

Linking Badminton Racket Design and Performance Through Motion Capture

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Abstract: Although badminton racket technology has advanced considerably, the relationship between design and performance are still rather poorly understood. By studying the dynamic behaviour of the racket during a stroke, different stroke parameters (e.g. racket speed at impact, maximum deflection) can be used to analyse the effects of different racket properties and different player skill levels. Motion capture is used to determine racket dynamics during a stroke. Standard kinematic analysis and an optimisation-based kinematic analysis implemented in the AnyBody Modelling System are compared. The optimised method proves effective in reducing position error and producing smoother kinematic profiles. Using this method, applications of studying racket dynamics through motion capture are presented. Analysing player skill level and racket stiffness can help link racket design and performance.

Keywords:

1 Introduction

Badminton is a game of speed, skill, and strategy. With record shuttlecock speeds reaching over 330 km/h, badminton is often claimed as “the fastest racket sport in the world” [1]. By comparison, the fastest tennis serve recorded is 246 km/h. The exact origins of the game are unknown; early forms of badminton were played in ancient China, England, Poland, and India [2]. The modern rules of the game are adapted from a version of the sport played in 1860s England, where the game first became known as badminton. Since then, badminton has become a “major sport in most countries of Northern Europe and Southeast Asia” [3]. The popularity of the game has also increased worldwide. The International Badminton Federation (now Badminton World Federation), founded by nine member countries in 1934, has grown to over 170 member countries. In 1992, badminton made its debut into the Olympic Games, which has been dominated by players from China, Indonesia, Malaysia, South Korea, and Denmark.

The badminton racket has also advanced over the years. The first rackets were made with wooden frames [3]. In the 1950s, steel and fibreglass began to replace wood. Eventually, these materials were replaced with aluminium, carbon, graphite, and boron. These advances in materials have led to stronger, stiffer, lighter rackets that can support higher string tensions, resulting in even faster game play. Despite these advancements, the link between the design and performance of the racket remains a mystery.

Modern racket designs have largely been developed using heuristic methods, relying on player intuition and manufacturer experience, and racket performance is subsequently assessed by player feedback. The badminton racket suffers from a severe lack of research, unlike other sports equipment like tennis rackets [4-10], golf clubs [11, 12], or baseball bats [13-15]. While racket sports all share some similarities, the differences between badminton and tennis are large enough to warrant racket design study specific to the sport of badminton.

The very first scientific investigation into the badminton racket was sponsored by Active Sportswear, owner of the Danish badminton brand, FZ Forza. The goals of the research project, launched in June 2007, were to build a better understanding of the interaction between player and racket by studying the dynamic behaviour of the racket during a stroke.

With an analytical approach, badminton rackets can perhaps be designed more efficiently and effectively. By establishing a better understanding of the relationship between the design of a racket and how it performs, the properties of a racket can be properly tuned in order to achieve the desired response. This can also help explain why different players like different rackets.

2 Badminton Basics

The performance requirements of a badminton racket are often described in terms of power and control. Power refers to the ability of the racket to impart speed to the shuttlecock at impact. Control is a measure of the racket’s manoeuvrability, the ability to direct the shuttlecock precisely where desired. As these qualities are based mostly on perception, it is necessary to assign some measurable quantities to these attributes, in order to perform a scientific study. For the purposes of this study, these performance characteristics are simplified into the following definitions. The racket’s “power” can be measured by the momentum transferred to the shuttlecock at impact, or more simply, the

shuttlecock exit velocity. The “control” of the racket can be loosely related to the consistency of the stroke, e.g. a measure of variation in the racket speed.

The badminton racket is composed of several parts: butt cap, handle, top cap, shaft, heart (or throat), frame (or head), and string bed (labelled in Figure 1). The important attributes of the racket can be divided into two main categories: mass properties and stiffness properties. The racket is often characterized by manufacturers in terms of balance and flexibility. Balance refers to the centre of mass location, measured from the butt end of the racket. Flexibility is a less specific measure, generally given as a rating from 1 (very flexible) to 5 (very stiff). While these give some information about the mass and stiffness properties of the racket to the consumer, there may be more useful measures to characterize the racket. For example, several studies have shown that swing speed is most highly correlated with the moment of inertia (MOI), or “swingweight”, of the sporting implement [8-10, 13-15]. This indicates that the racket’s MOI is the deciding factor in how fast the racket can be swung, rather than the total mass of the racket.

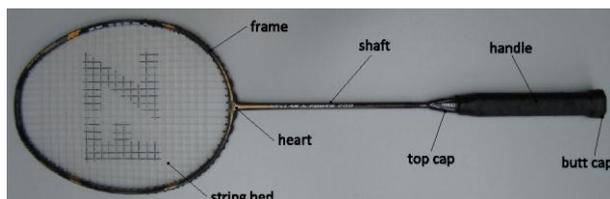


Figure 1. Anatomy of a badminton racket.



Figure 2. Basic phases of a badminton stroke: backswing (Frames 1-7), forward swing (Frames 7-10), contact (Frame 10), and follow-through (Frames 11-12).

The badminton stroke consists of four basic phases (illustrated in Figure 2): backswing, forward swing, contact, and follow-through. During a stroke, the inertial forces generated from the high accelerations cause the racket to bend. As the racket is swung forward, the racket bends backward and then recovers forward, returning to its original shape as impact occurs. This deformation can therefore provide some additional velocity to the racket at impact and affect the timing and dynamics of the racket during the stroke. The dynamics of the racket therefore consists of flexible-body motion as well as rigid-body motion.

By studying the dynamics of the stroke, the key characteristics of the racket can be identified. The relationships between the properties of the racket, the style and skill of the player, and the performance aspects of power and control can then also be determined by analysing the dynamic behaviour of the racket during the stroke.

3 Experimental Methods

To study the dynamic behaviour, the movement of the racket during the stroke can be measured using motion capture.

Motion capture is a technique used to digitally record movement in 3D space. The motion capture system involves several infrared cameras that pick up the motion of reflective markers placed on the object of interest. Through triangulation methods, the motion capture software is able to reconstruct the motion of markers in 3D if the marker is seen by at least two cameras during the motion.

A motion capture system (Oqus, Qualisys AB, Gothenburg, Sweden) of eight cameras was used to record ten trials of a smash stroke performed by an advanced player at the maximum rate of 500 frames per second (fps). Eight 10 mm spherical markers were placed on the racket, five on the handle and three on the head, illustrated in Figure 2.

Since motion capture measures only positions directly, velocities and accelerations are obtained by differentiating the position data with respect to time. Position data of the markers were passed through a zero-phase, second-order, low-pass Butterworth filter with a cut-off frequency of 60 Hz and subsequently fitted with a 6th order B-spline with the AnyBody Modelling System (AnyBody Technology, Aalborg, Denmark) to enable calculations of derivatives of measured marker trajectories.

4 Model

The marker trajectories were then used to determine 3D rigid body kinematics of the racket through (a) standard kinematic analysis and (b) an optimisation-based kinematic analysis, available in the AnyBody Modelling System [16].

The flexible racket was modelled as two rigid-body segments, the handle H and the frame F , connected by a universal joint, J , located at the base of the shaft, where rotation is about the y -axis and z -axis (Figure 3). This creates a mechanical system with a total of eight rigid-body degrees-of-freedom (dof) against the 24 coordinates measured by the eight markers.

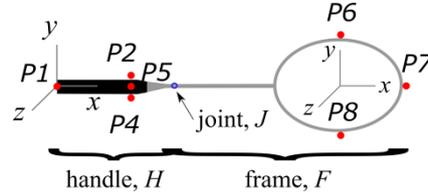


Figure 3. Illustration of marker placement and definition of body-fixed coordinate systems for the racket model used for marker processing.

The resulting kinematic over-determinacy is problematic in standard kinematic analysis. Therefore, only three handle markers ($P1$, $P2$, and $P4$) were used to define the body and determine the kinematics of the handle. These markers were chosen because they were seen most reliably by the cameras. Markers $P2$ and $P4$ defined the y -axis, and the x -axis is formed by $P1$ and the midpoint between $P2$ and $P4$. Markers $P6$ and $P8$ were used to define the frame segment. Angular velocities and accelerations were determined by central finite difference.

In the optimisation-based method, the kinematic over-determinacy can be used to reduce the measurement errors. Kinematic data for all markers were used to minimize the distance between the measured and modelled marker position to improve positioning of the racket segments. Details of this approach can be found in Andersen *et al.* [16].

4.1 Racket head speed

Since racket power is defined here as the momentum transferred to the shuttlecock at impact, determining the momentum of the racket just before impact is important to assessing racket power. Several factors contribute to racket momentum, including the velocity of the impact location on the racket head. This velocity can be determined using simple kinematic calculations.

The velocity of any point P along the racket frame can be expressed as:

$$\mathbf{v}_P = \mathbf{v}_J + \boldsymbol{\omega}_F \times \mathbf{r}_P \quad (1)$$

where \mathbf{v}_J is the velocity of joint J , $\boldsymbol{\omega}_F$ is the angular velocity of the racket frame, and \mathbf{r}_P is the position vector of point P from J . Similarly, the velocity of the joint J can be expressed as

$$\mathbf{v}_J = \mathbf{v}_{P1} + \boldsymbol{\omega}_H \times \mathbf{r}_J \quad (2)$$

where \mathbf{v}_{P1} is the velocity of point $P1$, $\boldsymbol{\omega}_H$ is the angular velocity of the racket handle, and \mathbf{r}_J is the position vector of point J from $P1$. Combining Eqs. (1) and (2), the velocity of point P can then be expressed:

$$\mathbf{v}_P = \mathbf{v}_{P1} + \boldsymbol{\omega}_H \times \mathbf{r}_J + \boldsymbol{\omega}_F \times \mathbf{r}_P \quad (3)$$

Head speed is defined here as the velocity normal to the face of the racket, calculated in the body-fixed coordinate system of the racket frame, shown in Figure 2. In this paper, ‘‘head velocity’’ refers to the total velocity vector of the head centre, while ‘‘head speed’’ refers to the normal component of this velocity vector. The head centre is defined here as the origin of the body-fixed coordinate system of the racket frame. From Eq. (3), the velocity of the head centre \mathbf{v}_C is given by:

$$\mathbf{v}_C = \mathbf{v}_{P1} + \boldsymbol{\omega}_H \times \mathbf{r}_J + \boldsymbol{\omega}_F \times \mathbf{r}_C \quad (4)$$

where \mathbf{r}_C is the position vector of the head centre from J . The z -component of this velocity represents the head speed. Written explicitly, the head speed is:

$$v_{head} = v_{P1z} - \omega_{Hy} r_{Jx} - \omega_{Fy} r_{Cx} \quad (5)$$

where v_{PIz} represents the z -component of the velocity of PI ; r_{Jx} and r_{Cx} represent the x -component of the position vectors \mathbf{r}_J and \mathbf{r}_C , respectively; and ω_{Hy} and ω_{Fy} represent the angular velocities of the racket handle and frame about the y -axis, respectively.

The total head speed can be separated into translational and rotational components. From Eq. (5), the translational contribution is given by the velocity of marker PI , and the rotational contribution comes from the angular velocities of the racket handle and frame. These components represent the translation and rotation of the racket alone, without considering the body segments.

4.2 Racket head deflection

The elastic deflection of the racket is taken at the head centre. Only the component normal to the racket face (in the z -direction) is considered here. The racket head deflection, w_{head} , is given by:

$$w_{head} = \mathbf{A}_{handle} \mathbf{p}_C \cdot [0 \ 0 \ 1] \quad (6)$$

where \mathbf{A}_{handle} is the transformation matrix for the handle segment from global to local coordinates, and \mathbf{p}_C is the position vector in global coordinates for the head centre.

The elastic velocity can also be determined. Assuming that the racket handle is completely rigid, the elastic velocity can be found by taking the difference between the motion of the handle and frame.

$$\mathbf{v}_{elastic} = (\boldsymbol{\omega}_F - \boldsymbol{\omega}_H) \times \mathbf{r}_C \quad (7)$$

Focusing again on the z -component of the velocities, the elastic velocity contribution to the head speed can be written explicitly:

$$v_{elastic} = r_{Cx} (\omega_{Fy} - \omega_{Hy}) \quad (8)$$

For all rackets used, $r_{Jx} = 0.220$ m and $r_{Cx} = 0.325$ m. All velocities reported here are presented in the body-fixed coordinate system shown in Figure 3.

5 Results

The kinematics of the racket during the stroke, determined by standard kinematic analysis and the optimisation-based kinematic analysis, were compared. The racket deformation profiles over the stroke, determined by the two methods, were also compared.

Linear and angular velocities of the frame and handle segments during the stroke are shown in Figures 4 and 5, respectively, as calculated by standard and optimised kinematic methods. For the frame, linear velocities are very similar between the two methods, while angular velocities are clearly smoother using the optimised method. Linear velocities of the handle are relatively similar between the two methods, but the optimised method shows definite improvement over the standard method in the angular velocities, especially about the x -axis of the handle.

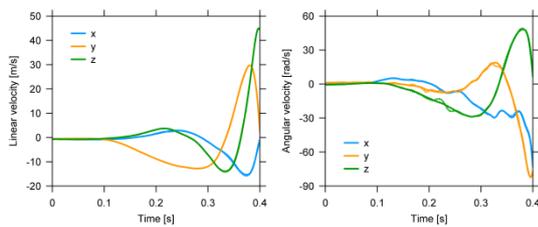


Figure 4. Linear and angular velocities of the racket **frame** segment during a stroke, as calculated by standard (dashed) and optimised (solid) kinematic methods. Impact occurs at $t=0.4$ s.

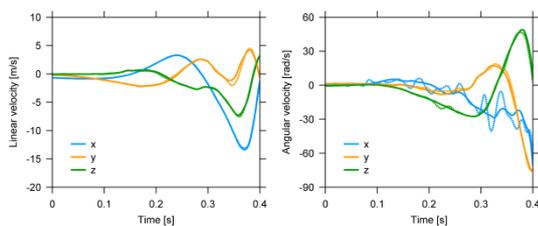


Figure 5. Linear and angular velocities of the racket **handle** segment during a stroke, as calculated by standard (dashed) and optimised (solid) methods. Impact occurs at $t=0.4$ s.

From the kinematics of the frame segment, the racket head speed at impact can be determined from the z -component of the linear velocity (45.1 m/s), and the y -component of angular velocity (80.9 rad/s) is indicative of the rotational contribution to the total head speed at impact.

Combining the kinematic data of the frame and handle segments, the elastic behaviour of the racket during the stroke can be determined from the orientation of the frame relative to the handle. Figure 6 shows the elastic deflection and velocity at the racket head.

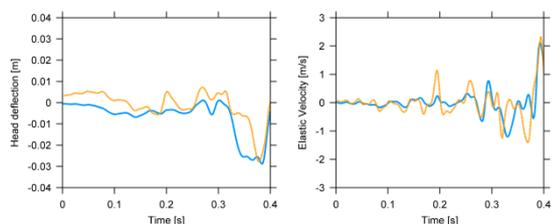


Figure 6. Elastic deflection and velocity of the racket head during a stroke, as calculated by standard (dashed) and optimised (solid) methods. Impact occurs at $t=0.4$ s.

Although both methods produce somewhat noisy results, the plots give a general idea of the magnitude of the maximum deflection (25 mm), deflection at impact (0 mm), and elastic velocity at impact (1.6 m/s). For a total head speed at impact of 45 m/s, this comes out to about a 3.7% increase in impact head speed due to racket elasticity.

For a more concrete assessment of the two methods, the error in racket marker location was calculated. Deviations of the measured marker locations from the rigid body racket model are expressed as a magnitude of error in position, shown in Figure 7.

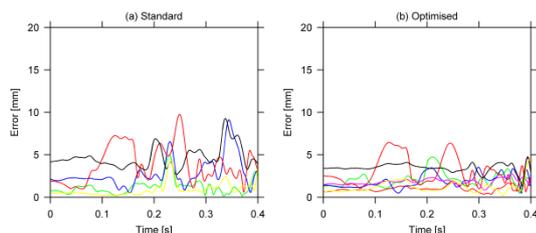


Figure 7. Magnitude of the position error between measured and model marker locations of all racket markers, using (a) standard and (b) optimised kinematic methods.

The optimised approach appears to be an improvement over the standard approach, with a peak error of 6.5 mm versus 9.7 mm. The optimised method also leads to improved kinematic data, especially in angular velocities and deflection profiles.

6 Applications

Using motion capture, the dynamic behaviour of a racket during the stroke can be observed to evaluate performance of different players or different rackets. By processing the motion capture data using the optimisation-based kinematic analysis, greater accuracy in the kinematic data is ensured. Two example applications of analysing performance through motion capture are given here. First, differences are observed with players of varying skill level, then with rackets of varying stiffness.

6.1 Player skill level

Motion capture data for a smash stroke performed by two advanced players (A and B) and two novice players (C and D) were recorded. Racket head speed profiles for each player are shown in Figure 8.

Players of different skill levels generate different racket head speeds at impact. Players A and B achieve speeds of around 45 m/s, whereas players C and D only reach 20-25 m/s. The relative translational and rotational contributions to impact head speed also vary between players. Linear velocities of the handle base account for 5-15% of the total head speed for players A and B, and 15-25% of the total head speed for players C and D. Advanced players therefore used more rotation than the novice players to generate their higher racket head speeds.

Other differences in technique can also be observed. Among the advanced players, player B has a much shorter backswing than player A. Advanced players also have a much more distinctive backswing phase; the backswing in the novice players are somewhat drawn out and less pronounced.

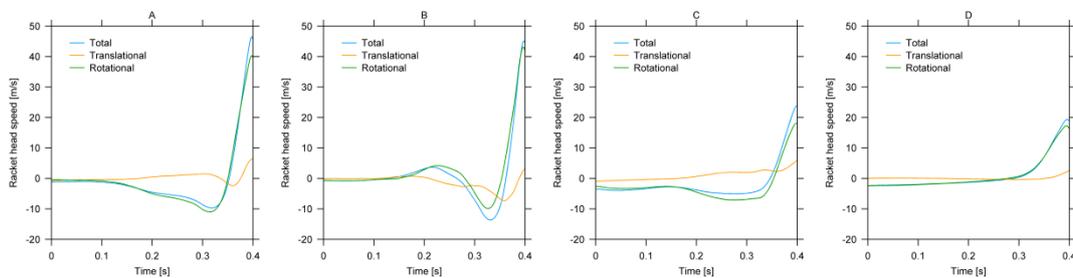


Figure 8. Racket head speed profiles, with translational and rotational contributions, for players A, B, C, and D. Impact occurs at $t=0.4$ s.

6.2 Racket stiffness

Motion capture data for a smash stroke performed by two advanced players with two different rackets were recorded. Racket 1 was ultra-stiff, with a carbon-fibre shaft of fibres all aligned at 0° ; and Racket 2 was ultra-soft, with the shaft made from carbon fibres at 45° only. Elastic deflection and velocity profiles for players E and F are shown in Figure 9.

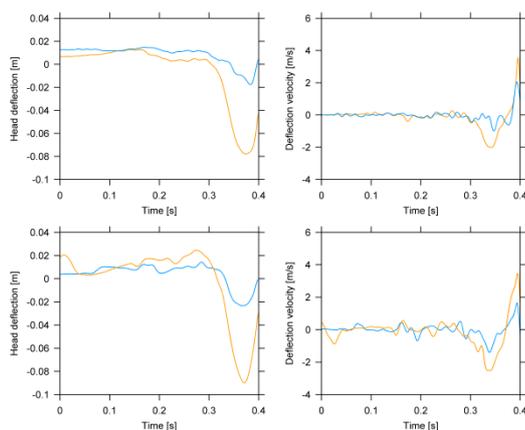


Figure 9. Elastic deflection and velocity profiles for players E (top) and F (bottom). Impact occurs at $t=0.4$ s.

The maximum deflection increases nearly 4 times with the ultra-soft racket compared to the ultra-stiff racket (8 vs 2 cm). The deflection at impact is near-zero with the ultra-stiff racket, and around -4 cm with the ultra-soft racket. A negative deflection indicates that the racket has not yet returned to its undeformed state at the time of impact. This may

have implications on racket control, where striking the shuttlecock with a racket that is still in a very deflected state may lead to imprecision in the desired shuttlecock trajectory.

The elastic velocity at impact is also much higher with the ultra-soft racket than the ultra-stiff racket, 3 vs 2 m/s, indicating that the more flexible racket can provide a greater boost to the impact head speed. However, a larger elastic velocity at impact could also cause greater difficulty in precise timing of the impact. One can imagine that a racket that is too flexible would be quite unwieldy.

7 Conclusions

The relationship between racket design and performance can be better understood by studying the dynamic behaviour of the racket. Motion capture can be used to determine racket kinematic and deformation profiles during the stroke.

Position data from motion capture can be filtered, splined, and differentiated using the AnyBody Modelling System. In addition, a rigid-body model of the racket can be created in order to optimise the location of the markers throughout the stroke. Using this optimisation-based approach, data from all available markers can be used rather than discarding some marker information to solve the problem of over-determinacy. This leads to smoother kinematic profiles, which can be difficult to attain in high speed applications such as a badminton smash stroke. This method is also helpful in situations where markers go missing due to obstruction by the hand at the handle or to ultra high velocities at the racket tip.

The optimisation-based method provides greater accuracy of the dynamic profiles, so that detecting small differences between different playing styles or different racket properties is possible. Accuracy near the time of impact is especially important for validating models of racket-shuttlecock impact and for determining consistency in the stroke.

Motion capture can be used to investigate several aspects of the racket-player interaction, including the effects of different player styles and different racket stiffnesses. Advanced players generate much higher racket head speeds at impact, by producing much higher angular velocities than novice players. Flexible rackets offer greater elastic velocities at impact, providing more of an additional boost to the impact racket head speed than stiff rackets. This indicates that more elastic rackets provide more “power.” However, a greater elastic velocity at impact may also introduce greater uncertainty in the precise positioning of the racket and timing of contact with the shuttlecock, causing a reduction in “control” of the racket. Advanced players appear to value control over power, preferring stiffer rackets than more flexible ones. This may also be due to the fact that the extra velocity provided by the racket’s elasticity is relatively small compared to the speeds they can generate with their technique.

Further studies involving other racket properties and their effects on racket power and control can also be performed using motion capture. Control is defined here as a measure of variation, or consistency in the stroke, which would require a large number of trials and highly accurate measurements. By piecing together the observations on racket properties, the player’s skill and style, and performance, an understanding of the intricate interaction between player and racket can be established and used to improve design and customization of the badminton racket.

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