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Abstract

In the sport of badminton, the racket plays an important role because it is the main instrument to drive the shuttlecock. A good design of the racket is crucial to achieve better game performance. However, there is inadequate scientific study in the development of badminton racket design. The aim of this research is to identify the characteristics of racket design parameters which influence the racket performance. Designing a racket requires one to fully understand the racket performance characteristics. Basically, racket performance is referred in terms of sweet spot, which is the spot on a racket head that produces more power and control if a shuttlecock hits on it. Determination of coefficient of restitution (COR) can help to determine the sweet spot on a racket. In this study, several designs of badminton rackets were analyzed using finite element approach to investigate the design parameters that influence a racket performance. Each racket model was created in three-dimensional CAD software (SolidWorks®) and imported into ABAQUS (Explicit) for finite element analysis. The finite element simulation mimics the collision between rubber ball and badminton racket. The results from finite element simulation were compared with experimental results for validation. The parametric studies were conducted using validated finite element model to investigate the effect of string tension, racket structural stiffness, and racket head shape designs with respect to racket performance. Reducing the string tension from 34 lbs to 14 lbs could increase 2.4 % of COR. There was at least a 6 % difference in COR between hollow shaft and solid shaft. Isometric head shape racket produces better COR compared to oval and round shape. It is recommended that, the racket design should consist of low string tension, stiffer racket shaft, and bigger head size in order to produce higher shuttlecock speed.

Contents

Chapter 1
Introduction

Abstract This chapter provides crucial information that was found to be relevant to the present study. Related information regarding the badminton games such as game's law and regulations, player's characteristic, player's performance, racket design parameters and a brief history about badminton racket evolution were presented. Additionally, several previous studies on the analysis of the racket performance were reviewed in order to improve the understanding about design parameters in badminton racket.

Keywords Badminton Racket · Racket Design Parameter · Racket Performance · Sweet Spot

Badminton was commonly known as the fastest racket sport due to the shuttlecock speed produced during games. Based on Guinness World Records, the official record for the fastest smash produced in competition was 332 km/h done by Fu Haifeng during the Sudirman Cup 2005 tournament [1]. In 2013, Malaysian men doubles, Tan Boon Heong has unofficially beaten this record by producing a smash speed of 493 km/h during the experiment conducted by Yonex to test their brand new racket model [2]. Thus, this shows that badminton is a highly intensive game which requires players to have good stamina, speed and agility [3]. The ability to produce powerful strokes was one of the advantages and a key point for players in the quest of winning a game. It was proven that a smash shot was indeed the most effective stroke in gaining points during a badminton game [4]. Moreover, besides the physical and physiological factors such as technique, strength, stamina and speed, the racket design is undoubtedly considered as among the key factor that brings significant improvement on stroke power and accuracy [5–7].

In badminton, the racket holds an important role in controlling the game whereby a good racket should have the ability to communicate effectively with its handler. Hence, racket design and its traits need to be highly reliable and maintain consistent performance throughout a match. The innovation in sports technology brings to the development of various racket designs and each design has its

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own functional criteria that would significantly enhance the racket performance. In essence, racket performance is usually assessed based on its ability in commanding good control and power [7, 8]. Power is referred to as the rebound speed of the shuttlecock, while control is the precision of the stroke [8, 9]. Therefore, within the same context, the development of a good racket design would be imperative in achieving an optimum speed, precision and accuracy of racket handling.

Previous tennis studies have done remarkable works in investigating the effect of racket design parameters on the racket performance. Based on tennis literatures, sweet spot, swing weight and swing speed were some of the parameters that affected the performance of the racket. Sweet spot can be described as the spot on the racket string that can improve power and accuracy to the shuttlecock [10–12]. For example, hitting the shuttlecock on the sweet spot can give a lot of advantages, such as reduce the jarring on the gripping handle, produce more accuracy, and imparts maximum speed to the shuttlecock [11]. Other contributing factors that would affect the performance of the racket are swing weight and swing speed. Theoretically, swing weight can be described as the moment of inertia (MOI) of the racket while swing speed is commonly referred to the angular velocity of the swinging racket [13]. Racket that is equipped with higher swing weight and swing speed is able to produce more power to the ball. Previous studies on tennis rackets were conducted to find the correlation between swing weight and swing speed to its performance [9]. Similar approach of studies should be emulated and performed on the badminton racket in order to produce a more responsive, highly reliable and enhanced commanding ability by its handler.

1.1 General About Badminton

The modern badminton game was developed in England during 1800s [14]. The game was played on a rectangular court and the opposition players were separated by net. This game can be played either in a single game with two opposing players or in a double game with two opposing pairs. Generally, players get points by striking a shuttlecock with their rackets so that it passes over the net and lands into their opponent's court [15]. Each side may only strike the shuttlecock once, before it passes over the net.

The popularity of badminton increased after it was officially contested in the 1992 Olympic Games in Barcelona [16]. Recently, this game has been dominated by Asian players especially from China, Malaysia and Indonesia. Compared to other racket sports such as tennis and squash, badminton is known as the fastest racket sport in the world. Tsai et al. recorded that the initial shuttlecock speed produced during smash was in the range of 55–70 m/s [17]. In 2013, the Malaysian badminton player, Tan Boon Heong broke the Guinness World Record for the fastest badminton smash with a shuttlecock speed of 493 km/h [2]. Thus, the aforementioned indicated that badminton players need to possess good agility, speed, strength, and motor skill in higher level of games [16, 18–20].

In order to achieve optimal games performance, racket selection is deemed among the critical factors that should be taken into account. As stated previously, a good racket would have the ability to communicate well with the player and ultimately complements the physical traits and skills that one has to deliver optimum performance in the context of power and accuracy. Recently, with the adoption of advanced technology in sports, the market is witnessing growing numbers and varieties of badminton racket designs. It is fairly common for racket manufacturers to claim that their products are far superior, have better built and design which can improve a player's performance compared to their fellow competitors. Hence, players need to be wise in making their selection whilst analysing every aspect and parameters of the said racket before making an informed-decision in choosing their racket. Both racket and player should be thoroughly analysed, taking into consideration the complementing and suitability factors before a selection can be made.

1.2 Player's Characteristics and Player's Performance

Each player is unique and poised to have different psychological and physical traits. Every aspect of these traits could be weighted collectively to create a character of a player. This character would be the driving force in determining the player's style, responsiveness and patterns during a match. One player may have the tendency to play offensive, defensive or control which is fully dependent on the character of the player itself. Thus, the design of a racket should be accustomed to the character and physical traits of the respective player.

An offensive player can be described as a player with the tendency to commit numerous fast smashes, fast drop shots and net shots to overwhelm their opponent. This type of personality is usually considered as aggressive, with good strength, agility and speed. Hypothetically, an offensive player would prefer to use a heavy head racket in order to improve the smashing power. On the other hand, a defensive player tends to enjoy long rallies by committing a lot of clear shots onto the backcourt and sharp drop shots near to the net. Usually, this type of player can be described as a calm player with good stamina and typically commits only few mistakes. A light weight racket with good manoeuvrability may be suitable for this class of player. A control player can be described as a deceptive stroke player who tends to trick their opponent by tricky shots. Basically, a control player has good skills, techniques and higher shot accuracy. This type of player usually uses a weight balance racket that provides ease to control. Another class of player would usually have a combination of two or more styles in their play. This kind of character is commonly seen among the elite players. Therefore, most world class manufacturers strive to improve the proprietary design of their racket based on the common characteristics and abilities of the players in order to improve the game performance. Figure 1.1 shows types of badminton player pattern play.

Fig. 1.1 Types of badminton player pattern play

In-depth analysis with understanding of the player's characteristics, allows researchers to understand the player's capabilities and help in the development and improvement of a racket design. Performance of a player can be influenced by physical and psychological factors among others. Physical and physiological factors are described as player physical abilities which includes the anthropometric, agility, speed, strength, and fitness of players [19, 21, 22]. A study done by Ooi et al. has shown the importance of physiological factors on a badminton player's performance [16]. Ooi et al. reported that elite Malaysian male badminton players have better physical strength compared to sub-elite players, and are capable in producing faster shuttlecock speed as opposed to the sub-elite players.

Psychology is another factor that affects the player's performance. The quality of decision making during games is relatively important as it executes motor skills and these are vitals in determining the successes of sports performance. Soltani et al. compared some physiological features of Turkish badminton elite players with amateur badminton players [21]. As a result, the elite players had lower level of somatic anxiety compared to non-elite badminton players and showed ability to perform well in major tournaments due to their ability in managing stress and pressure during matches.

Sportsmen are expected to be equipped with good technical skills, tactical, specific physiological fitness and psychological preparation in order to succeed. The same is expected with no exception to a badminton game as it requires players to master various technical skills especially stroke techniques such as service, drop shot, overhead smash, forehand stroke, backhand stroke, etc. These strokes are directly correlated to power and control, whereby power is referred to shuttlecock speed produced by a player while control is referred to the accuracy of a shot. Statistically, smash shot is the most effective stroke, contributing to a higher success in winning points [4]. Lo et al. concluded that the combination of power and speed in a smash makes it the most powerful offensive stroke in badminton [18]. A study done by Sakurai and Ohtsuki analysed the smash stroke between unskilled and skilled players. The result indicated that strokes of skilled players are relatively more accurate as opposed to the sub-skilled players [23]. Another study done by Tsai et al. established that elite players produced 15–20 % faster shuttlecock speed compared to collegiate players [17]. Based on these, it can be deduced that shuttlecock speed is among the parameters in determining a player's performance.

1.3 Law and Regulations of Badminton Racket

Most major sporting events around the world are governed by legislative bodies that function as the regulator that oversee the major fixtures, setting up rules and guidelines, and also directives in maintaining safety and effectiveness of matches. For example, soccer is governed by International Federation of Football Association (FIFA), basketball in North America by the National Basketball Association (NBA), Formula 1 by the International Automobile Federation (FIA) and badminton by the Badminton World Federation (BWF). These international governing bodies would also be responsible in laying out the fundamentals and specifications of every instrument used in each sport. In badminton, BWF provides rules on any question of whether any racket, shuttle, equipment or any prototype used in the playing of Badminton complies with the specifications. Such ruling may be undertaken on the Federation’s initiative or on application by any party, including any player, technical officer, equipment manufacturer or members of its association [15].

The BWF has outlined several guidelines to govern the overall shape, length and size of a badminton racket. These laws and regulations released by the BWF explicitly described the physical characteristic of a badminton racket and became the guiding principle for racket manufactures in developing a new racket design. Badminton rackets can be divided into several sections consisting of the head, string-bed, throat, handle, and shaft as shown in Fig. 1.2 [15]. According to the BWF, the overall racket dimension must not be more than 680 mm in length and 230 mm in width. The stringed area must be bounded to the racket head frame. The maximum tolerance size for the stringed area is 280 mm in length and 200 mm in width. The stringed area shall be flat and consisting of a pattern of

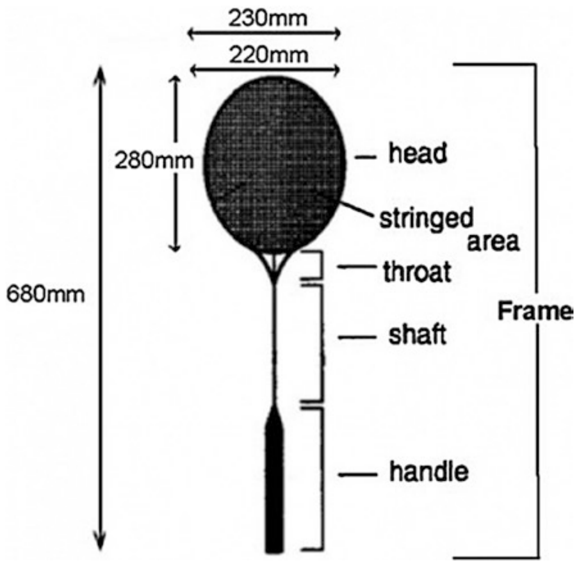

Fig. 1.2 Part and dimension of a badminton racket [15]

crossed strings either alternately interlaced or bonded between cross strings. The stringing pattern shall be generally uniform and, in particular, not less dense in the centre than in any other area.

1.4 Evolution of Badminton Racket

Major efforts have been undertaken by racket manufacturers to enhance the racket performance, by improving the material used and optimizing the racket designs and racket weight [10]. The early models for badminton rackets were made from wood with an oval head shape, used animal gut strings, and the racket handle was designed only for comfort rather than performance. This wooden racket was heavy and less flexible compared to its modern counterpart. In terms of ergonomics, the wooden racket was not very appropriate use due to its heavy weight and stiffness. In term of performance, players have to put lots of strength and energy to drive and swing the heavy racket [13].

The injuries that commonly happen to badminton players are shoulder impingement, shoulder dislocation, wrist injuries and tennis elbow [24]. Weir and Watson reported based on an epidemiology study in Ireland that badminton was among the top sports with the most injuries compared to other sports [25]. These problems bring to the development of the light weight racket where it was initially made from light steel material such as aluminium alloy. A study on the tennis racket done by Brody found that reducing the racket mass was one of the methods to improve the swing speed of the racket [13]. However, if both light weight and heavy weight rackets were swung at the same speed, the speed of ball generated by the light weight racket was lower compared to the heavy weight racket. Another tennis racket study done by Cross and Bower discovered that the swing speed of the racket can be increased by reducing the mass and length of the racket [9]. The development in advanced material technology brings to the latest carbon fibre that make rackets feels much lighter and more flexible.

During the 1960s, rackets with wooden frames and metal handles became widely popular after being used by several elite players. Indonesian badminton legendary player, Rudy Hartono employed Yonex B-6000 Five-Ace Deluxe, a racket with a combination of wood (head frame) and metal (shaft) that won him several titles. In the late 1960s, racket manufacturers further improved the material used in racket production by introducing a fully metal racket frame by either combining materials like aluminium and steel or fully aluminium.

During the 1970s, rackets became lighter when the manufacturers decided to produce rackets out of carbon materials. During that time, the carbon based racket emerged to be the most popular racket at that time. However, the price for rackets became increasingly expensive and the racket was less durable. To overcome the problem, racket manufactures came up with graphite rackets that gained popularity in the 1990s. By mixing titanium alloy and graphite, manufacturers were able to produce much lighter rackets without compromising its durability. Later in the

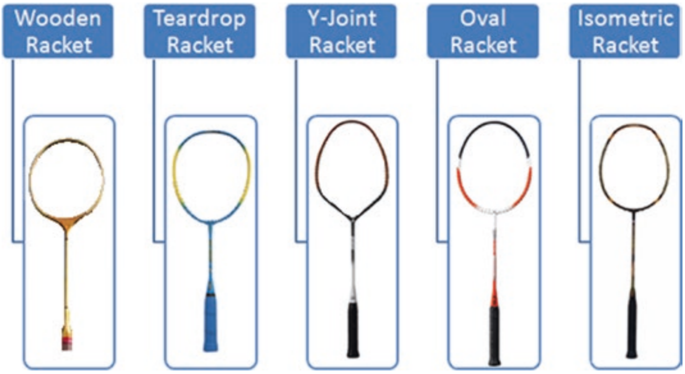

Fig. 1.3 Various design of badminton racket

20th century, the advancement of material designs for rackets became more evident when racket manufacturers began adding nanomaterials such as fullerene to graphite rackets to make the racket stronger. This advancement has enable significant improvement in racket design with superior badminton rackets being produced and utilised worldwide. As a result, faster smash shots can be achieved and more new smash shots are recorded periodically.

The racket development is not only confined to material development, it also involves the improvement of racket designs. The racket head was originally designed with a round shape. Further improvements on the head design were made by introducing several designs including teardrop, Y-joint, oval and isometric head designs (Fig. 1.3). In the early stage, the design of badminton rackets were only based from ecstatic point of views, players' feedbacks, and less scientific approach. Presently, the advancement in technology has witnessed the addition of the latest isometric head shape design that was claimed to have a much larger 'sweet spot' by racket manufacturers globally. The research on sweet spots of a rackets was initiated on the tennis racket. Brody managed to discover the existence of sweet spots in tennis rackets and located the exact locations for every sweet spot on the tennis racket [10, 11]. According to Brody, the head shape and size of a racket were some of the factors that influenced the enlargement of sweet spot in racket design.

String is another critical component in badminton rackets that affects the performance of a player [26–28]. Traditionally, badminton strings were made from natural animal gut. These animal gut strings did not stand higher tension due to its less mechanical material properties. Then, synthetic strings made from nylon were introduced and was ascertained capable of sustaining higher tension. There are many arguments on the effect of string tension on a player's performance. Bower and Cross's studies on tennis investigated the effect of string tension on a player's performance and found that about 27 % of the subjects tested were sensitive to various string tension and experienced 2 % ball speed increases by decreasing the string tension [5]. Another study conducted by Bower and Cross postulated that the string tension has significant effects to ball rebound speed and accuracy [28]. Increase of string tension improved about 15 % of ball accuracy while the lower string tension was more suitable for long shot accuracy.

1.5 Racket Performance and Racket Design Parameters

A racket's performance is usually described from the perspective of power and control where power is referred to as the ball speed and control is referred to as the shot accuracy. To be clear, a racket that is able to produce higher shuttle speed and accuracy is classified as an excellent racket. In essence, design parameters of a racket would greatly influence the racket performance. Improvement on racket design parameters will lead to better racket performance. Several terminologies are commonly used to describe racket design parameters namely sweet spot, dead spot, swing weight, and swing speed.

To the best of the author's understanding, there are similarities on the racket performance between tennis and badminton. This is especially evident and can be witnessed by looking into the concept of both types of rackets, functionalities and their abilities to swing and drive the shuttle. Based on apparent limited literatures and publications, it can be deduced that researches on badminton racket design parameters are very limited to almost non-existence. Therefore, tennis literatures have been used as the reference to analyse the design parameter on badminton racket.

1.5.1 Sweet Spot and Dead Spot

Lots of effort has been done in the study of tennis racket to investigate the characteristics of racket design parameters toward racket performances. The most interesting parameters that are commonly referred to are the sweet and dead spot. Sweet spot is a term widely used to describe the spot or the point in the racket that gives a sensational feel when hitting a ball thus producing more power and control [10, 11]. Head defines the sweet spot as the region on racket faces (string-bed area) that give the maximum coefficient of restitution (COR) when the racket handle is firmly clamped. This finding was supported by Brody in the research relating to sweet spots in tennis rackets. Brody elaborated the sweet spot into three areas which comprise of power region, centre of percussion and node point. He also managed to develop a mathematical model form of a physics equation to support the definition of each sweet spot. In order to analyse the sweet spot, Brody developed a system of apparatus consisting of a photodetector, an oscilloscope and laser to measure the dwell time of a tennis ball on the string tension of a racket (Fig. 1.4) [10]. The study discovered that hitting a ball on the right area or spot on a racket face can give added advantages such as reducing the jarring on the

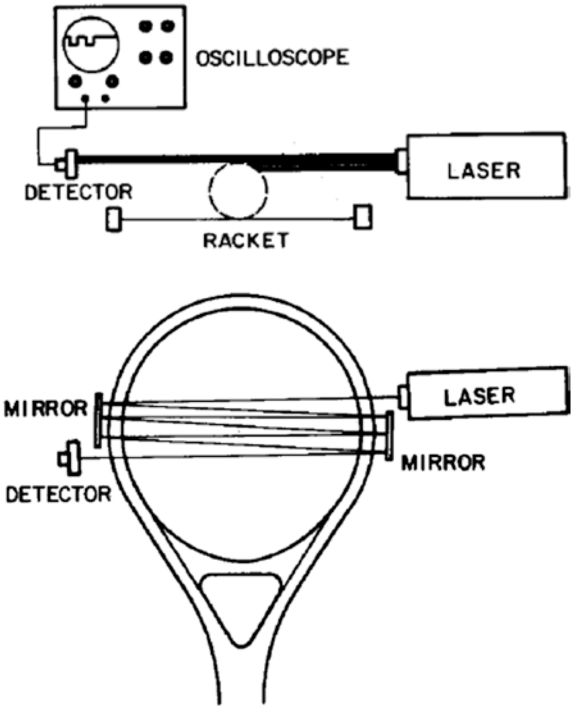

Fig. 1.4 The illustrations of experimental setup to measure the dwell time of a tennis ball on the string-bed of tennis racket [10]

gripping handle, producing more accuracy and imparting maximum speed to the ball. Brody also described power regions as the area on the string-bed that generates the maximum rebound velocity of a ball. Power region can be found on the longitudinal axis between the tip and throat of a racket where it indicates the maximum COR. Furthermore, the values of COR can be controlled by two main parameters which are the stiffness of the racket and the string tension.

According to Brody, the centre of percussion (COP) and the node point were related to the vibration of the racket [11]. The COP was an impact point on the racket string-bed to produce the right combination between translational and rotational motion of a racket during collision with a ball. The node point was a point on the string-bed where impact on it can generate maximum vibration on the racket handle. Hitting on these spots produce great rebound velocity of a ball and less collision force is transmitted to the gripping hand where it vibrates less. Therefore, most of the researches in tennis were focused on reducing the vibration of the racket. Tennis scholars mentioned that often injuries on tennis happen due to the high impact from the ball that resulted in elbow injuries. It was recommended to use a vibration damper to reduce the impact of vibration. In badminton, injuries related to vibration of rackets were not significant with only 5 % of reported injuries [24]. Figure 1.5 shows the location of the sweet spot on a tennis racket.

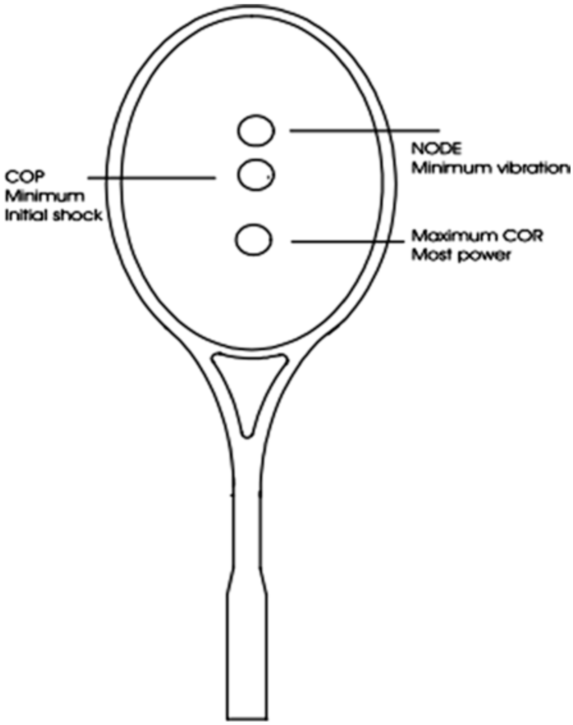

Fig. 1.5 The sweet spot on a tennis racket [10, 11]

Cross discovered a new spot on the tennis racket and recommended the spot as the best place to hit during serving and smashing [29]. This spot is called the dead spot and was defined as the point where an incident ball stops statically on a stationary racket. Therefore, the dead spot was the area on the racket head that generated minimum values of COR. Based on the analysis of the tennis racket, Cross concluded that the dead spot was located near to the tip area of the racket head (string-bed area). This conclusion leads to the development of overhead size tennis rackets.

1.5.2 Swing Weight and Swing Speed

Another important parameter that affects the performance of a racket is swing weight and speed. The relationship between swing weight and swing speed to sport equipment performance was widely discussed in several swinging sports. Research done by Cross and Nathan investigated the importance of swing weight on the performance of sport equipments in three major swing sports including tennis, baseball and golf [30]. Other than that, Schorah et al. investigated the relationship between swing weight and swing speed in nine major swinging sports including badminton, tennis, cricket, etc. [31]. The finding shows that badminton rackets produced higher swing speed but lower swing weight when compared to other swinging sports such as tennis, baseball and golf.

Another study of the tennis racket conducted by Brody described swing weight as the moment of inertia (MOI) of the racket [13]. He managed to analyse several variety of tennis rackets in order to obtain its MOIs. It was found that rackets with heavy heads had larger swing weight and can improve ground stroke power. The values of MOI can be controlled by manipulating the length, mass, and balance point in the racket. In practice, the MOI of the racket can be improved by adding weight to the edges of standard size racket or making the racket head wider. Another study done by Cross and Bower analysed the effect of swing-weight on swing speed by representing the racket as uniform rod [9]. The study found that mass, length, and balance point were the parameters that influenced swing-weight and swing speed. This study discovered that increase of swing weight could reduce swing-speed.

1.6 Finite Element Analysis

Recently, finite element simulation was extensively adopted in the development of sport equipment mainly in racket-based sports. This approach allows researchers to conduct a more competitive analysis without having to produce prototypes and ultimately reducing cost and time. Several analytical studies on racket design parameters on tennis rackets were done using this method. Glynn et al. analyzed two tennis racket models using finite element simulation to investigate the effect of string tension, head size design, weight, length, and balance point of racket on the racket's performance [32]. Moreover, Goodwill et al. developed a finite element model of a tennis ball to simulate the oblique impact between a ball and a rigid surface [33]. This finite element simulation was validated through an experiment using high speed camera to determine the velocity, angle, and spin of the ball during impact.

Banwell et al. applied finite element analysis in tennis study to determine the natural frequency and corresponding mode shapes of a racket [34]. This simulation used a string-bed model that was created as a single plane to represent the actual inter-woven shape. Banwell et al. continued the finite element study on the tennis racket by analysing the frequency, damping ratio of freely suspended racket and hand gripped rackets in order to determine the characteristics of the impact vibration on racket handle [35]. Another finite element study on the tennis racket was performed by Gu and Li. The vibration characteristics of two different string tensions were compared to obtain the mode shape of the racket. The results indicated almost 70 % reduction of vibration frequency on higher tension in handle clamped condition [36]. It was supported by Li et al. on the study of string tension effect in several impact locations [26]. This study found that reducing string tension can increase vibration, while at the same time increasing COR. Furthermore, vibration of the racket can be reduced by hitting the ball at node point in string-bed area [11, 26, 37].

Allen et al. developed several finite element simulations in order to analyse racket performance [38, 39]. Allen et al. managed to develop a finite element model of string-bed of tennis racket in inter-woven patent to imitate the actual condition [39]. The simulation mimics the impact of a tennis ball on a freely suspended racket to investigate the effect of racket stiffness and ball inbound spin speed on racket performance. Another simulation done by Allen et al. analysed the effect of resultant rebound velocity and spin for a simulated groundstroke [38]. Allen et al. compared several racket models consisting of various racket design parameters such as racket stiffness, balance point, and mass to investigate racket performance in various impact locations on the string-bed area. Based on the results, Allen et al. recommended that the rebound speed and topspin of the ball can be increased by adjusting the racket balance point closer to the racket tip.

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Chapter 2
Coefficient of Restitution in Badminton Racket

Abstract This chapter explains in greater detail on the development of generating the finite element model for badminton racket using ABAQUS (Explicit). Among the details involved material selections, measurement and important boundary conditions of the finite element models were presented. Several relevant theories behind the analysis of the badminton racket's performance, such as the equation of coefficient of restitution, COR in badminton racket were explained. Other than that, the important information about the experimental procedures and apparatus setup were explained in detail. The experimental analysis is crucial since the results will be used to validate the finite element model.

Keywords Coefficient of Restitution · Sweet Spot · Finite Element Analysis

2.1 Coefficient of Restitution (COR)

The theory of coefficient of restitution (COR) was commonly used to analyse the performance of racket based sports such as badminton, tennis, squash and table tennis. In theory, the coefficient of restitution (COR) was a measurement of the energy loss between collisions of two bodies, whereas COR was ranged at $0 \le \text{COR} \le 1$ [1–3]. In ideal cases, COR = 0 was referred to as perfectly inelastic collision while COR = 1 was for perfectly elastic collision. In the collision between ball and racket, COR was defined as the ratio of ball rebound velocity, v_2 to the ball incident velocity, v_1. The COR can also be determined by using the equation

$$COR = \frac{v_2}{v_1} = \sqrt{\frac{h_r}{h_d}} \tag{2.1}$$

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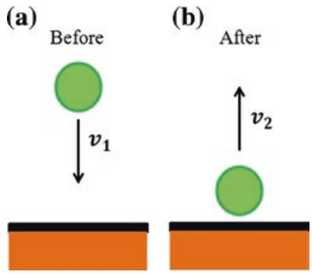

Fig. 2.1 Illustration of collision between a ball and a surface complying with COR theory, **a** incident velocity, v_1, **b** rebound velocity, v_2

where,

v_1 is the incident velocity,
v_2 is the rebound velocity,
h_r is the ball rebound height, and
h_d is the ball drop height.

The common procedure in obtaining COR was by dropping a ball onto the racket string-bed with the racket handle or racket head clamped [1, 3, 4]. Normally, rackets that produce higher COR value is categorised as a good racket. Thus, the value of COR is used to measure the potential performance for specific racket. Figure 2.1 shows the illustration collision between a ball and a surface complying with the COR theory.

2.2 Finite Element Model

In this study, finite element simulation was developed as a tool to analyse the racket design parameter towards racket performance. Basically, the finite element model for this simulation consists of three major components; the racket frame model, the string-bed model and the rubber ball model. Each 3D model was created in SolidWorks® 2012 and then imported to ABAQUS Explicit for the employment of finite element analysis. Then, results from this simulation were compared with experimental results for validation processes. The complete methodology for the development of finite element analysis on the badminton racket is summarized in Fig. 2.2.

2.2.1 Racket Frame Model

The main finite element model of the badminton racket frame was developed based on an isometric head shaped racket design. The overall dimensions of the isometric head frame are 197 mm in width, w and 249 mm in length, l. This racket frame model has the total overall length, l_o of 516 mm. This model also consists of

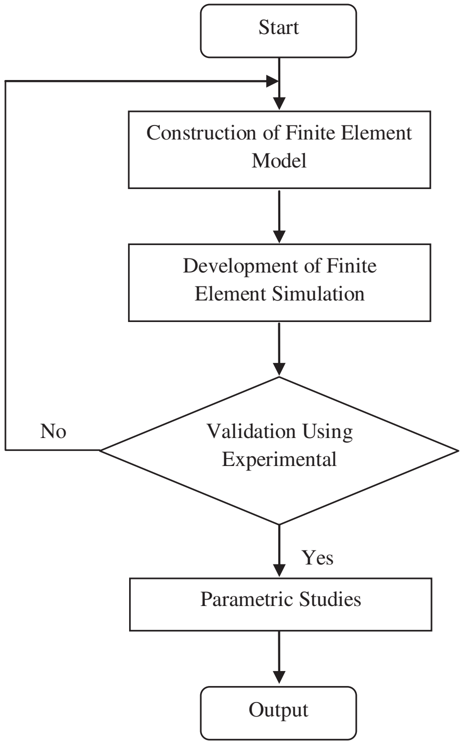

Fig. 2.2 Research framework of finite element simulation of badminton racket

the shaft cross-sectional diameter, d_o of 7 mm and shaft cross-sectional thickness, t of 1 mm. Figure 2.3 shows the schematic diagram of the badminton racket frame model.

The finite element model of the badminton racket was assigned with linear elastic material to enable the deformation of the racket frame during the simulation [5]. The material used for the racket frame model was carbon fiber material which had Young's modulus, E of 25,000 MPa, density, ρ of 1750 kg/m^3, and Poisson's ratio, ν of 0.3.

2.2.2 String-Bed Model

The string-bed model was inter-woven to replicate the actual string-bed design. Figure 2.4 shows the schematic diagram of the isometric string-bed model. The isometric string-bed model had the overall dimensions of 239 mm length, l and 187 mm width, w with 22 main (longitudinal axis) and 22 cross strings.

The diameter of cross-section area of the string, ϕ was set at 0.66 mm. The material used for the string was made of nylon having a Young's modulus, E of 7200 MPa, density, ρ of 1100 kg/m^3 and the Poisson's ratio, ν of 0.3 [6]. The

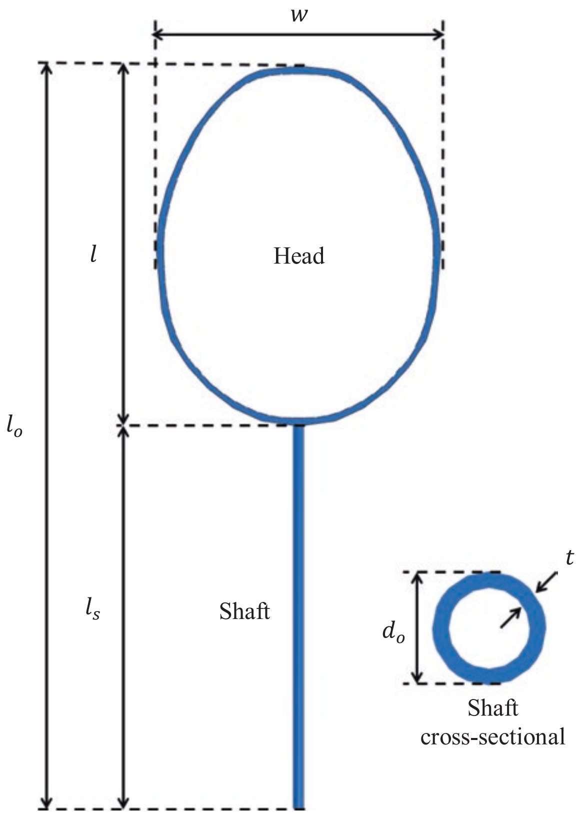

Fig. 2.3 Schematic diagram of badminton racket frame model

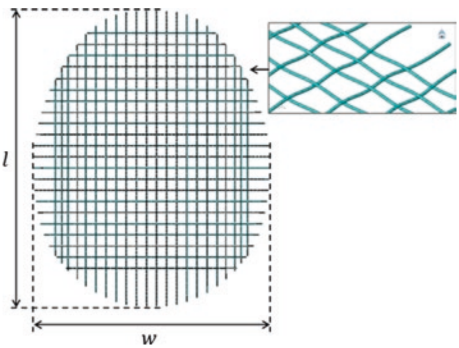

Fig. 2.4 Schematic diagram of inter-woven string-bed model of a badminton racket

interaction between string in the string—bed area was defined as surface-to-surface contact (explicit) with a friction coefficient of 0.4, while the interaction of rubber ball and the string-bed was defined as surface-to-surface contact with a friction coefficient of 0.1 [6]. Since there were limited studies done on the badminton racket, the friction coefficient of 0.4 and 0.1 for the string and string-bed and also rubber ball and the string-bed respectively, were selected as the reference obtained from previous studies on tennis rackets. These coefficients were used merely to set a benchmark in designing the finite element analysis of the badminton racket. The latter may be expanded and further investigated once the fundamentals of the finite element model for the badminton racket have been clearly established. The interaction of surface-to-surface contact was set based on ABAQUS Explicit's requirement to prevent any unintended penetration between string-to-string and string-to-ball. To connect the string-bed with the racket head, the end of each string was applied using tie constraint with outer surface of the racket head frame.

The tension of the string is another important boundary condition that should be considered in order to simulate the actual string-bed condition. In this finite element study, the most critical boundary condition is to ensure the string-bed behaves such in a constant initial tension condition. Theoretically, if the string was applied with tensional force at the end of the string, internal normal stress would be present. Therefore, in order to replicate the behaviour of string tension, another alternative method was applied using normal stresses on the string-bed. This can be done by applying stress in INITIAL CONDITION using Edit Keywords function in ABAQUS Explicit [5]. By applying this technique, the string-bed would be constantly in tension condition.

2.2.3 Rubber Ball Model

In this study, the rubber ball has been chosen to replace the shuttlecock for the simulation impact on the badminton racket's string-bed. The shuttlecock has several limitations that would greatly affect the COR result in the finite element simulation. Basically, the cork section is heavier compared to the feather section, thus, the difference of the weight distribution of the shuttlecock makes it less stable and more inclined to flip during the collision. As a result, inconsistent values of rebound velocity will be obtained and affect the COR performance. Due to the geometry issue of the shuttlecock, the rubber ball has been utilised in order to obtain precise and consistent results of COR.

The dimension of the simulated rubber ball model is based on the real-life rubber ball dimension used in the experiment whereby the outer diameter, d_o of this model was set at 43.5 mm and thickness, t of 4.5 mm (Fig. 2.5). The rubber ball

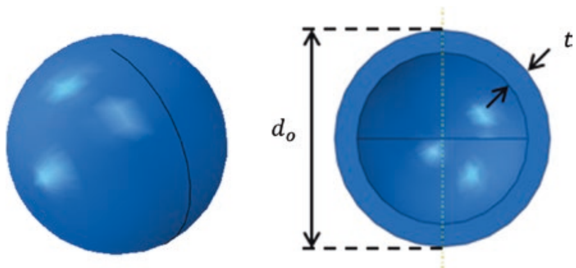

Fig. 2.5 Schematic diagram of rubber ball model

model consists of Mooney-Rivlin hyper elastic material model with constants $C_{10} = 0.69$ MPa, $C_{01} = 0.173$ MPa and $D_1 = 0.0145$ MPa^{-1} [5]. The density, ρ of the rubber ball was set to be 1068 kg/m^3.

2.3 Finite Element Simulation

This finite element simulation mimics the collision between a rubber ball and a badminton racket. The simulation was performed using an isometric head shaped racket model with the total overall racket length, l_o of 516 mm, shaft cross-sectional diameter, d_o of 7 mm and shaft cross-sectional thickness, t of 1 mm. The head of this racket model was anchored as a boundary condition for this simulation as shown in Fig. 2.6 to prevent any uncalled head movement during collision.

The simulation was carried out with varying string tension from 14, 20, 24, 28 and 34 lbs. The rubber ball was dropped with initial height, h_d of 10 mm under the gravitational acceleration, g of 9.81 m/s^2 onto the COM of the racket string-bed. Then, the maximum rebound height, h_r of the ball was analysed to obtain the values of COR. Later, the results from this simulation were compared with experimental results for validation analysis.

2.4 Experimental Procedures

The main purpose of conducting this experiment was to validate the finite element simulation of the badminton racket. The experiment was performed by colliding the rubber ball with the badminton racket. The racket head was clamped in order to preserve the integrity of the shaft's structural stiffness and thus, preventing any involuntary effect as a result from the collision on the COR performance. Therefore, the performance of COR was only affected by string parameters. The racket head frame was assumed to behave as a rigid body condition where there was no deformation of the said frame during the impact.

Then, the rubber ball was freely dropped from a 10 mm height, h_d onto the centre of mass (COM) of the string-bed [7]. The COM of the string-bed is the softest

Fig. 2.6 Badminton racket frame model in anchored boundary condition

Fig. 2.7 Phantom V12.1 high speed camera

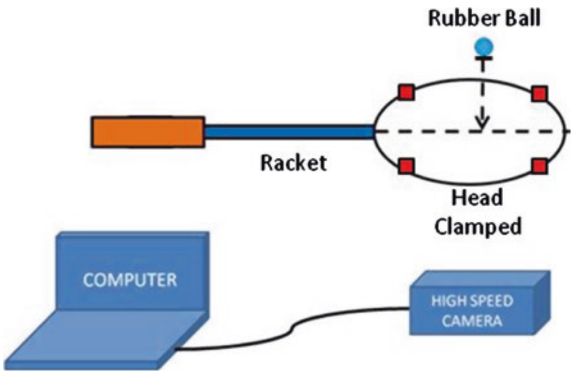

Fig. 2.8 Illustration of the experimental apparatus setup

area on the racket string-bed whereby it produces the maximum value of COR [4]. The location of COM of the string-bed was obtained based on the measurement from a 3D model of an isometric racket in SolidWorks®. This experimental procedure was repeated 10 times to get the average values of ball rebound height, h_r. The rebound heights, h_r of each trial were recorded using a Phantom V12.1 high speed camera (HSC) with frame rates of 1000 fps (Fig. 2.7) [6, 8]. Figure 2.8 shows illustration of the apparatus setup for this experiment while Fig. 2.9 shows the picture of the experiment setup. Later, the data obtained were analysed using Phantom Camera Control Version: 9.3.692.0-C PhCon:692 software in order to determine the maximum values of ball rebound height, h_r.

2.5 Validation

The validation of finite element model is very essential and necessary in order to ensure the reliability and accuracy of the finite element simulation results. Theoretically, the finite element model is reliable if the simulation results have

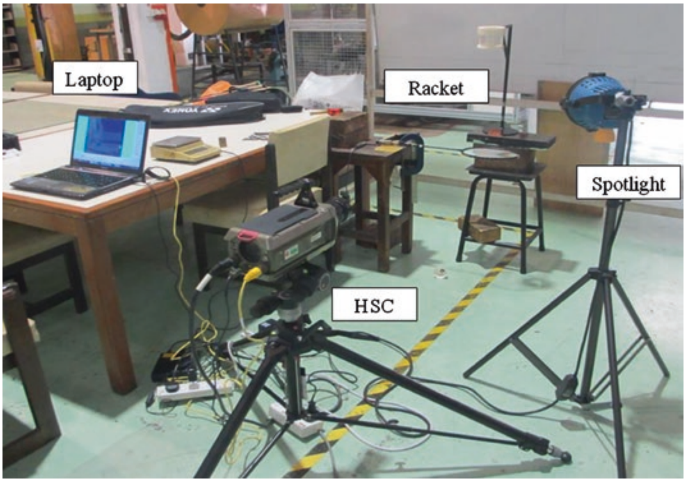

Fig. 2.9 Picture of the experimental apparatus setup

good correlation with the experimental results. Since the accuracy and reliability of the simulation results are important, therefore, mesh convergent study was conducted to determine the sufficient number of elements for this simulation.

2.5.1 Mesh Convergence Study

The convergence study was done to determine the appropriate number of elements that could compromise between the accuracy of the results and the time consumed in finite element analysis. Figure 2.10 shows the COR results of the collision between the rubber ball and the centre of the racket string-bed in various numbers of elements. It was observed that the COR was converged on the increasing number of elements from 7985 elements until 217210 elements. Referring to Fig. 2.10, the suitable number of elements that could be used in this simulation was in the range of 7985–217210 elements, where the results observed between these elements were slightly constant.

One of the criteria that should be considered in convergence study is the simulation time. The computer utilised in this simulation study was equipped with Intel® Xeon® 2.30 GHz processor and an installed memory, RAM of 16 GB. With this computer capacity performance, the simulation using 217210 elements takes about 136 h to complete and it was the longest time taken to finish the simulation. Meanwhile, the simulation using 7985 elements took about 65 h to complete. Basically, the higher number of elements took a longer duration to complete the simulation compared to the lower number of elements.

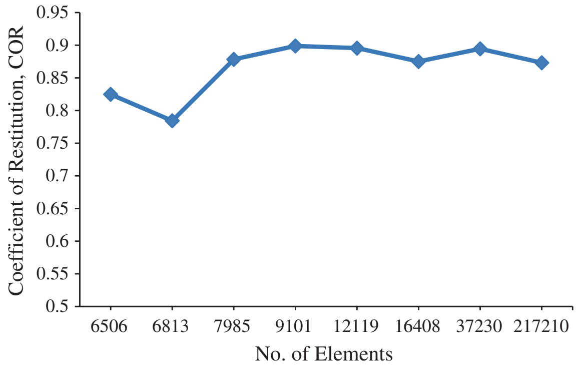

Fig. 2.10 Mesh convergence results of finite element simulation

Table 2.1 Results accuracy and time consumption of the finite element simulation

No. of elements	Accuracy (%)	Time (h)
6506	5.5	54
6813	10.2	59
7985	0.6	65
9101	2.3	69
12119	2.6	75
16408	0.2	82
37230	2.4	88
217210	0	136

Other than that, the accuracy of the data must also be considered in choosing the appropriate number of elements. Table 2.1 shows the accuracy, % and the simulation time consumed by each number of elements used in this finite element analysis. In order to obtain the accuracy, each COR was compared with the COR obtained from 217210 elements. Based on the results, the accuracy of data obtained using 7985 elements had a difference of only 0.6 % compared to the data using 217210 elements. Therefore, due to time constraint and computer performance limitations, the elements number of 7985 was considered as the most appropriate element to be selected in this simulation study.

2.5.2 Validation of Finite Element Simulation

Figure 2.11 shows the comparison between COR obtained from the experiment and simulation against various string tensions. Referring to Fig. 2.11, both results from experiment and simulation showed that the values of COR slightly decreased as the string tension increased.

In comparison between the results obtained from the experiment and simulation, the recorded overall percentage error was less than 7 % whereas the

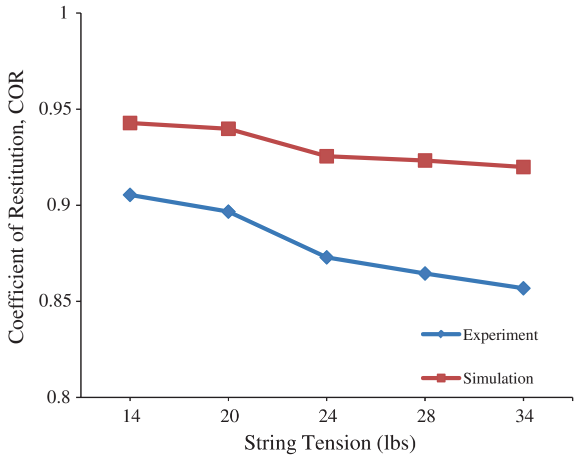

Fig. 2.11 The COR from the experiment and the simulation against various string tensions

Table 2.2 The COR percentage error of the simulation

String tension (lbs)	Experiment	Simulation	Error (%)
14	0.9054	0.9428	3.97
20	0.8967	0.9398	4.59
24	0.8729	0.9255	5.68
28	0.8645	0.9233	6.37
34	0.8568	0.9199	6.86

maximum error was 6.8 % at string tension of 34 lbs while the minimum error recorded was 3.9 % at string tension of 14 lbs. Table 2.2 enlists the percentage error of the simulation of various string tensions. Therefore, there was an agreement on COR between the experiment and simulation, since the error falls within the acceptable limit.

The sequence from the finite element model for an impact at the COM of the string-bed is shown in Fig. 2.12. During the pre-impact phase, the ball started to fall onto the COM of the string-bed at a height of 10 mm under gravitational acceleration, g of 9.81 m/s^2. Then, during the impact phase, the string-bed absorbs the energy from the ball and causes the deformation of the string. Finally during the post-impact phase, ball has left the string-bed and stops until reaches the maximum rebound height. The maximum rebound heights were recorded to calculate the COR.

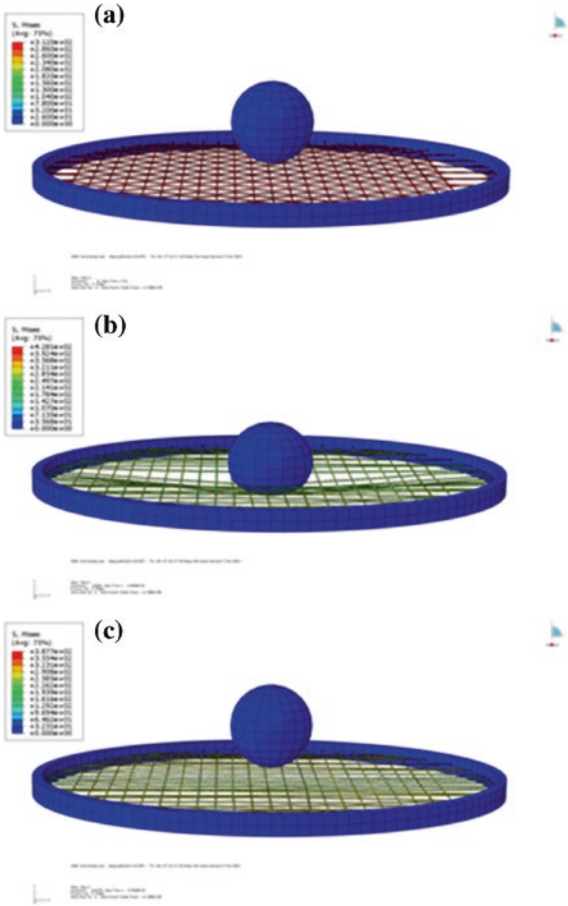

Fig. 2.12 Sequence from the finite element model for an impact at the COM of the string-bed. **a** Pre-impact, **b** during impact, **c** post-impact

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Chapter 3
Effect of String Tension Toward Racket Performance

Abstract This chapter provides the analysis of the effect of string tension toward badminton racket. Generally, string tension is one of the crucial parameters on the racket that influences the values of coefficient of restitution (COR) in badminton racket. Therefore, several finite element simulations were carried out to determine the relationship between string tension and deflection of string. The simulations were carried out in varying string tension in order to measure the maximum rebound height and to determine the value of COR. From the finding, the reducing values of string tension leads to higher values of COR. This finding will contribute to the enlargement of sweet spot in badminton racket as well as improving the player performances.

Keywords Deflection of String · String Tension · Racket Structural Stiffness

3.1 Fundamental of Deflection of String

In the analysis of deflection, the racket string was represented as a fully supported beam where both ends of the string were anchored as shown in Fig. 3.1. Basically, the maximum deflection of a single string is located at the centre of string length. However, taking the entire racket system as a whole, the maximum deflection of string-bed is located at the centre of mass, COM of the racket string-bed [1]. The maximum deflection of a string, y_{max} can be expressed as

$$y_{max} = \frac{PL^3}{48EI} \tag{3.1}$$

where,
P is the concentrated load applied perpendicular to the string longitudinal axis,
L is the length of string,
E is the material's modulus of elasticity, and
I is the moment of inertia of cross section about its neutral axis.

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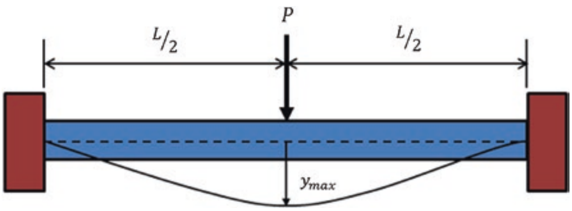

Fig. 3.1 Schematic diagram of fully supported beam

3.2 Finite Element Study on Effect of String Tension Toward Racket Performance

The aim of this simulation is to determine the effect of string tension to the COR performance. The racket model that was used for this simulation was the isometric head shaped racket model with 7 mm of shaft cross-sectional diameter, d_o and 1 mm of shaft cross-sectional thickness. Generally, this simulation was divided into two types of simulations in which both simulations were performed in distinguishing racket constrain boundary conditions. For the first simulation, the racket head was set as anchored while for second simulation the racket handle was set as anchored (Fig. 3.2).

In order to investigate the effect of string tension toward COR performances, the racket model was simulated with various string tensions which consisted of 14, 20, 24, 28, and 34 lbs. These string tensions were considered from the range of lower string tensions until the higher string tensions that are normally used by

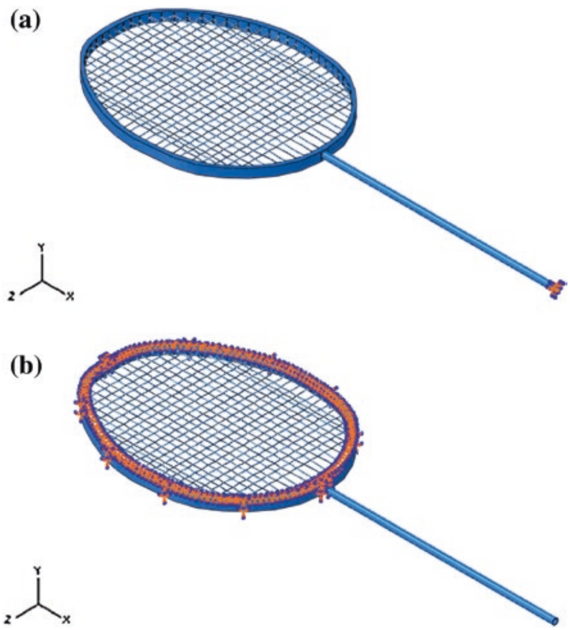

Fig. 3.2 Constraint boundary conditions of the racket model. **a** Head anchored, **b** Handle anchored

players. Basically, this finite element study simulated the collision of a ball onto the COM of a racket string-bed [2]. The ball's initial velocity, v_1 before the collision was set at 10 m/s. The initial velocity of the ball was chosen based on previous simulations and studies conducted on the tennis racket since there were limited publications and studies performed on the badminton racket. The initial velocity was selected as a benchmark in designing the framework of parameter studies for the badminton racket. Therefore, a velocity of 10 m/s is considered adequate to provide the basis in computing the COR. Once the framework of parameters has been established, further in-depth investigation may be performed on varying velocities. Then, the rebound velocity, v_1 of ball for each simulation was taken to obtain COR.

3.2.1 Relationship Between String Tension and Deflection of String

Figure 3.3 represents the relationship between COR and various string tensions when the racket head was in an anchored condition. As shown in Fig. 3.3, the string tension of 14 lbs indicated the highest COR of 0.9427 while the lowest COR was 0.9199 where the string was strung at 34 lbs. Figure 3.3 shows a good correlation between COR performances and string tension where COR decreased slightly with the increment of string tensions. There is a reason to anchor the racket head in this simulation. Since the racket head was anchored, the effect of racket structural stiffness in COR performance can be neglected. With this, the performances of COR were only affected by the string tension. Based on these results, lower string tension produced better COR compared to higher tension.

During the collision between ball and string-bed, the kinetic energy from the moving ball was transferred and dispersed onto the string-bed. This impact causes

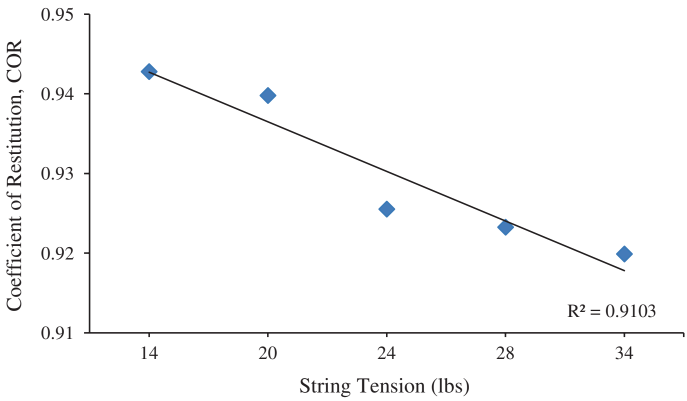

Fig. 3.3 The COR values at different string tension (Head Anchored)

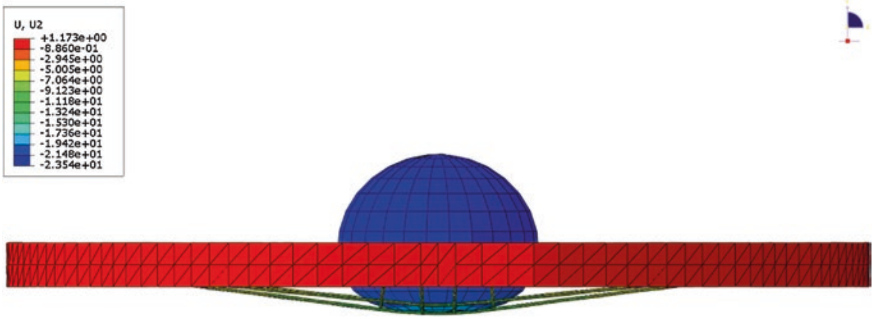

Fig. 3.4 Maximum deflection of string-bed (string tension 24 lbs, head anchored)

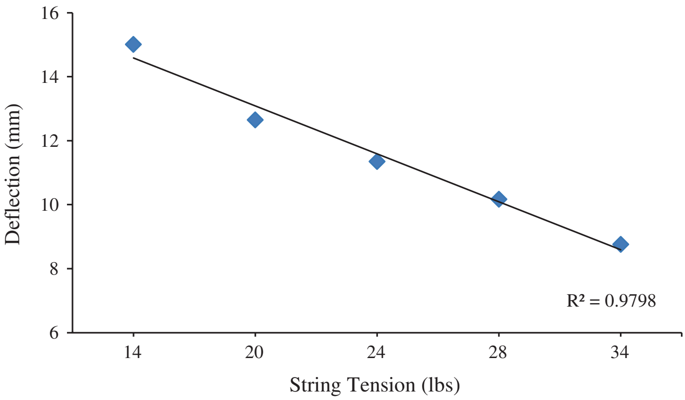

Fig. 3.5 Maximum deflection of string-bed against various string tensions (Head Anchored)

the string-bed to deform and due to this deformation the string now stores the elastic potential energy. The elastic potential energy was the factor that influenced the string to deform back into its original shape. Figure 3.4 shows the maximum deflection of the string-bed during the simulation impact.

Figure 3.5 shows that the deflection of string-bed was inversely proportional to string tension. Thus, it was indicated that the deformation of string-bed is more apparent in a condition of lower tension rather than in higher tension. Theoretically, the string-bed will deform to absorb the energy from the collision. In the case of lower tension, a huge amount of energy has been absorbed by the string-bed. Therefore, lot of energy has been transferred back to the ball for the ball to rebound and as a result, produce higher COR (Fig. 3.3). While in the condition of higher string tension, there was less occurrence of deformation of string-bed observed during the impact (Fig. 3.5). The string-bed in higher tension reacted as a rigid surface where the string-bed becomes stiffer. This condition made the string-bed less deformable and as a result less energy was transferred back from string-bed to ball. Therefore, the COR of ball was lower for this condition (Fig. 3.3). Although lower sting tension was better compared to higher string tension in terms of producing higher COR, however, if the string tension was set extremely low (no tensional force acting on it), the string-bed will behave like a damper to the ball. This condition has to be prevented because the kinetic energy from the ball will be fully absorbed by the huge deformation of the string-bed. Hence, there will be massive energy losses due to the energy dissipated on the string-bed deformation. As a result, the ball will statically stop on the string-bed of the racket after the collision.

3.2.2 Effect on Racket Structural Stiffness on String Tension Performance

Figure 3.6 shows the relationship between string tensions and COR at the COM of the string-bed when the racket handle was anchored. Figure 4.7 indicated that the COR increased slightly when the string tension was decreased. Based on the results, COR was observed to be of maximum value at 14 lbs tension and of minimum value at 34 lbs tension with the COR reading of 0.407 and 0.383 respectively. Hence, the results show that reducing the tension of the string still could increase the COR performance even though there is effect from racket structural stiffness. As a conclusion, the relationship between string tension and COR performance still remains the same with lower string tension generating higher COR.

The comparisons between the COR obtained from head-anchored and handle-anchored conditions are shown in Fig. 3.7. Based on Fig. 3.7, it obviously indicates that the COR was lower when the racket handle was in an anchored condition compared to the head-anchored position. It can be concluded that COR performance dropped drastically when there is an effect from racket structural stiffness. Even though the COR from both anchored conditions show huge

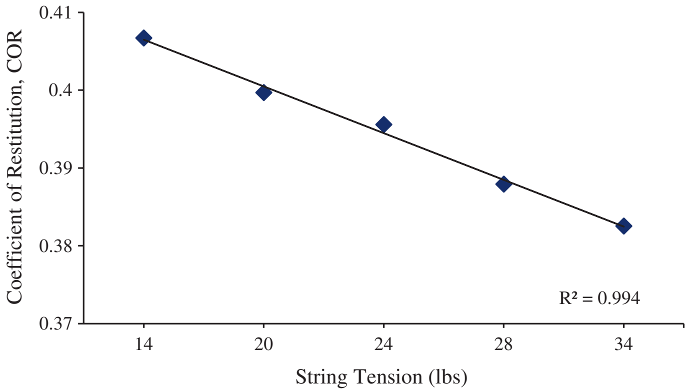

Fig. 3.6 The COR at different string tension (Handle Anchored)

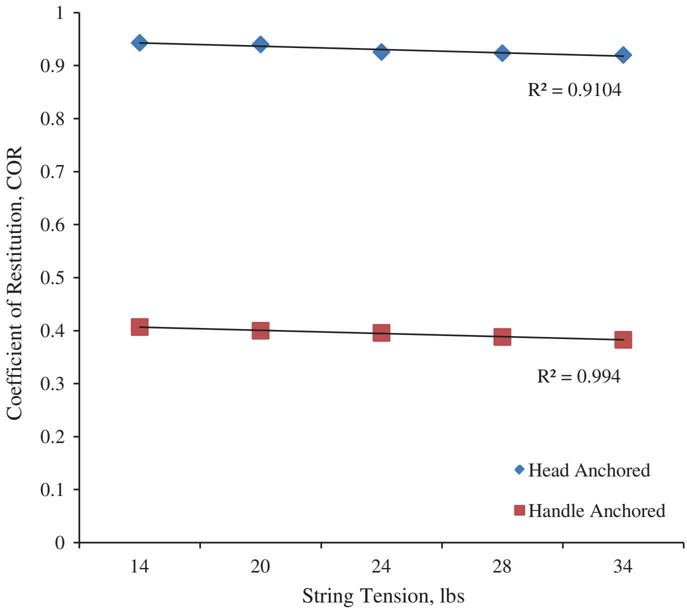

Fig. 3.7 Comparisons between COR from head-anchored and handle-anchored conditions

disparity of 58 % reductions, the correlation between string tensions and COR performance still remained the same. The reduction percentage was determined by comparing the COR results from both boundary conditions. Both results indicated that lower string tensions produced more COR compared to higher string tensions. Based on the results obtained in Fig. 3.7, it can be concluded that 58 % energy was lost during the collision due to the effect of racket structural stiffness. Therefore, one of the alternatives to increase COR performance was to use a stiffer racket where less energy will be lost and less racket shaft deformation will occur [1].

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Chapter 4
Stiffness of Badminton Racket

Abstract In this chapter, the effects of racket structural stiffness toward racket performance were widely discussed. Parametric studies were conducted using a validated finite element model of badminton racket consist of various shafts cross-sectional designs and lengths to determine the correlation between shaft design and racket structural stiffness toward racket performance. Based on the results, the design of racket shaft influence the structural stiffness of badminton racket and had a significant effect on the racket performance. The research finding shows a good argument that helps in the development of racket shaft design.

Keywords Racket Structural Stiffness · Deflection of Racket · Racket Shaft Design

4.1 Relationship Between Stiffness and Deflection of Badminton Racket

Generally, racket stiffness is one of the racket design parameters that affect the racket performance [1–3]. In theory, the stiffness of the racket could be affected either from material stiffness or structural stiffness of the racket. In this study, the main focus is to identify the effect of structural stiffness on racket performance rather than analysing the material effect.

In theory, deflection of the racket shaft can be expressed through the cantilever beam system. Defining the deflection is necessary in order to determine the structural stiffness of a racket as the relationship between the former and the latter can be evident as expressed in Hooke's Law. If the racket frame model is considered as a cantilever beam, the maximum deflection should be obtained at the tip of the beam as illustrated in Fig. 4.1. The equation of maximum deflection, y_{max} of racket shaft is defined by

$$y_{max} = \frac{PL^3}{3EI} \tag{4.1}$$

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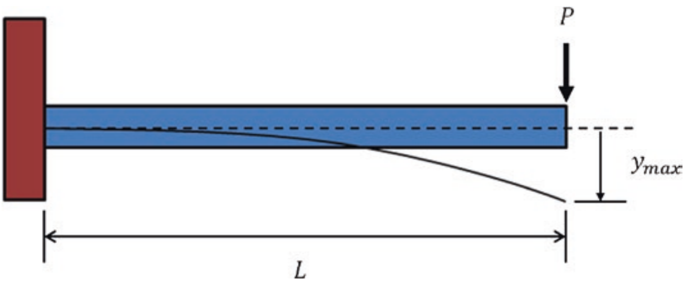

Fig. 4.1 Schematic diagram of cantilevered beam

where;

P is the concentrated load applied vertically to the free end of the racket shaft,
L is the length of the racket shaft,
E is the material's modulus of elasticity, and
I is the moment of inertia (MOI) of the racket shaft cross-section at its neutral axis.

The MOI of the shaft cross section, I and shaft length, L have been the focus of this study in which these parameters would be manipulated based on various shaft designs to determine their influence on the deflection of the racket [4, 5].

Stiffness of the badminton racket, k is one of the important parameters that would influence a racket's performance [3, 6, 7]. The relationship between stiffness, k and deflection of racket, y_{max} can be expressed in the Hooke's law equation,

$$k = \frac{P}{y_{max}} \tag{4.2}$$

where;

P is the concentrated load applied vertically to the free end of racket shaft,
y_{max} is the maximum deflection of the racket.

4.2 Effect of Shaft Cross-Sectional Design Toward Racket Performance

Several racket models consisting of different shaft cross-sectional designs and lengths were used to analyse the effects of racket structural stiffness on racket performance. It is worth noting that, each racket model was applied with the same material properties to allow no stiffness effect resulting from the material. The racket models used for the simulations were the isometric racket model consisting of various shaft designs. The properties of each racket model can be divided into

Table 4.1 Details of racket model shaft design

Shaft design	Dimension (mm)	Mass, m (mm)	Area moment of inertia, I (m^4)
Shaft cross-sectional diameter, d_o	5	64.3	30.68
	6	68.3	63.62
	7	73.1	117.86
	8	78.6	201.06
	10	91.8	490.87
Shaft cross-sectional thickness, t	0.50	59.9	54.24
	0.75	62.0	72.94
	1.00	63.9	87.18
	1.50	67.2	105.29
	2.00	69.8	113.88
Shaft length, l	100	58.4	87.18
	150	60.1	87.18
	200	61.7	87.18
	250	63.4	87.18
	300	65.0	87.18

three main groups according to the shaft designs which are of various shaft lengths l, shaft cross-sectional diameter d_o, and shaft cross-sectional thickness t.

The shaft lengths, l group were the racket models that have hollow shafts with the outer shaft diameter, d_o of 7 mm and shaft thickness, t of 1 mm. For the shaft cross-sectional diameter, d_o group, were those racket models described as solid shaft rackets with the shaft length, l of 267 mm. Meanwhile, the shaft cross-sectional thickness, t group was described as the hollow shaft racket with the outer shaft diameter, d_o of 7 mm and shaft length, l of 267 mm. Table 4.1 details out the design for each racket model used in the simulation.

4.2.1 Structural Stiffness of Badminton Racket

Based on the cantilever beam theory, several simulations were carried out in order to determine the structural stiffness of each racket models. Each racket model was anchored at the handle and a load of 0.5 N, P was applied at the tip of the racket head. The illustration of the simulation is depicted in Fig. 4.2. The maximum deflection of the racket was taken to determine the structural stiffness of each racket model.

Figure 4.3 shows the finite element simulation results for the maximum stress and maximum deflection of a badminton racket frame with a 7 mm cross-sectional diameter shaft (solid shaft). Based on Fig. 4.3, it was indicated that the maximum deflection was 6.79 mm located at the tip of the racket, while the maximum stress was 6.61 MPa spotted near to the anchored handle.

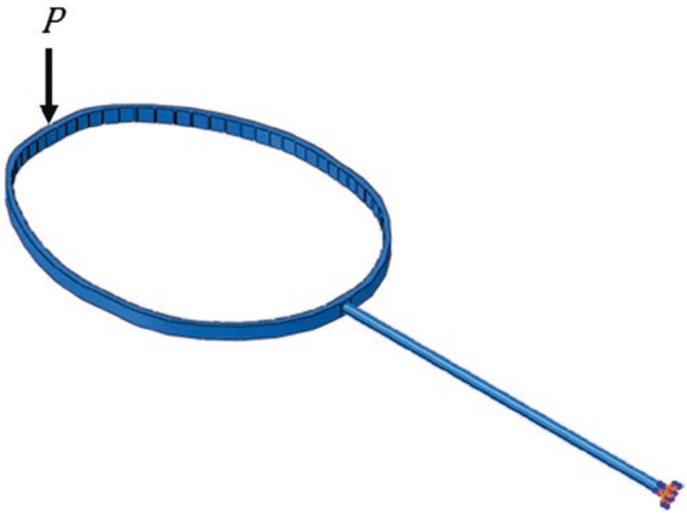

Fig. 4.2 Illustration of boundary condition for simulation of deflection of badminton

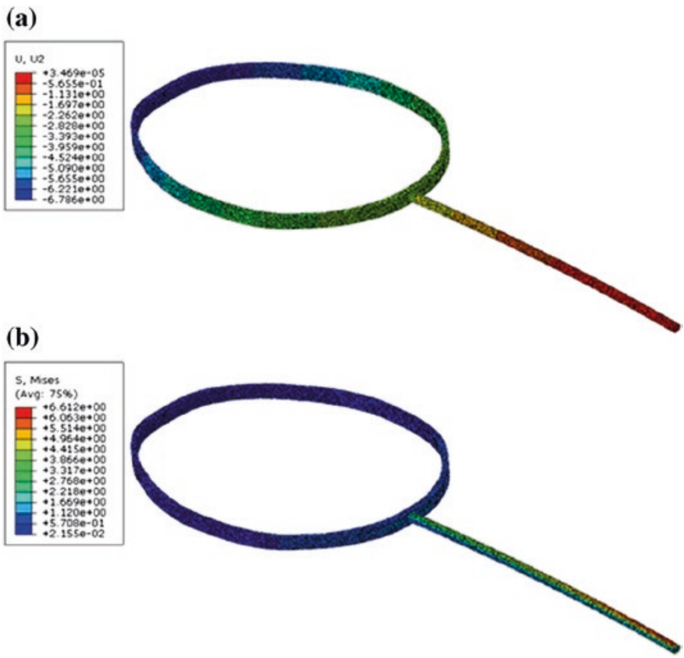

Fig. 4.3 Structural stiffness of badminton racket for 7 mm diameter-solid shaft, **a** Maximum deflection, **b** Maximum stress

Table 4.2 Deflection of badminton racket for various shaft designs

Shaft design	Dimension (mm)	Maximum deflection, y_{max} (mm)	Maximum stress, σ (MPa)	Maximum strain, ε (× 10^{-4}mm/mm)	Structural stiffness, k
Shaft cross-sectional diameter, d_o	5	24.47	18.71	7.21	0.020
	6	12.01	10.54	4.19	0.042
	7	6.79	6.61	2.62	0.074
	8	4.19	4.45	1.79	0.119
	10	2.00	2.37	0.94	0.250
Shaft cross-sectional thickness, t	0.50	9.58	11.1	4.30	0.052
	0.75	7.09	8.25	3.29	0.071
	1.00	5.99	6.76	2.70	0.084
	1.50	4.92	5.21	2.09	0.102
	2.00	4.43	4.83	1.92	0.113
Shaft length, l	100	2.09	5.44	2.17	0.239
	150	3.59	6.73	2.68	0.139
	200	5.15	6.76	2.70	0.097
	250	7.27	7.94	3.16	0.069
	300	10.38	9.26	3.69	0.048

Table 4.2 shows the results obtained in the simulation of the deflection of the badminton racket with different shaft designs. By analysis, these results indicated that stiffer structures can be categorised as structures that have less bending deformation when there a load was applied on it. Hence, a stiffer racket is referred to as a structure that has low deformation, low strain, and low stress. Referring to Table 4.2, there were two main design parameters that affected the structural stiffness of the badminton racket shaft which were the shaft length and the MOI of shaft cross-sectional area. Based on this analysis, it can be concluded that structural stiffness can be increased by reducing the shaft length and increasing the MOI of shaft cross-sectional area.

4.3 Parametric Study on Shaft Cross-Sectional Design

Parametric studies were conducted to analyse the effect of shaft cross-sectional design towards racket performance. The studies were carried out by simulating each racket model according to shaft designs of various shaft lengths l, shaft cross-sectional diameter d_o, and shaft cross-sectional thickness t. Generally, each simulation was performed with the same boundary conditions where the racket handle was anchored in order to determine the racket structural stiffness effect to the racket performances. The initial velocity, v_1 for the ball was set at 10 m/s and the rebound velocity, v_2 of the ball after impact was measured to determine the

Fig. 4.4 Illustration of collision simulation procedures

COR. The simulation results of each racket model were compared to find the correlation between shaft designs and racket performance. Figure 4.4 shows the illustration of boundary condition for the simulation of collision between the ball and the COM of string-bed.

4.3.1 Effect of Shaft Cross-Sectional Diameter

Figure 4.5 shows the relationship between COR at the COM of the string-bed of various shaft cross-sectional diameter, d_o when the racket handle was anchored. Referring to Fig. 4.5, the COR increases as the shaft diameter, d_o increases. Based

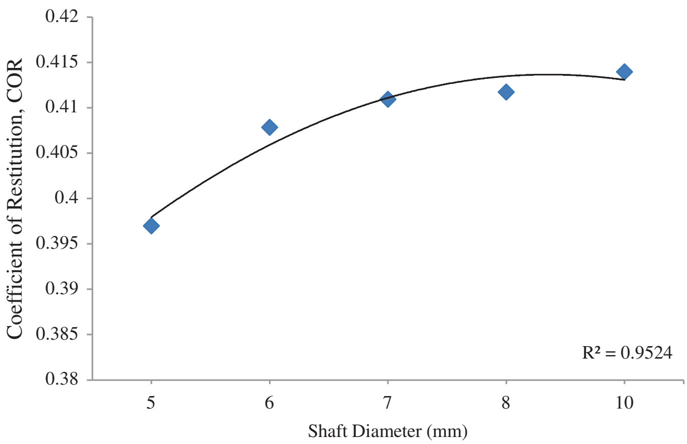

Fig. 4.5 The COR values at various shaft diameters

on the results, the maximum reading for COR was 0.413 at a diameter, d_o of 10 mm while the minimum COR was 0.397 at diameter, d_o of 5 mm.

The study of racket flexibility or stiffness is an interesting topic commonly discussed when designing superior rackets. Referring to Table 4.1, the shaft of 10 mm cross-sectional diameter, d_o has the highest area of MOI of cross-sectional shaft compared to other shaft designs. Thus, it shows that the shaft of 10 mm cross-sectional diameter d_o was the stiffest among the other shafts. In theory, the stiffer shaft absorbed less energy during the collision due to less deformation. Consequently, a good combination between string tension (lower tension) and structural stiffness (stiffer shaft) is necessary in order to generate higher COR.

4.3.2 *Effect of Shaft Cross-Sectional Thickness*

Figure 4.6 shows the relationship between COR and various shaft cross-sectional thicknesses, t when the racket handle is anchored. The graph shows that the COR increases as the shaft cross-sectional thickness, t increases. Based on Fig. 4.6, the shaft of 0.5 mm thickness, t produces minimum COR with the reading of 0.392 while the maximum COR was at the shaft of 2 mm thickness, t where the COR was recorded at 0.413. It can be observed that, with the increase of shaft cross-section thickness, t the COR slightly increased.

Both results from Figs. 4.5 and 4.6 clearly show that the racket's shaft cross-sectional design is one of the factors that affect the performance of a racket. Both figures indicated significant results where the COR increased with the increase in area of MOI of cross-sectional shaft design. Generally, the solid shaft has much higher MOI than the hollow shaft (Table 4.1). Thus, these results proved that the solid shaft is much stiffer than a hollow shaft.

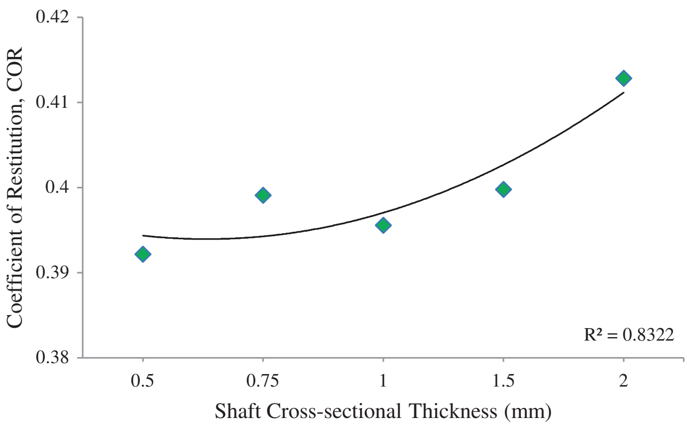

Fig. 4.6 The COR values at various shaft cross-sectional thicknesses (7 mm shaft diameter)

In addition, the shaft with a higher area of MOI has greater stiffness and produced higher COR that leads to better rebound velocity of the ball [5]. Although the solid shaft was adequate enough in producing higher COR, it tends to make the racket much heavier (Table 4.1). Therefore, to avoid a racket that is overweight, the other alternative was to change the material used for the racket. Usually, a good racket has good flexibility and is light weight. A heavy racket is not appropriate to be used because it could reduce the swing speed of a racket [4, 8].

4.3.3 Effect of Shaft Length

Figure 4.7 shows the effect of various shaft lengths on COR when the racket handle is clamped. It can be seen on Fig. 4.7, the COR slightly decreases when the shaft length, l increases. Based on the results, maximum COR was indicated at 100 mm of shaft length, l where the value was 0.455 while the minimum COR was spotted at 300 mm of shaft length, l with the COR value of 0.399. From the findings, it was clearly indicated that shaft length has significant effect to the performance of the racket.

In theory, the shaft structural stiffness can be increased by reducing the shaft length, l [4]. Although each shaft was made from the same material that produces equal material stiffness, designing a shorter shaft will make the shaft stiffer compared to the longer shaft [4]. As a result, a shorter shaft produces greater COR compared to a longer shaft. However, a shorter shaft is not a practical design to be employed during actual games. In this simulation, the racket was placed in a static condition whereby the racket was not swung. Therefore, the racket performance in this simulation was free from swing speed and swing weight effect. This

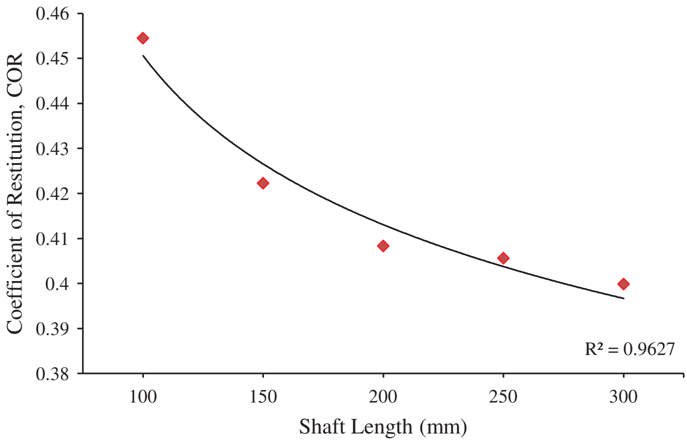

Fig. 4.7 The COR values at various shaft lengths (7 mm shaft diameter with 1 mm thickness)

was different with a real match situation where players are required to swing the racket. If the swing has to be considered, the swing speed and swing weight factor have to be analysed as well. In addition, shaft length, l is one of the factors that affect the swing weight and swing speed. Shorter shaft will reduce swing speed and swing weight of the racket and at the same time reduce shuttle rebound speed [4, 5].

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Chapter 5
Head Shape Design Analysis of Conceptual Badminton Racket

Abstract In this chapter, various racket head designs were evaluated to identify the parameter that influences the performance of the racket. Based on the analysis, performance of racket head design was affected by two main factors which are the area of string-bed and the deflection of sting. In-depth analysis on the relationship between string-bed surface area and deflection of string were discussed in greater details. Furthermore, this finding provides the understanding in development for greater head shape design in future.

Keywords Racket Head Design · Coefficient of Restitution

5.1 Finite Element Simulation of Racket Head Design

Several racket models consisting of various head designs were analysed in this simulation to investigate the effect of head design on racket performance. There are at least four different designs deployed, including the round, oval, isometric and rectangular design as shown in Fig. 5.1.

Generally, every head design has the tolerance of 197 mm in width, *w* and 249 mm in length, *l,* with the exception to the round design having a width, *w* and length, *l* measurement of 197 mm respectively. Table 5.1 shows the detailed measurement for each racket head design model.

There were at least four string-bed designs created in order to fit with four differing shapes of racket model heads. The details of each head's shape dimensions are presented in Table 5.2.

The boundary condition for each model in this simulation was anchored on the racket head. By anchoring the racket head, the analysis was focused on the design of the racket's shape rather than the whole racket system whereby the shaft stiffness effect can be neglected. Furthermore, string tension for all racket models were set as constants at a tension of 24 lbs. In general, this study performed the simulation of collision between the ball and string-bed area where the impact

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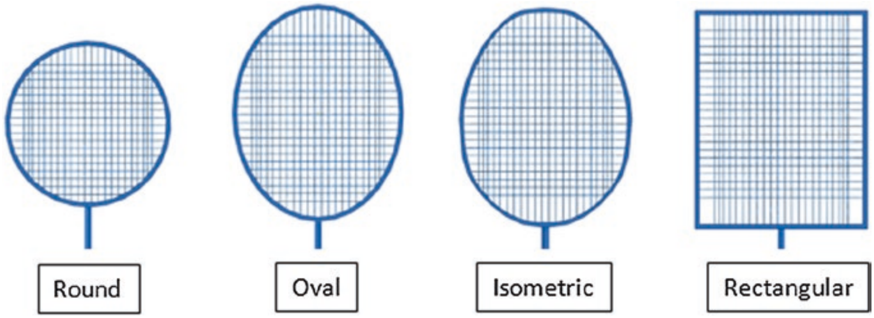

Fig. 5.1 Various designs of racket head models

Table 5.1 The detail measurement for each racket head design model

Racket head design	Head length, *l* (mm)	Head width, *w* (mm)
Round	197	197
Oval	249	197
Isometric	249	197
Rectangular	249	197

Table 5.2 String-bed surface area, *A* of various racket head design

Racket head design	Head length, *l* (mm)	Head width, *w* (mm)	String-bed surface area, *A* (mm^2)
Round	187	187	0.0275
Oval	239	187	0.0350
Isometric	239	187	0.0385
Rectangular	239	187	0.0447

location was selected at the COM of each head design. The ball was initially hit at the string-bed with an initial velocity, v_1 of 10 m/s. Then, the rebound velocity, v_2 after impact was obtained from each simulation in order to measure the COR.

5.2 Effect of Racket Head Shape Design Towards Racket Performance

Figure 5.2 shows the comparison between various racket head designs against the performance of COR.

Based on Fig. 5.2, the rectangular shape generated the highest COR of 0.9367 compared to the other head designs. The second highest COR was produced by the

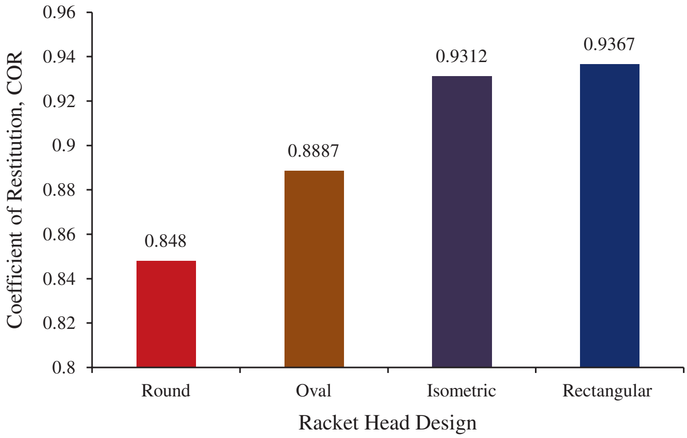

Fig. 5.2 The COR values of various racket head designs

isometric shape with COR of 0.9312 whereby this design is common in the current commercial head design for badminton rackets. Meanwhile, conventional head designs such as the oval and round shaped indicated lower COR values of 0.8887 and 0.8480 respectively. Thus indicating that the design of racket heads significantly affects the performance of the badminton racket. In this simulation, each racket model was anchored at the racket head and the impact point for the collision was located at the COM of each string-bed. Therefore, the COR performance was not affected by shaft structural stiffness. In theory, the COM is the softest area on the string-bed, thus generating the maximum string-bed deformation and resulting in higher COR. By considering the design factors, the size of the string-bed area was the main parameter that affected the performance of COR. Wider area of the string-bed produces softer COM and higher COR.

Based on Fig. 5.3, the rectangular shaped head design displayed the highest string deflection during the collision with a deflection of 11.36 mm while the round shaped head produced the lowest deflection of string-bed with 9.36 mm height. By considering a single string as a fully supported beam where both ends were anchored, the parameters that influenced the deflection of the string were the string thickness, material of string, string length and impact load. Since each model in this simulation used the same type of string (same material and thickness) and the same type of ball during collision (same impact load), therefore, the factor that affected the string-bed deflection was the area of the string-bed. Applying this theory on a bigger scale in string-bed condition, the area of the string-bed was the factor that affected the deflection where the length of the string was one of the components of area. Referring to Table 5.1, the rectangular shaped head has the biggest string-bed area compared to the other head designs. Thus, this reflects on the deflection of the string whereby a bigger area of string-bed produces higher deflection of string-bed. As a result, increasing the area of the racket head size can improve the performance of a racket by producing higher COR [1, 2].

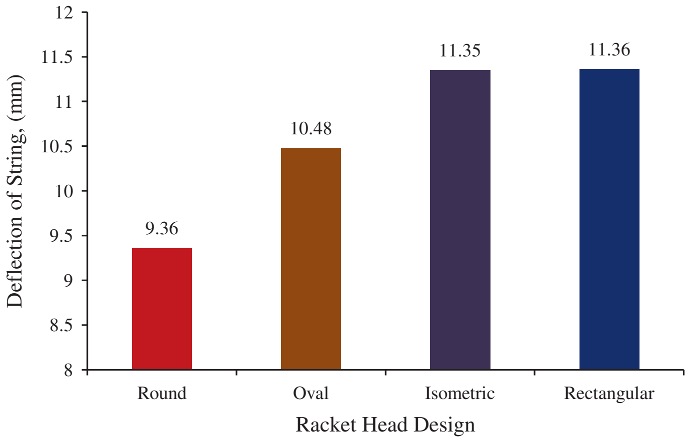

Fig. 5.3 The maximum deflection of string-bed for various head designs

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Chapter 6
Conclusion

This study managed to analyse several racket design parameters that affected the performance of badminton rackets. The understanding about the correlation between racket design parameters and racket performances were successfully obtained. As a result, string tension, racket structural stiffness and head design were proven to have major impact on the racket's performance. In conclusion, the rebound velocity of a shuttlecock can be increased by reducing string tension, increasing stiffness of racket shaft and enlarging the racket head size. Moreover, the findings helped to improve players' understanding regarding the design characteristics of a badminton racket. This understanding allows players to make a good decision in racket selection criteria. The finite element simulation proposed in this study could be used on the development of new badminton racket designs. This approach allows researchers to analyse several rackets designs in order to develop an optimal design. In order to develop 'superior racket' which produce higher rebound velocity of shuttlecock, several design characteristics should be followed. It was recommended the racket design should consist of low string tension, stiffer racket shaft and bigger area of string-bed (bigger head size).

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