velocity and y-axis was set perpendicular to the *x*-and *z*-axes.

Participants were asked to practice before starting the trials (recordings). They were asked to perform forehand drop shot and long shot services. The served ball must land at the target area (Figure 3.15). During trials, each player was allowed the freedom to execute service from any position from the table. However, each player must serve the same position and distance during both services. A marker was placed at the position of each player's prior recording to make sure they served from the same position in all the trials.

The target area for drop shot service was adopted from Lanzoni, Michele, and Merni (2014) and the target area for long shot service was adopted from Ghoneim and Salem (2008). The location of the first bounce for drop shot service should be near the net of server's table side, while for long shot service should be between the end of server's table side to the middle of server's table side. The third bounce for drop shot service must be located near the middle of opponent's table side while there was no third bounce for long shot service, which it was out of the table area. The location of the first and third bounce was adopted from Heaton (2009). A successful trial was based on the ball landing within the designated target area and player's feedback based on his subjective judgement on the intended stroke, the smoothness of swing and the quality of ball flight. The players' judgement for each stroke was adopted from Iino and Kojima (2009). Figure 3.16 showed the postures to perform forehand service implemented by the participants. Ball spin is important in table tennis, however it could be difficult to calculate it without a suitable equipment. In this study, the participants were asked to define their ball spin, whether it was low or high spin right after the execution of successful services. Recording for each participant was repeated until five successful trials.

Participants were asked to wear 17 markers on upper limb based on Vicon upper limb template. The markers were attached at both anterior superior iliac spine, both posterior superior iliac spine, clavicle, sternum, 7th cervical vertebrae, 10th thoracic vertebrae, right back, both acromio-clavicular joints, right upper arm between elbow and shoulder markers, lateral epicondyle approaching right elbow joint, right lower arm between the wrist and elbow markers, right wrist joint (thumb and little finger side) and just below the head of the second metacarpal at right wrist. A marker was attached at the head of the racket and some reflective tapes were attached at the ball without changing its weight (0.9 % heavier than the original weight). The details of the attached markers on upper body, racket and ball can be referred in Figure 3.17 and Figure 3.18.

The Vicon motion analysis was further used for digitization. Gaps were filled for missing markers in certain frames during this process. Only several frames for each trial that missing some markers during this process. As suggested by the Vicon system, pattern fill or spline fill can be performed for missing markers. This procedure was supported by Alexander and Schwameder (2016). The Woltring filter was used to cut off the frequency and automatically smoothen the coordinate data. This procedure was supported by Yu, Shao, Baker and Gu (2018). The results after digitized and filtered can be referred in Figure 3.19.

Figure 3.14: The experimental setup. CAM = Camera; SYS = Vicon system; → = Global axis

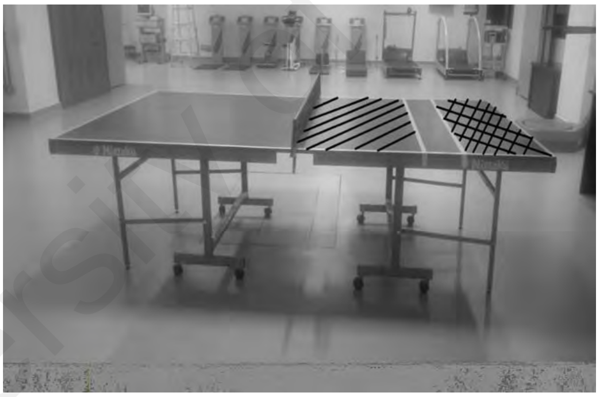


Figure 3.15: The target landed service ball on the opponent side of table

= the target area for drop shot service; = the target area for long shot service

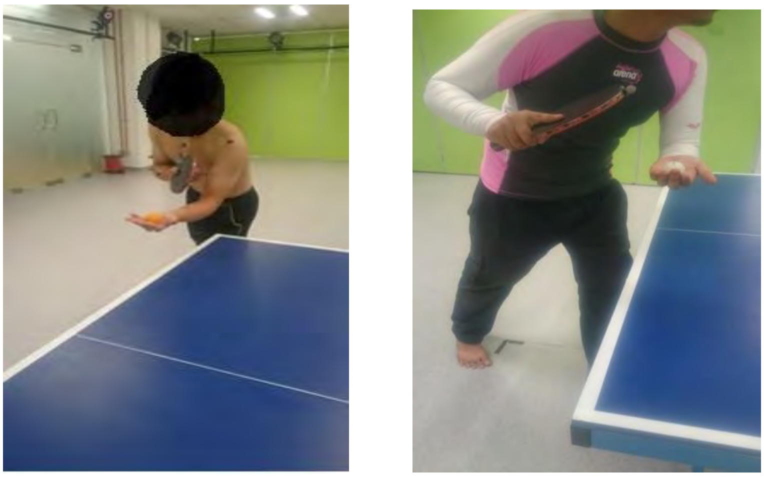


Figure 3.16: Postures to perform forehand service implemented by participants

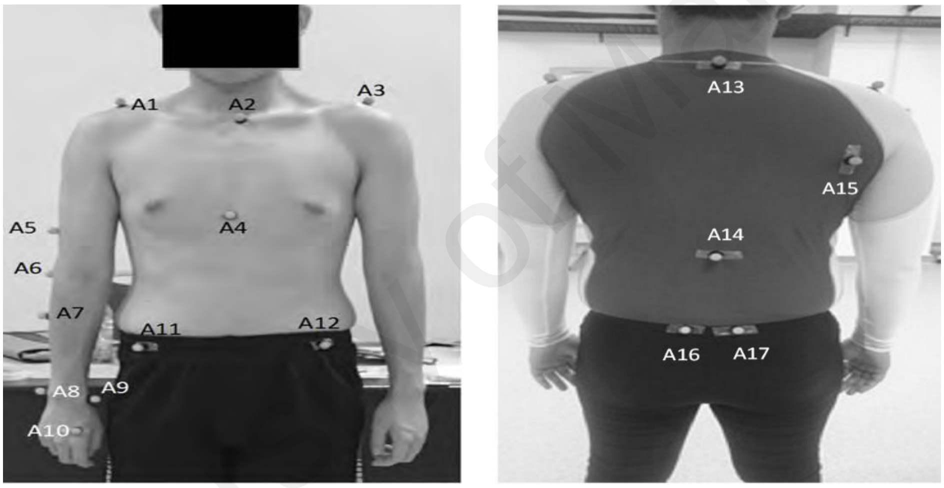


Figure 3.17: Seventeen markers on upper body for experimental procedure. A1 and A3 = both acromio-clavicular joints; A2 = clavicle; A4 = sternum; A5 = right upper arm between elbow and shoulder markers; A6 = lateral epicondyle approaching right elbow joint; A7 = right lower arm between the wrist and elbow markers; A8 and A9 = right wrist joint (thumb and little finger side); A10 = just below the head of the second metacarpal at right wrist; A11 and A12 = both anterior superior iliac spines; A13 = 7th cervical vertebrae; A14 = 10th thoracic vertebrae; A15 = right back; A16 and A17 = both posterior superior iliac spines

Figure 3.18: The markers and reflective tapes attached on the tip of racket and ball

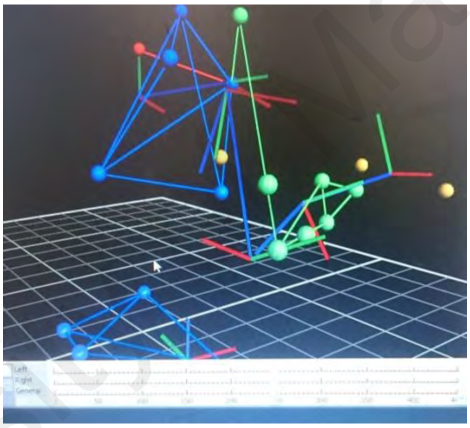


Figure 3.19: The results after digitized and filtered

3.7.3 Kinematic Analysis

The relative axis was more appropriate than global axis to be used in the present study since the study analyzed arm movement. Hence, the kinematic quantities (7 DOF of arm segment) from the Vicon motion analysis system were applied to the 3D arm segment kinematic model (the developed algorithm). Figure 3.20 showed the segment reference frame and relative axis fixed on arm segment based on Yamaguchi's model. The three linked segmental models were upper arm, lower arm and hand with racket which were adopted from Yamaguchi (2006). Hand and racket were assumed to move as a single segment during serving (Iino & Kojima, 2009). The segmental coordinate system of each rigid body reference frame was defined as setting *x*-axes point anteriorly, *z*-axes vertically downward and y-axes perpendicular to *x*- and *z*- axes (refer to Yamaguchi, 2006). However, the horizontal ball and racket head velocities were obtained directly from the system.

The arm segment angles (7 DOF at arm segments) were identified after the digitization process. The authors identified the arm segment angles after performing preliminary experimental procedures.

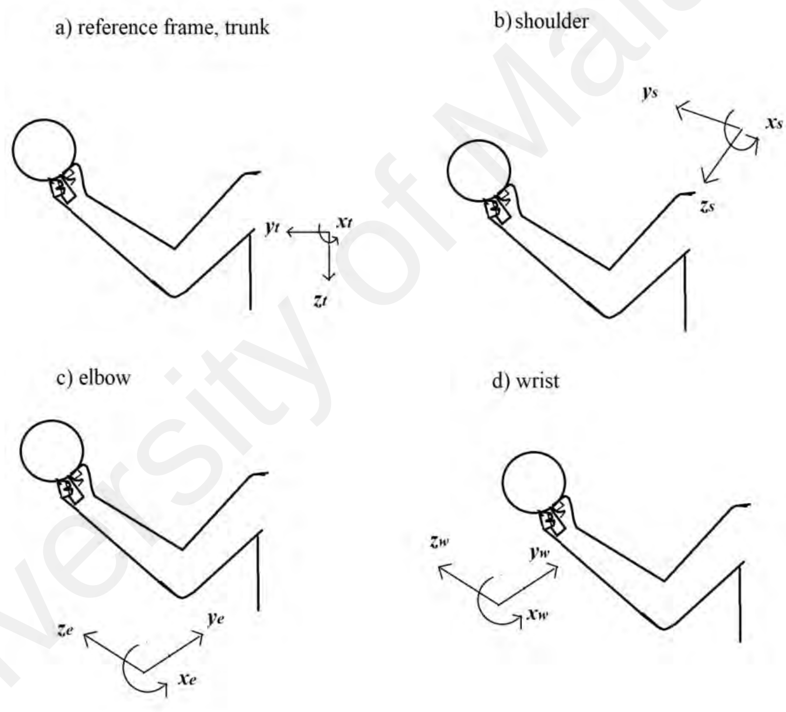
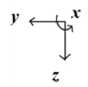


Figure 3.20: Definition of segment reference frame and relative axis fixed on shoulder, elbow and wrist


= axis of rotation; *t* = trunk; *s* = shoulder; *e* = elbow; *w* = wrist

Method in Winter (2009) was used to calculate the angular velocity of each frame of arm segment. The details of the method used in Winter (2009) can be referred in Figure 3.21 and equation (3.15). Later, these values were applied to the developed algorithm. The rest of the kinematic data were obtained from the algorithm.

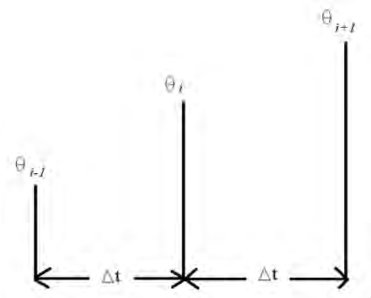


Figure 3.21: Method to calculate the angular velocity of each frame adopted from Winter (2009). Δt : time difference in a frame; θ_{i-1} : angle at previous frame; θ_i : angle at present frame; θ_{i+1} : angle at next frame

Below is an equation of angular velocity of each frame adopted from Winter (2009).

$$\omega_i = \frac{\theta_{i+1} - \theta_{i-1}}{2\Delta t} \qquad (3.15)$$

where ω_i = angular velocity at present frame.

3.7.4 Statistical Analysis

SPSS Statistics 23 (IBM, Inc., Armonk, NY, USA) was used to conduct statistics analysis on service motion. The significance was set at $P < 0.05$. There were no controlled parameters in this study. In this study, the participants were given freedom to serve forehand drop shot and long shot services based on their subjective judgement. The demographics of participants and characteristics of the experimental tools has been declared in this chapter under titles the “experimental procedures” and “participants”.

Non-parametric correlation coefficient (Spearman's Rho) was used to determine the relationship between the kinematic of arm segment rotations, horizontal ball and racket head velocities at impact during forehand drop shot in table tennis serving. Temporarily, parametric correlation coefficient (Pearson) was used to determine the relationship between the kinematic of arm segment rotations, horizontal ball and racket head velocities at impact during forehand long shot in table tennis serving. The non-parametric correlation coefficient was selected for analysis since some of the variables were not normally distributed after using Shapiro-Wilk test. Furthermore, the non-parametric paired t-test, Wilcoxon Signed Ranks Test was selected to find the significant difference between the velocity of arm segment rotations, joints angle, horizontal ball and racket head velocities during forehand drop shot and long shot services. The non-parametric paired t-test was selected for analysis since some of the variables were not normally distributed after using Shapiro-Wilk test. Shapiro-Wilk test was selected to determine the normal distribution of each variable since the sample size of the study was less than 50 (Arifin, 2015).

The overall methodology process to analyze the table tennis serving movement (kinematics) was explained in Figure 3.22.

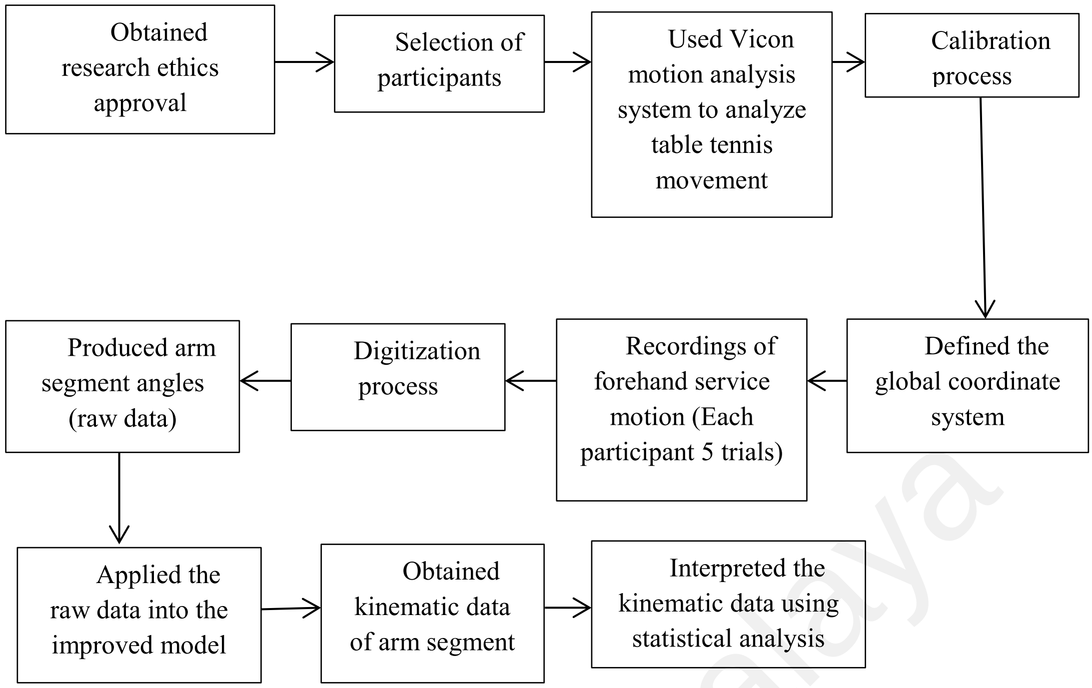


Figure 3.22: The methodology process to analyze the table tennis kinematics

CHAPTER 4: RESULTS AND DISCUSSIONS

In this chapter, the results will be detailed and the findings will be discussed. These findings were used to fulfill the objectives of the study. The improved model and its algorithm were developed after adding some parameters and validated. The improved model equations were described from the proximal end of segment until the COM of segment. The radiography images which were used to obtained specific positions at arm segment were discussed. Furthermore, the validation process of the improved model was described, interpreted and discussed. Then, the improved model will be used to obtain kinematic data of table tennis arm segment. The kinematic data will be utilized in the statistical analysis to understand the table tennis kinematics. Finally, the table tennis kinematics were discussed to find the relation and contributions to the improvement in table tennis.

4.1 Results

4.1.1 The Improvement of the Existing 3D Kinematic Model of Arm Segment

Equations (4.0) – (4.7) are the improvement of the existing 3D kinematic model of arm segment from Yamaguchi (2006). The notational convention of equations (4.0) – (4.7) in improved model can be referred in Table 3.1. This model will be used to obtain the kinematic data.

The velocity from trunk to the center of mass (COM) of humerus

$$ {}^{N}\vec{v}^{A*} = {}^{N}\vec{v}^{A_0} + {}^{N}\vec{\omega}^{A} \times \vec{p}^{A_0 A*} \tag{4.0} $$

The velocity from trunk to the COM of ulna

$$ {}^{N}\vec{v}^{B*} = {}^{N}\vec{v}^{B_0} + {}^{N}\vec{\omega}^{B} \times \vec{p}^{B_0 B*} \tag{4.1} $$

The velocity from trunk to the COM of radius

$$^{N}\vec{v}^{C*} = {}^{N}\vec{v}^{C_0} + {}^{N}\vec{\omega}^{C} \times \vec{p}^{C_0C*} \tag{4.2}$$

The velocity from trunk to the COM of hand

$$^{N}\vec{v}^{D*} = {}^{N}\vec{v}^{D_0} + {}^{N}\vec{\omega}^{D} \times \vec{p}^{D_0D*} \tag{4.3}$$

Acceleration from trunk to COM of humerus

$$^{N}\vec{a}^{A*} = {}^{N}\vec{a}^{A_0} + {}^{N}\vec{\omega}^{A} \times \left({}^{N}\vec{\omega}^{A} \times \vec{p}^{A_0A*} \right) + {}^{N}\vec{\alpha}^{A} \times \vec{p}^{A_0A*} \tag{4.4}$$

Acceleration from trunk to COM of ulna

$$^{N}\vec{a}^{B*} = {}^{N}\vec{a}^{B_0} + {}^{N}\vec{\omega}^{B} \times \left({}^{N}\vec{\omega}^{B} \times \vec{p}^{B_0B*} \right) + {}^{N}\vec{\alpha}^{B} \times \vec{p}^{B_0B*} \tag{4.5}$$

Acceleration from trunk to COM of radius

$$^{N}\vec{a}^{C*} = {}^{N}\vec{a}^{C_0} + {}^{N}\vec{\omega}^{C} \times \left({}^{N}\vec{\omega}^{C} \times \vec{p}^{C_0C*} \right) + {}^{N}\vec{\alpha}^{C} \times \vec{p}^{C_0C*} \tag{4.6}$$

Acceleration from trunk to the COM of hand

$$^{N}\vec{a}^{D*} = {}^{N}\vec{a}^{D_0} + {}^{N}\vec{\omega}^{D} \times \left({}^{N}\vec{\omega}^{D} \times \vec{p}^{D_0D*} \right) + {}^{N}\vec{\alpha}^{D} \times \vec{p}^{D_0D*} \tag{4.7}$$

4.1.2 Values of Positions, $\vec{p}$ at Arm Segment

The details of specific positions at arm segment can be referred in Yamaguchi (2006) and under "methods to obtain value of positions at upper extremity", Chapter 2 section. The value of the positions on the arm segment was obtained from the x-ray data (Table 4.1). The results were compared with previous studies to ensure that the procedures to obtain the value of the positions were accurate. This study managed to get values of forearm and upper arm lengths from the previous studies. It was revealed that the current results and those in the previous studies were similar. From the best authors' knowledge, there were no values of other positions from previous studies.

The length of the proximal end to the COM of arm segment (ρ_A, ρ_B and ρ_C) was calculated using method from de Leva (1996). It was concluded that l_B and l_C were similar in values (l_B = 0.25 ± 0.01 m; l_C = 0.25 ± 0.01 m). To date, there were no methods to calculate COM of ulna and radius separately.

Table 4.1: The mean values of positions on arm segment

Positions	Mean ± SD	De Leva. (1996)	Winter (2009)
l_A	0.34 ± 0.20 m	0.35 m	0.31 m
l_B/l_C	0.25 ± 0.10 m	0.25 m	0.25 m
r	0.21 ± 0.02 m	N/A	N/A
φ	5.2 ± 0.63°	N/A	N/A
l_{CB}	0.26 ± 0.10 m	N/A	N/A
δ	0.24 ± 0.03 m	N/A	N/A
ρ_A (length from proximal end of humerus until COM humerus)	0.20 m	N/A	N/A
ρ_B (length from proximal end of ulna until COM ulna)	0.11m	N/A	N/A
ρ_C (length from proximal end of radius until COM radius)	0.11 m	N/A	N/A
ρ_D (length from proximal end of hand until COM racket)	0.15 m	N/A	N/A

4.1.3 Validation of the Improved Model

From the survey, all of the participants performed the service with low spin. It was found that all participants hit the ball to land at the middle of the opponent's table side. Table 4.2 showed the mean arm segment angular velocities, horizontal ball and racket head velocities at impact. It was revealed that the horizontal racket and ball velocities (2.90 ± 1.45 m/s; 2.91 ± 0.53 m/s, respectively) were quite similar with results in Yoshida, Sugiyama, and Murakoshi (2010) and Wang et al. (2008). However, the findings disagreed with Iino and Kojima (2009).

Table 4.2: The mean arm segment angular velocities at impact

Parameters	Value (rad/s)
Shoulder abduction	0.75 ± 1.34
Shoulder flexion	0.76 ± 1.21
Shoulder internal rotation	-5.77 ± 2.53
Elbow flexion	4.48 ± 1.98
Forearm supination	1.83 ± 2.31
Radial deviation	2.75 ± 3.65
Wrist palmar flexion	2.96 ± 2.81
Horizontal racket head velocity	2.90 ± 1.45 m/s
Horizontal ball velocity	2.91 ± 0.53 m/s

The angular velocity of arm segment rotations from prepared phase until contact phase were compared with previous study (Iino and Kojima, 2009) to verify the developed algorithm. In general, the figure of the graph of arm segment rotations angular velocity vs. time in the study was approaching the same pattern as reported by Iino and Kojima (2009) (Figure 4.1). However, the graphs in Iino and Kojima (2009) showed that it was curvier as compared to the present study.

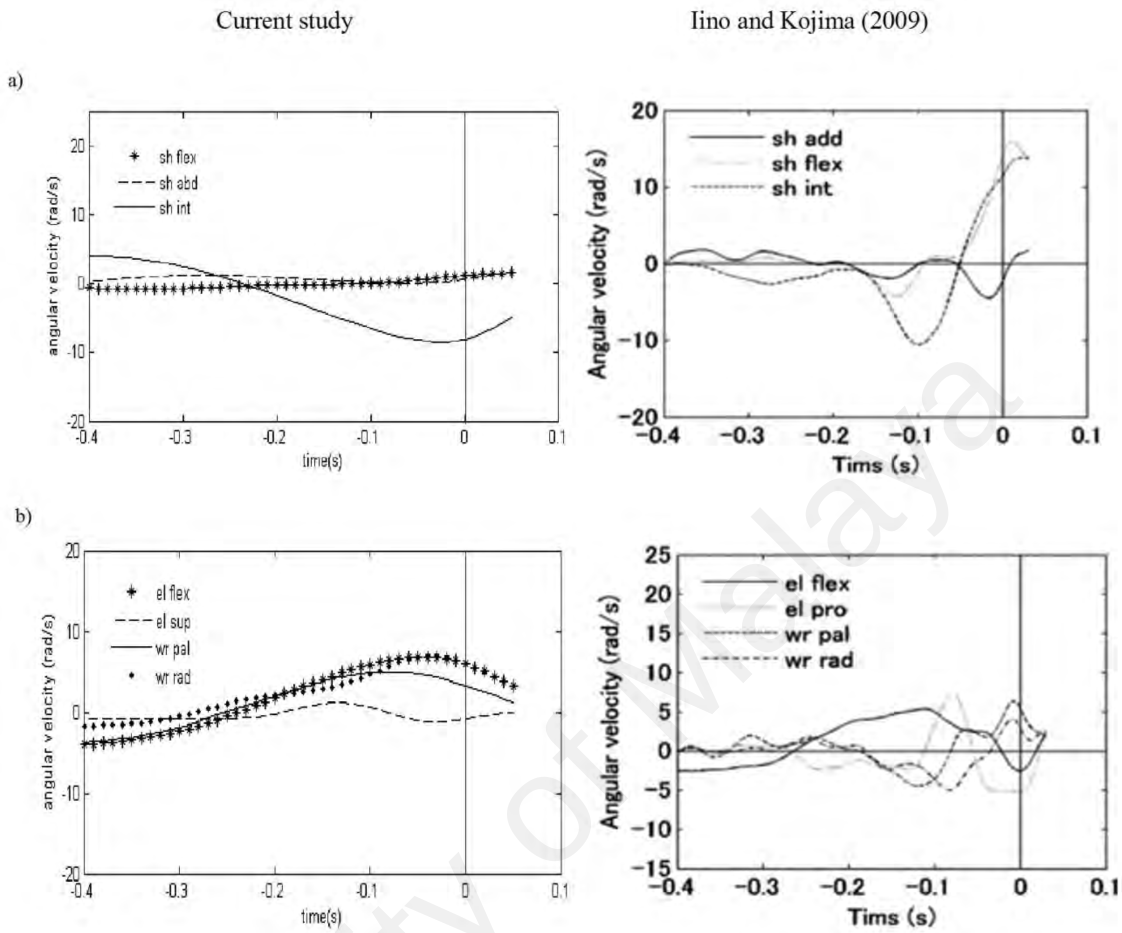


Figure 4.1: Reproduce material Figure 3 from Iino and Kojima (2009). The angular velocities of upper extremity rotations from prepare to contact phases during forehand stroke/service in current study and Iino and Kojima (2009). Time 0 (s) corresponds to ball impact. sh add = shoulder adduction; sh abd = shoulder abduction; sh flex = shoulder flexion; sh int rot = shoulder internal rotation; el flex = forearm flexion; el pro = elbow pronation; el sup = elbow supination; wr pal = wrist palmar flexion; wr rad = radial deviation

4.1.4 Correlation between Arm Segment Rotation and Horizontal Ball and Racket Head Velocities during Forehand Drop Shot in Table Tennis Service

Based on the survey of right after the execution of successful trials, it was found that all participants produced low spin during service. The results showed that the mean horizontal ball velocity immediately after impact was 3.06 ± 0.51 m/s. The mean horizontal racket head velocity immediately before impact was 2.82 ± 1.17 m/s. The angular velocity of shoulder, elbow and wrist were not gradually increased (Table 4.3).

Table 4.3: The mean arm segment rotations angular velocity at impact during forehand drop shot service.

Parameters (rad/s)	Mean ± SD
Shoulder abduction	1.15 ± 1.44
Shoulder flexion	0.39 ± 1.24
Shoulder internal rotation	-5.23±2.91
Elbow flexion	4.20 ± 2.09
Forearm supination	0.95 ± 3.71
Wrist radial deviation	2.51 ± 4.75
Wrist palmar flexion	3.06 ± 4.69
Horizontal racket head velocity	2.82 ± 1.17
Horizontal ball velocity	3.06 ± 0.51

Horizontal ball and racket head velocities demonstrated a significant positive correlation (r_s = 0.697, P < 0.01, Figure 4.2). Wrist radial deviation angular velocity at impact was significantly positively correlated with horizontal ball velocity (r_s = 0.647, P < 0.01, Figure 4.3) and horizontal racket head velocity (r_s = 0.638, P < 0.01, Figure 4.2). The remaining angular velocity of arm segment rotations showed no significant correlation with horizontal ball and racket head velocities (Figure 4.2, Figure 4.3).

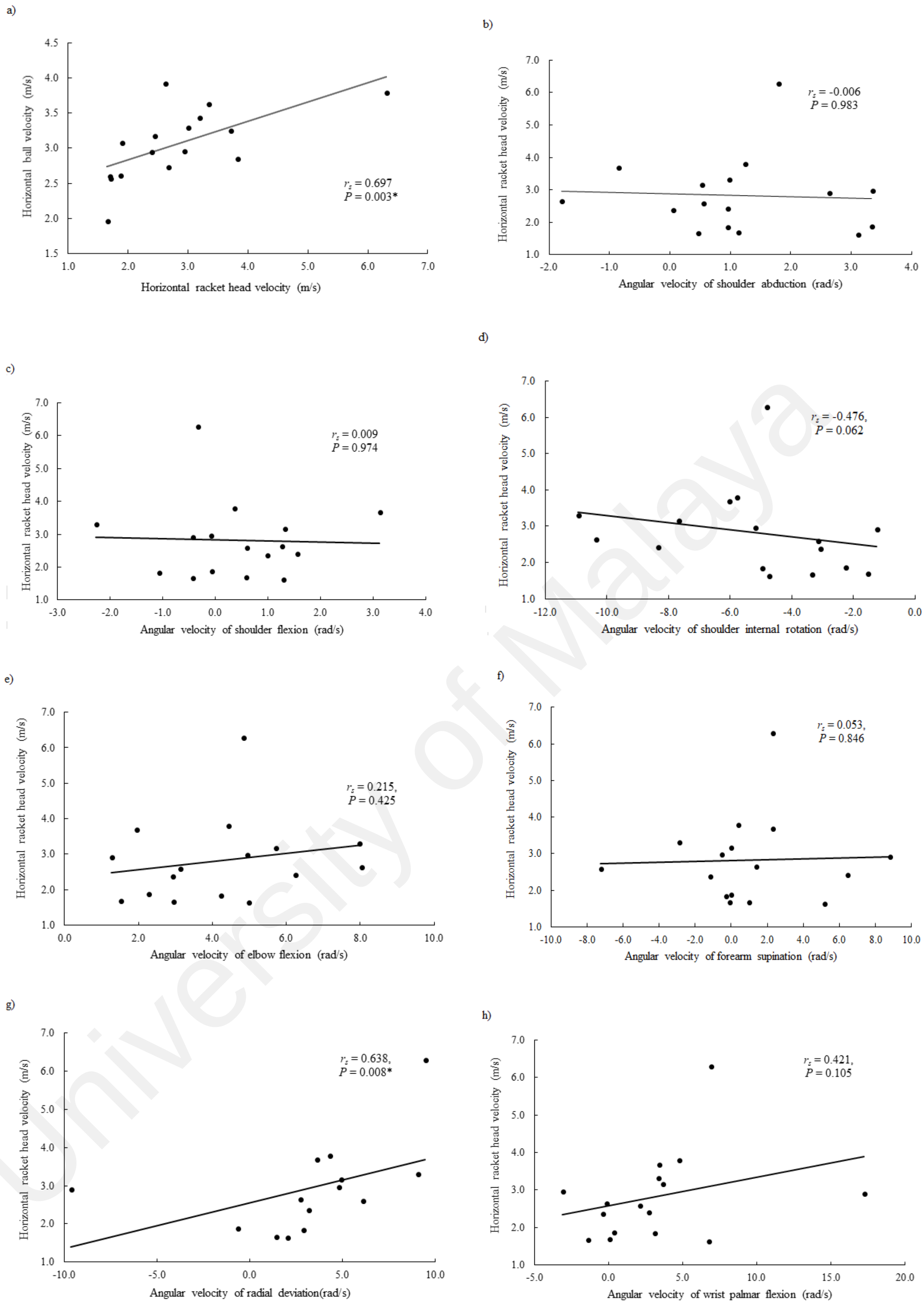


Figure 4.2: Correlation between arm segment rotations angular velocity at impact and horizontal racket head velocity during forehand drop shot service. *P < .05

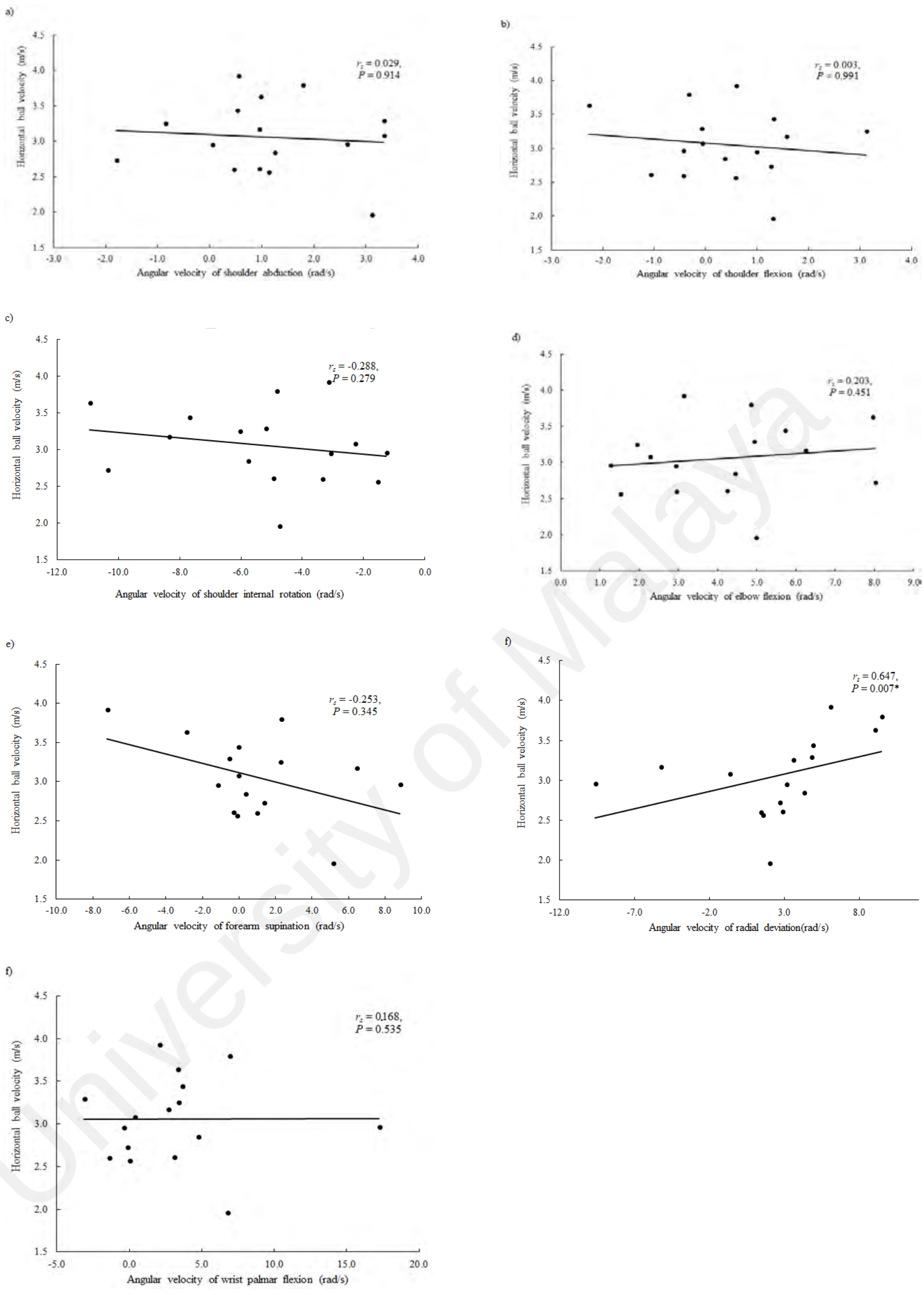


Figure 4.3: Correlation between arm segment rotations angular velocity at impact and horizontal ball velocity during forehand drop shot service. ***P* < .05**

4.1.5 Correlation between Upper Extremity and Horizontal Ball and Racket Head Velocities during Forehand Long Shot in Table Tennis Service

Based on the survey right after the execution of successful trials, it was found that 13 participants produced low spin while others produced high spin during the service. From the results, it showed that the mean horizontal ball velocity immediately after impact was 5.21 ± 0.66 m/s. The mean horizontal racket head velocity immediately before impact was 4.13 ± 0.88 m/s. The angular velocity of shoulder, elbow and wrist were not gradually increased (Table 4.4).

Table 4.4: The mean arm segment rotations angular velocity at impact during forehand long shot service

Parameters (rad/s)	Mean ± SD
Shoulder abduction	3.84 ± 2.21
Shoulder flexion	-0.43 ± 1.31
Shoulder internal rotation	-6.36 ± 2.84
Elbow flexion	5.70 ± 2.59
Forearm supination	0.28 ± 3.56
Wrist radial deviation	5.56 ± 5.08
Wrist palmar flexion	1.67 ± 6.82
Horizontal racket head velocity	4.13 ± 0.88
Horizontal ball velocity	5.21 ± 0.66

Horizontal ball velocity showed no significant correlation with horizontal racket head velocity ($r = 0.460$, $P = 0.085$, $P > 0.05$, Figure 4.4). The results showed that wrist radial deviation and wrist palmar flexion angular velocities at impact were significantly positively correlated with the horizontal racket head velocity ($r = 0.803$, $P < 0.05$; $r = 0.737$, $P < 0.05$, respectively). The remaining angular velocity of upper extremity rotations showed no significant correlation with horizontal ball and racket head velocities (Figure 4.4, Figure 4.5).

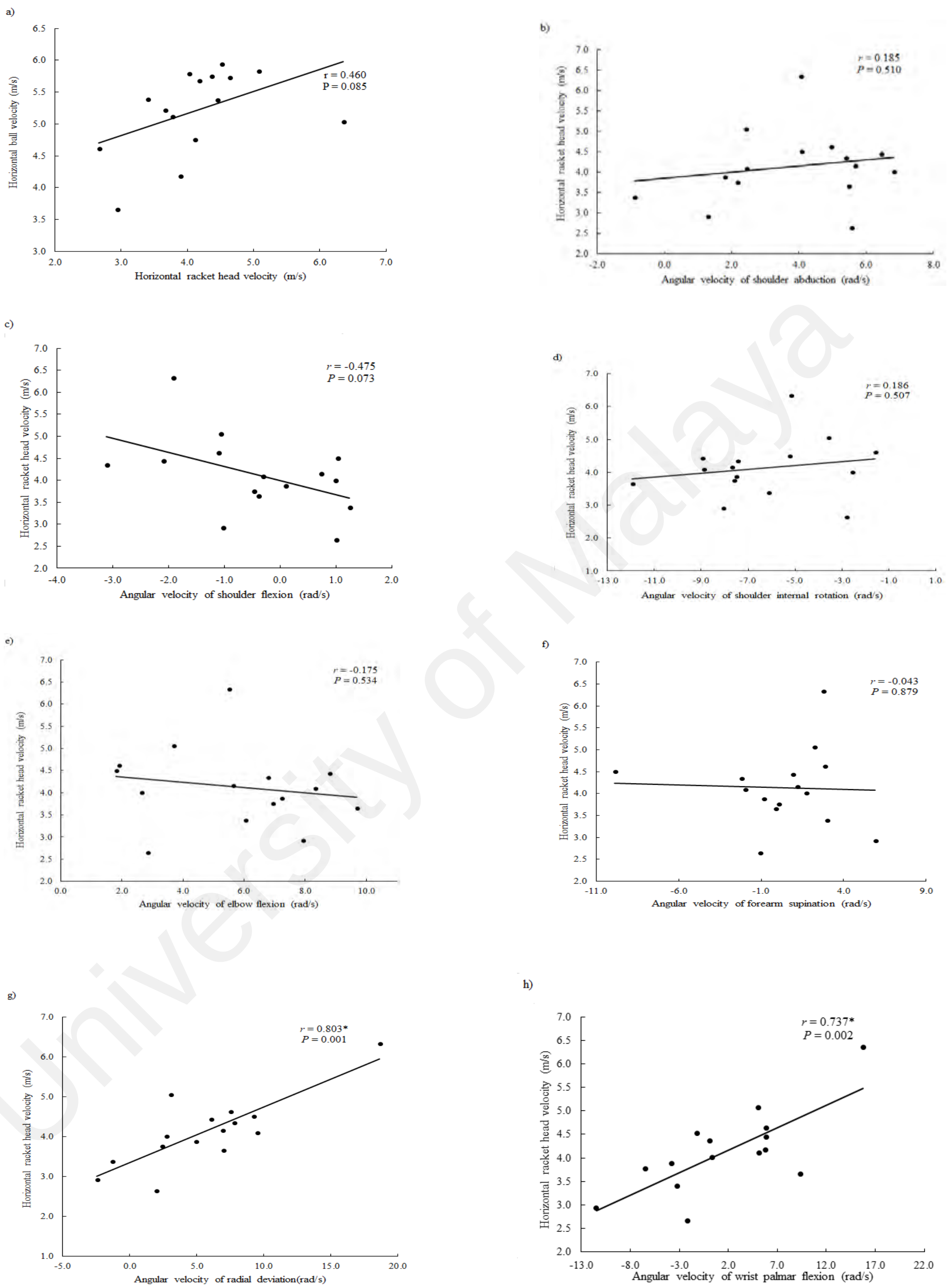


Figure 4.4: Correlation between arm segment rotations angular velocity at impact and horizontal racket head velocity during long shot service. *$P < 0.05$

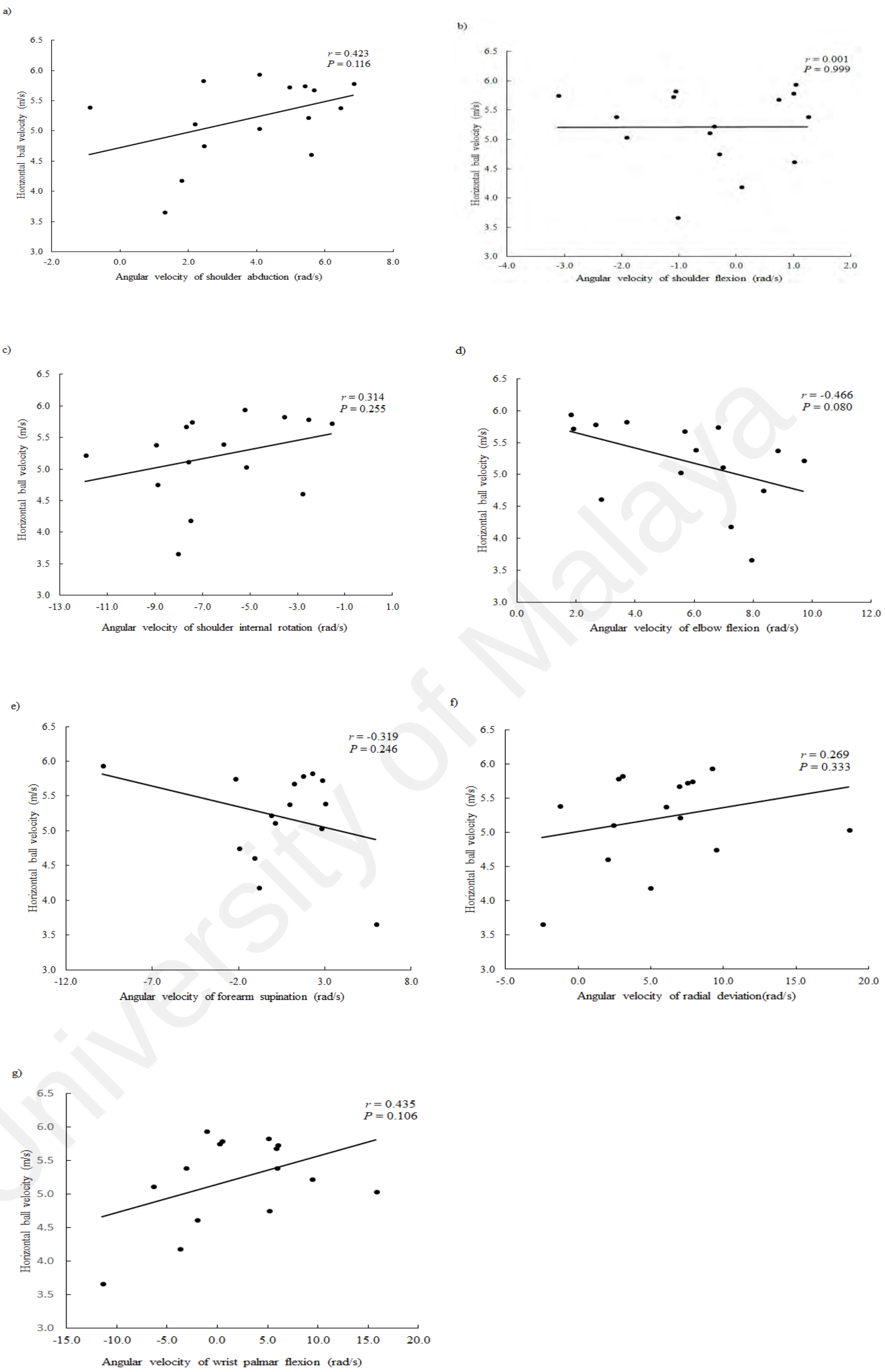


Figure 4.5: Correlation between arm segment rotations angular velocity at impact and horizontal ball velocity during long shot service

4.1.6 The kinematic differences between forehand long shot and drop shot services

The authors used the same data as above (arm segment angles data from forehand drop shot and long shot services kinematics) to analyze the kinematic differences between forehand long shot and drop shot services.

The horizontal ball velocity immediately after impact was significantly higher in the long shot compared to the drop shot services (5.21 ± 0.66 m/s vs. 3.06 ± 0.51 m/s, p = 0.001). The horizontal racket head velocity immediately before impact was significantly higher in the long shot compared to drop shot services (4.13 ± 0.88 m/s vs. 2.82 ±1.17 m/s, p = 0.001). In addition to this, the velocity of shoulder flexion was significantly higher in the long shot compared to the drop shot services (2.00 ± 0.66 m/s vs. 1.26 ± 0.53 m/s, p = 0.001). However, the velocity of shoulder internal rotation was significantly higher in the drop shot compared to long shot services (-0.11 ± 0.43 m/s vs. -0.84 ± 0.54 m/s, p = 0.005). Other velocity of arm segment rotations showed no significant difference between the two types of services (Table 4.5).

Table 4.5: Velocity of arm segment rotations of the two types of table tennis services at impact. *$p < 0.05$

Parameter/ arm segment rotations	Forehand drop shot service (m/s)	Forehand long shot service (m/s)	*p*-value
Shoulder abduction	-1.15 ± 0.62	-1.16 ± 0.56	0.955
Shoulder flexion	1.26 ± 0.53	2.00 ± 0.66	0.001*
Shoulder internal rotation	-0.11 ± 0.43	-0.84 ± 0.54	0.005*
Elbow flexion	-0.24 ± 0.44	0.07 ± 0.75	0.100
Forearm supination	0.11 ± 0.56	0.76 ± 0.97	0.078
Wrist radial deviation	-0.44 ± 0.97	-0.62 ± 1.44	0.532
Wrist palmar flexion	0.95 ± 1.37	1.23 ± 1.23	0.532
Racket speed	2.82 ± 1.17	4.13 ± 0.88	0.001*
Ball speed	3.06 ± 0.51	5.21 ± 0.66	0.001*

The joint angle of shoulder flexion was significantly higher in the drop shot compared to the long shot services (7.76˚ vs. -0.48˚, p = 0.009). Others joint angle of arm segment rotations showed no significant difference between the two types of services (Table 4.6).

In general, the curves of the graph of arm segment rotations angular velocity vs. time (Figure 4.6) were similar between the two types of services. However, there were some noticeable differences. The time needed to perform forehand long shot service was longer than drop shot service. Furthermore, the amplitude of the graph during long shot service (Figure 4.6) was less sharp compared to the graph during drop shot service (Figure 4.6) particularly in shoulder internal rotation, elbow flexion and wrist palmar flexion. Thus, the graphs depicted that a higher angular velocity in a less time before impact is executed in the drop shot compared to the long shot services. Both graphs showed the values of the arm segment rotations were 0 at the preparation phase and started to rise or descend at the beginning of the backswing phase (Figure 4.6). They showed that a change of direction (from negative to positive or vice versa) of angular velocity arm segment rotations when changing from backswing to forward swing phases. It was observed that the sudden increase of values of arm segment rotations occurred just before impact for both serves.

Table 4.6: Joints angle of arm segment rotations of the two types of table tennis services at impact. *$p < 0.05$

Parameter/arm segment rotations	Forehand drop shot service (°)	Forehand long shot service (°)	*p*-value
Shoulder abduction (0° at nuetral)	39.74 ± 19.55	45.64 ± 21.85	0.532
Shoulder flexion (0° at neutral)	7.76 ± 16.73	-0.48 ± 16.04	0.009*
Shoulder internal rotation (0° at neutral)	2.52 ± 14.34	5.80 ± 20.88	0.281
forearm supination (105° at neutral)	77.11 ± 33.58	83.78 ± 40.62	0.460
Elbow flexion (0° at full extension)	110.13 ± 24.68	107.17 ± 24.98	0.609
Wrist radial deviation (12° at neutral)	19.96 ± 23.67	22.46 ± 19.93	0.650
Wrist palmar flexion (0° at neutral)	-2.84 ± 17.69	-4.18 ± 23.88	0.999

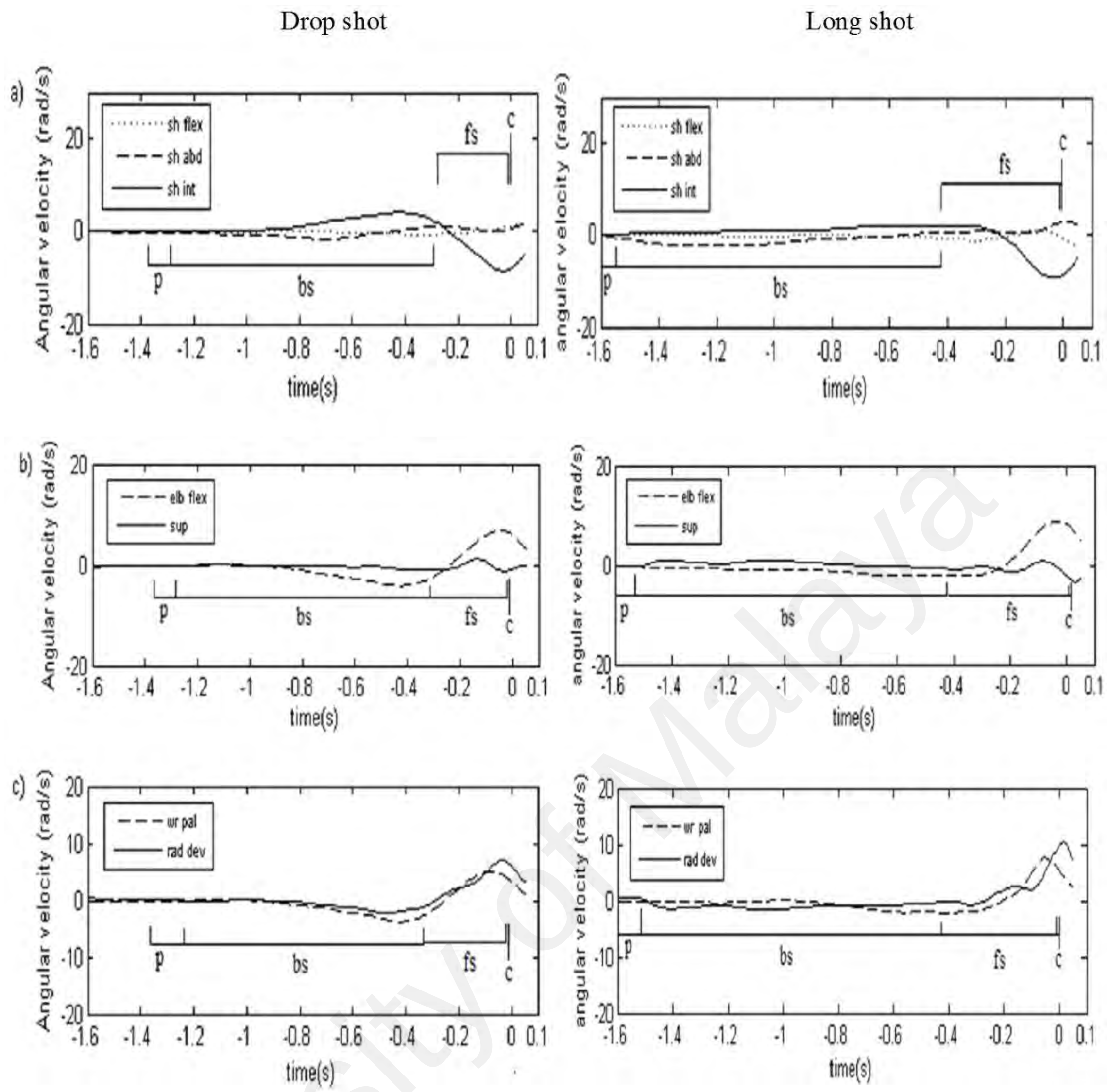


Figure 4.6: The angular velocity of arm segment rotations from prepare to contact phases during forehand drop shot and long shot services. Time 0 (s) corresponds to ball impact. sh abd = shoulder abduction; sh flex = shoulder flexion; sh int = shoulder internal rotation; elb flex = forearm flexion; sup= forearm supination; wr pal = wrist palmar flexion; rad dev = radial deviation; p = preparation phase; bs = backswing phase; fs = forward swing; c = contact phase.

4.2 Discussion

4.2.1 The Improvement in 3D Kinematic Model of Arm Segment

The diverse methods for solving human motion problems lead to the utilization of dynamic model. Yamaguchi (2006) explained the utilization of Kane's method that allowed the development of 3D dynamic model of body segments. The dot and vector, which were utilized in the kinematic model of arm segment were proven capable of dealing with 3D problems (Winter, 2009). The specific positions, $\vec{p}$ at the arm segment in the model were determined in Yamaguchi (2006). It was stated by Yamaguchi (2006) that the position of proximal end of segment to the COM must be determined to find the velocity and acceleration of each segment. To date, the equation of velocity and acceleration of each segment remain unknown. This study improved the Yamaguchi's model until the COM of segment.

The positions are necessary to obtain the velocity and acceleration of segments (refer to Yamaguchi, 2006). To date, the value of specific positions at arm segment remained unknown (Yamaguchi, 2006). Therefore, the value of positions was obtained from the arm segment radiography images to complete the kinematic model of arm segment (Table 4.1). To ensure the method used to calculate the positions of arm segment is accurate, a comparison of results between the present study and previous studies was performed. It was revealed that the results (length of upper arm and forearm) were similar which showed that the method used to calculate the positions on the arm segment was accurate. To date, there is no finding on value of other positions from previous studies (Table 4.1). Therefore, it was difficult to compare the results (value of other arm segment positions) with previous studies.

The calculation of the velocity and acceleration of the segment can be determined by calculating the COM segments' length (Yamaguchi, 2006). The positions at arm segment developed by Yamaguchi (2006) were described from or at the proximal end of segment. Thus, de Leva (1996) method was selected to calculate the COM segments' length because the method described the COM segments' length similar to Yamaguchi (2006). After all the above steps were performed, the rest of the kinematic data can be obtained from the improved model.

4.2.2 The Improved Model and its Validation

The 3D kinematic model of arm segment used MATLAB to allow data analysis in the musculoskeletal motion areas. This method is useful for MATLAB users.

Defining $q_i(t); i=1 \ldots 7, \varphi$ is important to ensure that the flow of the algorithm were smoothly performed. Other functions in MATLAB, such as addition, differentiation, simple, substitution and collect, can be successfully developed in the algorithm only after the aforementioned process is executed (refer to "algorithm for Yamaguchi's 3D kinematic model of arm segment", Chapter 3 section). The algorithm created in the MATLAB followed the equations from the improved model. When all above steps were executed, the algorithm of the kinematic equations can be obtained. A new sheet of 'editor window' was created to apply a wide range of data into the model. To create the algorithm, the positions, angles of arm segment rotations and its values were defined in the new 'editor window'. The algorithm of the kinematic model of arm segment, which obtained from the 'command window' sheet earlier, was copy and paste into the new 'editor window'. The rest of kinematic data of the arm segment can be obtained from the new 'editor window'.

The algorithm was tested in the musculoskeletal motion field (table tennis serving) to validate the improved model. The angular velocity of arm segment rotations were compared with previous study by Iino and Kojima (2009). The present study has conducted a study case in table tennis serving which may result in slight difference to Iino and Kojima (2009) who conducted a study in table tennis forehand stroke. Furthermore, the study (Iino & Kojima, 2009) was not detailed whether the forehand stroke that produced by the participants were long or short distance. Different distance would affect the kinematic results. To the author's best knowledge, there was no research reported on the graph of arm segment kinematics vs. time for table tennis serving. Thus, the results from Iino and Kojima (2009) were selected to verify the algorithm because the study was the most similar to the present study. Although the method to calculate angular velocity of segments was different in both studies, at the end the values of the angular velocity must be the same to prove that the basic theorem used in both studies were accurate. Future research should consider validating data with the same movement.

The slope of the angular velocity at the wrist joint (Figure 4.1) demonstrated similar shape just before impact in present study and in Iino and Kojima (2009). This revealed that produce higher velocity on wrist joint just before impact was needed to perform a good stroke in table tennis in both studies. In general, the figure of the graph of arm segment rotations angular velocity vs. time (Figure 4.1) in the study was approaching to the same pattern as reported by Iino and Kojima (2009). However, the graphs in Iino and Kojima (2009) showed curvier pattern compared with the present study. This means that less speed was required to perform table tennis forehand serving as compared to forehand stroke. It was stated by Heaton (2009) that the forehand stoke produced more speed as compared to service. Furthermore, the procedures in table tennis serving which require players to toss a ball before hit will minimize speed and limit the movement in service. It was concluded that the forehand stroke movement contributed curvier graph compared to the forehand service because the forehand stroke produce more speed than forehand service. The pattern and values in angular velocity vs. time graphs in both studies were slightly different, but it was considered that both figures were reasonably comparable based on the reasons given above. With these findings, the improve model were verified.

The horizontal racket and ball velocities (Table 4.2) were quite similar with results in Yoshida, Sugiyama, and Murakoshi (2010) and Wang et al. (2008). Yoshida, Sugiyama, and Murakoshi (2010) found that the speed of service ball was 4 m/s. Meanwhile, Wang et al. (2008) reported that the racket speed at impact was 4.3 m/s and 4.26 m/s for long shot and drop shot services, respectively. Furthermore, they reported that the ball speed at impact was 4.98 ms^{-1} and 4.76 ms^{-1} for long shot and drop shot services, respectively (Wang et al., 2008). However, the findings disagreed with Iino and Kojima (2009), which obtained 17.9 m/s and 16.7 m/s for racket speed and ball speed at impact, respectively. This is probably attributed by the differences in speed for different stroke between both studies. Furthermore, it was known that the racket and ball speeds at impact for forehand stroke was higher than forehand service.

4.2.3 The Contributions of Arm Segment Rotations towards Ball Impact during Forehand Drop Shot and Long Shot Services

This study examined the effects of horizontal ball and racket head velocities towards arm segment rotations during forehand service among advanced and intermediate players. Therefore, the findings will be useful for these ranked players. However, other ranked players may find this study useful to understand the behaviour of kinematics service.

The mean horizontal ball and racket head velocities upon contact were 3.06 ± 0.51 m/s and 2.82 ± 1.17 m/s, respectively during drop shot service. The results approached the same values with Yoshida et al. (2010). They found that the speed of serviced ball was 4 m/s (Yoshida et al., 2010). It was unclear whether the service was described as long shot or drop shot services in Yoshida et al. (2010).

Meanwhile, the mean horizontal ball and racket head velocities upon contact were 5.21 ± 0.66 m/s and 4.13 ± 0.88 m/s respectively during long shot service. These results were nearly similar to Wang et al. (2008). They reported that the mean of racket velocity was 4.26 m/s and 4.3 m/s for drop shot and long shot services, respectively. Furthermore, they obtained the mean of ball velocity after impact was 4.76 m/s and 4.98 m/s for drop shot and long shot services, respectively.

These findings were reasonably similar to the existing studies since not all others data of related studies can be accessed.

4.2.3.1 Drop Shot Service

Horizontal ball and racket head velocities exhibited a significant positive correlation (Figure 4.2). This suggested that the horizontal ball velocity immediately after impact will increase if the horizontal racket head velocity is increased immediately before impact. These findings supported previous report (Carr, 1997) which stating that increasing racket speed will increase the ball speed. From the results, it was revealed that by increasing the radial deviation angular velocity, the ball and racket head velocities during drop shot service will increase (Figure 4.2, Figure 4.3). Previous studies indicated that the wrist joint is the important segment to play in table tennis (Heaton, 2009; Hilton and Eaton, 1985). Furthermore, it was reported that by rotating the body segment quickly, it will apply more force to the racket which eventually will accelerate the ball at impact (Ackland et al., 2009; McGinnis, 2013). In addition, by altering the wrist joint correctly, it will increase the ball velocity at impact (Carr, 1997). Our findings showed that wrist radial deviation was the significant contributor to speed up the ball at impact. These findings revealed that altering the wrist correctly will accelerate the ball at impact.

Heaton (2009) stated that the benefit of shake-hand grip will allow the utilization of wrist mobility in the games. Since all participants were shake-hand grip players, thus, the findings could be relayed to the statement by Heaton (2009). It was concluded that by increasing the wrist radial deviation angular velocity will increase the horizontal ball and racket head velocities at impact during forehand drop shot service for shake-hand grip players.

4.2.3.2 Long Shot Service

The results showed that wrist radial deviation and wrist palmar flexion angular velocities at impact were significantly positively correlated with horizontal racket head velocity (Figure 4.4). Thus, the findings discovered that increasing the wrist radial deviation and wrist palmar flexion rotations will enhance the racket head velocity immediately before impact during forehand long shot service. It was reported by Ackland et al. (2009) and McGinnis (2013) that increasing the body segment rotations will apply more force to the racket which will produce higher velocity at impact. Thus, increasing the wrist radial deviation and wrist palmar flexion angular velocities will apply more force to the racket which in return will produce higher velocity at impact. Heaton (2009) reported that the benefit of shake-hand grip could enable the use of wrist mobility in the games. Since all participants were shake-hand grip player, it was concluded that increasing the wrist radial deviation and wrist palmar flexion rotations will increase racket head velocity at impact during forehand long shot service for shake-hand grip players.

In addition, there was insignificant correlation between arm segment rotations and horizontal ball velocity (Figure 4.5). This means that the ball velocity at impact was not influenced by the arm segment rotations. Furthermore, the findings indicated that there was insignificant correlation between the horizontal ball and racket head velocities at impact (Figure 4.4). Thus, the findings discovered that the effect of ball velocity at impact could not be influenced by the racket speed performance. However, it was claimed by Carr (1997) and McGinnis (2013) that by producing higher racket velocity will produce higher ball velocity. Yet, the resultant ball speed will change based on the contact conditions between racket and ball at impact in tennis game (Tanabe and Ito, 2007). Thus, it was concluded that other parameters such as angle of inclined racket, contact point on ball and ball spin could influence the horizontal ball velocity at impact rather than the arm segment rotations and racket speed. Further investigation on this matter is suggested in the future. However, it was suggested to the players not to concern on the relation between racket speed and arm segment rotations which could not accelerate the ball at impact during long shot service.

4.2.3.3 Relation between Long Shot and Drop Shot Service

The contributions of arm segments rotation towards drop shot and long shot services were not the same. Although it was the same forehand service, different length of flight ball lead to different contributions of arm segment rotations towards ball impact. It was revealed that increasing the radial deviation velocity will increase the ball and racket head velocities at impact during drop shot service. However, increasing the wrist radial deviation and wrist palmar flexion velocities will increase racket head velocity at impact during forehand long shot service for shake-hand grip players. The results highlight several correct postures to increase racket and ball speed at impact during forehand service at different length of flight ball among advanced and intermediate players.

In contrast, Iino and Kojima (2011) and Tanabe and Ito (2007) stated that the utilization of shoulder internal rotation may increase the performance of players in table tennis and tennis service. Furthermore, Heaton (2009) reported that shoulder joint is the main important joint for table tennis drive strokes. However, our findings discovered that there was no contribution from shoulder internal rotation towards horizontal ball and racket head velocities. This contrasted with the findings in Iino and Kojima (2011) and Tanabe and Ito (2007). It is worth noting that their studies were on table tennis forehand stroke and tennis service which would affect more on shoulder internal rotation.

4.2.4 The Kinematic Differences between Forehand Long Shot and Drop Shot Services

This study aimed to find the kinematic differences in arm segment rotations between forehand long shot and drop shot services. It was revealed that the duration to serve for drop shot was less than long shot (Figure 4.6). Furthermore, the graph was curvier in drop shot compared to long shot. In addition, comparatively, a higher angular velocity of arm segment rotations coupled with lesser time before impact in performing drop shot compared to long shot services as depicted in the graphs (Figure 4.6). In application, players should be aware of the change of arm segments speed and time needed by opponent to serve which would distinguish the two types of services.

The graph of drop shot service was curvier than long shot service but both graphs depicted similar pattern indicating that the players played both services in the same posture but at different speed (Figure 4.6). This finding partly supported the report in

Heaton (2009) which stated that skilled players constantly performed different services with the same postures but adjusting the racket angle and contact point on ball or racket just before the impact. Interestingly, both graphs showed that a sudden increase values of arm segment rotations occurred just before impact. Furthermore, they were approaching similar values in both services. Thus, to conceal the technique of different services, the authors suggest the players to serve in similar posture but different speed and only to increase the arm segment speed just before impact.

The horizontal ball and racket head velocities at impact were significantly higher in the long shot compared to the drop shot services (Table 4.5). Since the findings followed the theorem of biomechanics which speed will increase for longer distance, thus, at this point, the players were good in performing the two types of services.

The velocities of shoulder flexion and shoulder internal rotation were significantly different at impact between the two types of services (Table 4.5). Joint angle of shoulder flexion was significantly higher in the drop shot compared to the long shot services (Table 4.6). These results suggested that the shoulder flexion was the only parameter that exhibited a significant different between the two types of services in velocity and joint angle upon impact. Hence, the ability to change the type of service from drop shot to long shot services and vice versa was influenced mainly by shoulder flexion. The significant difference in shoulder flexion and shoulder internal rotation at impact is assumed affected the adjustment of the racket angle and contact point of ball or racket just before impact. However further investigation using high speed cameras (e.g. 300 Hz) are suggested to examine the statement. The findings also showed that the significant differences at impact between both services were occurred at the shoulder joint. The body rotation movement during backswing phase will generate a force that will determine the distance, pathway and velocity of a flight ball (Carr, 1997).

Therefore, it was concluded that the body rotation movement during backswing phase affected the shoulder joint rotation at impact which will determine different distance of the landed ball.

Wang et al. (2008) utilized female elite table tennis players to find the kinematic differences between long shot and drop shot services in a top-level game. They reported that the ball velocity immediately after impact was 4.98 m/s and 4.76 m/s for long shot and drop shot services, respectively (Wang et al., 2008). In addition, they found that the racket velocity just before impact was 4.3 m/s and 4.26 m/s for long shot and drop shot services respectively (Wang et al., 2008). These differences in both racket and ball velocities for the two types of services however were not statistically significant ($p > 0.05$). The values of racket and ball velocities in Wang et al. (2008) were reasonably similar to our results. However, they found that the arm segment velocities at impact were similar between both services. Some of their findings were different from current study possibly because of the different laboratory environment (temperature and humidity) and the different profile of players (gender difference and the level of play). Furthermore, different method and experimental procedure was performed with their study using 2-dimensional compared to our 3-dimensional simulation. Thus, a direct comparison of the findings with Wang et al. (2008) is not possible. However, the authors would like to highlight that the results in 3-dimensional would be more accurate as it approaches the reality of the arm segment motion (Lloyd, Alderson, & Elliot, 2000).

The summary of the contributions of arm segment rotations towards horizontal racket and ball velocity during training can be referred in Table 4.7. This information is important and can be interpreted to the coach and table tennis players in a way to make them understand and improve their techniques.

Table 4.7: Contributions of arm segment rotations towards horizontal racket and ball velocity during training

Increasing radial deviation at impact (move the hands towards the body)	Forehand drop shot and long shot
Increasing speed of wrist palmar flexion at impact (bend hand downwards)	Forehand long shot
Posture of shoulder flexion at impact (move arm to the middle of body)	Forehand long shot
Posture of shoulder flexion at impact (move arm upwards a little)	Forehand drop shot
A sudden of increase arm segment speed just before impact	Forehand drop shot and long shot

4.2.5 Limitation

Possible errors in calculating the racket velocity was insignificant in the present study as supported by Iino and Kojima (2009). The calculation of ball spin upon impact was not included in the study because of limited high end technology and expensive equipment (i.e., 300 Hz high speed camera). However, the survey method was executed to define the ball spin at impact for both services. Furthermore, other parameters, such as the height of impact point, the height of ball toss and contact ball on racket could improve our insights of the factors influencing the service performance.

Furthermore, the errors (standard deviation) were big in the results of the kinematic data (angles, angular velocity and velocity) for the analysis of table tennis serving movement because the demographic of the participants (age, height, weight and dietary) and the participants' postures to perform forehand service were not controlled in this study. The slight different in size among the participants was not a research matter as long as they have been participated in the college tournaments. The participants were allowed to strike a ball with a free movement which would be like in the actual games.

The different in postures during service lead to different arm segment angles which affected the research findings.

The findings of the present study were achieved from the simulating play in games under the experimental constraints. Different laboratory environments could yield different findings. Interpretation of the present findings should take this into account.

The sample size of the present study was collected from sixteen male collegiate players. Interpretation results from different sample size and players' profile (gender and level of players) could give different conclusions.

Although it was stated that played down the line and cross-court will contributed to different body rotations kinematics (Lanzoni et al. 2018), the present study aimed to produce findings based on simulation play in experiment environment as it would be like real match. This simulation will allowed players a freedom to strike a ball based on his best judgement. However, future research should consider the details of body kinematics during cross-court and down the line during games.

CHAPTER 5: CONCLUSIONS AND FURTHER RECOMMENDATION

5.1 Conclusions

Recently, biomechanical analysis was widely used by researchers for future development in athlete performance in various sports (Iino & Kojima, 2016b; Rusydi, Huda, Rusydi, Sucipto, & Sasaki, 2016; Shorter, Nealon, Smith, & Lauder, 2011). Although there were several studies in biomechanical analysis of table tennis stroke such as Iino and Kojima (2009), Iino and Kojima (2016a) and Lee and Xie (2004a), to the author's best of knowledge there was limited study that focused on biomechanical analysis in table tennis, specifically in service.

Wang et al. (2008) studied on female elite table tennis players in regard to the kinematic arm segment rotations during drop shot service in a tournament. They focused on 2D kinematic analysis which were different from the present study which analyzed the study in 3D simulation. However, authors would like to highlight that the results in 3D would be more accurate as it approaches the reality of the arm segment motion. Focusing on the findings (refer to Chapter on "Results" and "Discussions") during training may allow players to anticipate his opponent's service and gain advantage of the game.

The overall aim of the present study was to determine the kinematic involved in arm segment rotations towards horizontal ball and racket head velocities during forehand service in table tennis, whereby these findings can improve players' performance. The following conclusions are drawn from the objectives of the study, which were recognized to meet the overall aim of the study.

1. **The Yamaguchi's model of arm segment was improved after adding parameters (calculation until COM of segment and values of positions at arm segment) to complete the model, which can be used to analyze arm segment movement. The improved model and its algorithm were verified.**

Several steps were required to improve the previous kinematic model. The first step was to determine the velocity and acceleration of each segment. The calculation of the velocity and acceleration of each segment can be determined by identifying the COM of segments. In this study, de Leva (1996) method was selected to calculate the COM of segments. Certain positions at arm segment are necessary to obtain the velocity and acceleration of segments. Therefore, the value of positions was obtained from the arm segment radiography images to complete the kinematic model. When all the above steps were performed, the rest of kinematic data can be obtained from the improved model. The improved 3D kinematic model of arm segment used MATLAB to allow data analysis in the musculoskeletal motion areas. The developed algorithm was tested in the table tennis serving to validate the improve model. In general, the pattern and values in angular velocity vs. time graphs in Iino and Kojima (2008) and present study were reasonably comparable. These findings verified that the improved model is accurate and can be applied to other related studies to produce the arm segment kinematic data.

2. **Increasing the wrist radial deviation will increase ball and racket velocity at impact during drop shot service. Furthermore, increasing wrist radial deviation and wrist palmar flexion will increase racket velocity at impact during long shot service.**

This study examined the contributions of arm segment rotations towards horizontal ball and racket head velocities at impact during forehand drop shot and long shot services. The present study found that increasing the radial deviation rotation will increase the ball speed at impact for shake-hand grip players during drop shot service. Meanwhile, it was concluded that increasing the radial deviation and wrist palmar flexion rotations will enhance the horizontal racket head velocity immediately before impact during forehand long shot service for shake-hand grip players. However, it was recommended to the players that not to concern on the relation between racket speed and arm segment rotations as it could not accelerate the ball at impact during long shot service. Although, it was the same forehand service, different length of flight ball lead to different contributions of arm segment rotations towards ball impact. The present findings highlight several correct postures to increase racket and ball speed at impact during forehand long shot and drop shot services among advanced and intermediate players.

3. **The change in shoulder flexion and shoulder internal rotation at impact will distinguish between drop shot and long shot services. Furthermore, different speed of arm segment during service will distinguish between drop shot and long shot services.**

In summary, the kinematics differences between forehand long shot and drop shot services in table tennis were deliberated in the study. It was revealed that the ability to change the type of service from drop shot to long shot services or vice versa was influenced mainly by shoulder flexion. It is recommended that players should be aware of the change of arm segment's speed and time needed by opponent to serve which distinguish the two types of services. To conceal the technique of services, it was suggested to serve in similar posture but different speed, only to increase the arm segment speed just before impact. Focusing on the recommendations above during training may allow the player to anticipate his opponent's service and gain advantage over the game.

5.2 Further Recommendations

In this study, the author discussed the kinematic analysis of arm segment rotations towards horizontal ball and racket head velocities during forehand long shot and drop shot services. The findings may give benefits to coach and players in gaining advantage of the game. However, this research can be extended in order to gain more knowledge and improve strategy to achieve advantage of the game.

It is recommended to further this research to other body segments, such as the upper limb and lower limb. Deep knowledge on contributions of other body segments during table tennis serving will allow the coach and players to organize strategy to improve their performance. Furthermore, study on contributions of body segments towards various types of table tennis serving are suggested. Different types of service would affect different body segments rotations. In the present study, increasing the wrist dorsiflexion and radial deviation rotations during forehand long shot service will increase the horizontal racket head velocity at impact whereas increasing the radial deviation will increase the horizontal ball and racket head velocities during drop shot service.

Study on other parameters in table tennis serving that can affect the contributions of arm segment rotations during table tennis serving is suggested. Spin of ball is as important as ball and racket speeds in a table tennis game. Other parameters such as the height of impact point, the height of ball toss, contact ball on racket, the racket face angle and the direction of racket path are suggested to be analyzed to provide more information on mechanics of table tennis service. Currently, the research will not discuss this matter because of time consuming, limited high end technology and financial issue on experimental cost. The high speed cameras (i.e., 500 Hz high speed cameras) are suggested for use to achieve results in this matter.

It is recommended to increase the sample size of the research for larger populations to obtain decisive conclusions on the effects of ball and racket speeds towards the table tennis forehand service kinematics. Interpretation from different sample size results could give different conclusions. However, the present study has used adequate sample size to get accurate results (Iino & Kojima, 2016a; Iino & Kojima, 2016b; Ikeda, Ichikawa, Nara, Baba, Shimoyama, & Kubo, 2016).

In the present study, the data were collected when the participants were not playing in a tournament but simulating play in games under the experimental constraints. It is suggested to collect data from different laboratory environments, such as during tournament which could give significant findings. However, the experimental procedures will be slightly different from the present study. It is suggested to look into previous studies that organize data collection from a tournament such as Rambely (2008).

Male collegiate players from the author's institution were selected to participate in the present study. However, different gender and levels of players could give different findings. Furthermore, a kinematic comparison between different players' profile (gender and level of players) during table tennis service is suggested to execute which will give interesting conclusions. The findings from the suggested matter will give extra information to understand the mechanical behaviors of different players' profiles during game.

It is suggested to further the study in kinetic analysis of body segment rotations. Kinetic analysis will give more knowledge and mechanical explanations on the postures or movement in sports activities (Iino & Kojima, 2016b). To the author's knowledge, there are a lot of dynamic model that can be tested and applied to the sports. However, deep knowledge on the dynamic field and a long period time is needed to succeed in this matter.

The algorithm of the improved kinematic model can be applied to other available software packages depends on convenience, easy access, financial issue in experimental cost or difficult access to other current methods. MATLAB Software package was selected in this study to develop the algorithm because of the above factors.

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LIST OF PUBLICATIONS AND PAPERS PRESENTED

1. Ibrahim, N., Abu Osman, N. A (2020). Contribution of the arm segment rotations towards the horizontal ball and racket head velocities during forehand long shot and drop shot services in table tennis. Sports Biomechanics. ISI index.
2. Ibrahim, N., Abu Osman, N. A (2020). The improved 3D kinematic model of arm segment based on Yamaguchi's model. Medical & Biological Engineering & Computing. (Under review). ISI index.
3. Ibrahim, N., Abu Osman, N. A (2017). Contribution of the arm segment rotations towards the horizontal ball and racket head velocities during forehand drop shot service in table tennis. International Technical Postgraduate Conference. University of Malaya. Proceedings seminar.
4. Ibrahim, N., Abu Osman, N. A (2016). The 3D generated kinematic modelling of upper extremity. International Conference of Mathematical Sciences. Palm Garden Hotel, Putrajaya. Proceedings seminar.