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Computer aided performance prediction and estimation system for a tennis racket in terms of power and stability

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ABSTRACT: Since tennis should be learned from experience, it is a subjective thing. Thus, it is quite difficult to see how the physical properties of a tennis racket have an effect on the performance of a player. This paper introduces a computer aided prediction and estimation system for racket performance in terms of power and stability or ball control. The predicted results with a forehand stroke model could explain the difference in mechanism of performance between the new type racket with active piezoelectric fibers and the conventional passive rackets. It shows that this new type racket provides higher coefficient of restitution over the whole area of the string face and also gives larger rebound power coefficients at the topside and bigger powers on the whole area of the string face but the difference is not so large. It was found that the racket-related improvements in play are relatively small and the players themselves continue to improve, accordingly there is a gap between a perception and reality.

INTRODUCTION

According to the recent news (McClusky, 2003), several former grand slam champions, including John McEnroe, Boris Becker and Martina Navratilova, sent a letter to the ITF encouraging the governing body to revisit the question of rackets. In the letter, the players wrote that tennis has become "unbalanced and one-dimensional." "Rackets today allow players to launch the ball at previously unthinkable speeds, approaching 150 mph." "The reason for this change is clear to see," they wrote. "Over a period of years, modern racket technology has developed powerful, light, wide-bodied rackets that are easier to wield than wooden rackets were and have a much larger effective hitting area. There's even a racket with a chip built into the handle that allows the racket to stiffen upon impact with the ball. All of this technology has led to major changes in how the game is played at the top level." However, since tennis should be learned from experience, it is a subjective thing. Thus, it is quite difficult to see how the physical property of a tennis racket has an effect on the performance of a player (Ashley, 1993; Davis, 1997; Kawazoe, 1989, 1992, 1997b, 2000; Kawazoe *et al.* 1997, 2003).

This paper introduces a computer aided prediction and estimation system for racket performance in terms of power and stability or ball control. This system is based on the experimental identification of the dynamics of the ball-racket-arm system and the approximate nonlinear impact analysis with a simple swing model. It can predict the various factors associated with the frontal impact, such as impact force, contact time, deformation of ball and strings, and also estimates the racket performance such as the coefficient of restitution, the rebound power coefficient, the post-impact ball velocity and the racket stability as well as the sweet areas using a small computer. The predicted results explain the difference in mechanism of performance in terms of power and stability or ball control between the new type racket with active piezoelectric fibers (Kotze *et al.* 2003) and the conventional passive rackets, and also shows the relationship between the racket-related improvements in play and the improvement of players themselves. Figure 1 shows a racket with active piezoelectric fibers and a chip that allows the racket to stiffen upon impact with the ball according to McEnroe (McClusky, 2003).

PREDICTION OF IMPACTS AND COEFFICIENT OF RESTITUTION BETWEEN BALL AND RACKET

Figure 2 shows the non-linear impact model of a ball-string system. The approximate impulse could be obtained using the mass m_B of a ball, the reduced mass M_r of a racket-arm system at the hitting location, and the pre-impact velocity (V_{Bo} - V_{Ro}) between a ball and a racket. The contact time T_C could be obtained using m_B, K_{GB} of the stiffness of ball/strings system and M_r. The relationship between the equivalent force F_{mean} and corresponding K_{GB} against the pre-impact velocity (V_{BO} - V_{RO}) is given by

$$F_{mean}= (V_{BO}- V_{RO})(1+ e_{BG})\, m_B^{1/2}\, K_{GB}^{1/2} / \pi(1+ m_B /M_r)^{1/2} \qquad (1)$$

where e_{BG} is the measured coefficient of restitution when a ball strikes the clamped string bed for estimating energy loss of the ball and the strings.

On the other hand, from the approximated restoring force F_{GB} can be expressed as the function of the stiffness K_{GB} in the form

$$F_{GB} = f(K_{GB}). \qquad (2)$$

From Eq.(1) and Eq.(2), K_{GB} and F_{mean} against the pre-impact velocity can be obtained, accordingly the contact time T_C can also be determined against the pre-impact velocity. A comparison between the measured contact times during actual forehand strokes and the calculated ones when a ball hits the center of the strings face of a conventional type racket, showing a good agreement (Kawazoe,Y., 1993). Since the force-time curve of impact has an influence on the magnitude of racket frame vibrations, it is approximated as a half-sine pulse, which is almost similar in shape to the actual impact force. The mathematical expression is

$$F(t) = F_{max} \sin(\pi t/ T_c) \quad (0 \leqq t \leqq T_c) \qquad (3)$$

where $F_{max} = \pi F_{mean}/2$.

The vibration characteristics of a racket can be identified using experimental modal analysis (Kawazoe, 1989, 1992, 1994a, 1994b, 1997a) and the racket vibrations can be simulated by applying the impact force-time curve to the hitting portion on the string face of the identified vibration model of the racket. When the Fourier spectrum $S_j(2\pi f_k)$ of the impact force component of k-th frequency f_k applies to the point j on the racket face, the amplitude X_{ijk} of k-th mode component at point i is obtained using the residue r_{ijk} of k-th mode between arbitrary point i and j (Kawazoe, 1993). Figure 2 shows non-linear impact model of a ball-string system, and Fig. 3 string meshes for vibration model and impact locations for impact simulation. Figure 4 shows the examples of the calculated shock shape during impact, where the ball strikes the center on the string face at a velocity of (a) 20 m/s and (b) 30 m/s, respectively. Figure 5 shows the example of predicted vibration amplitude of the racket struck by a ball.

The energy loss due to the racket vibration induced by impact can be derived from the amplitude distribution of the vibration velocity and the mass distribution along the racket frame. The coefficient of restitution e_r (COR) can be derived considering the energy loss E_1 due to racket vibrations and E_2 due to large deformations of a ball and strings corresponding to the coefficient e_{BG}. If a ball collides with a racket at rest ($V_{Ro}= 0$), the coefficient of restitution e_r corresponding to the total energy loss E (= $E_1 + E_2$) can be obtained. The ratio of rebound velocity against the incident velocity of a ball when a ball strikes the freely suspended racket ($V_{Ro}= 0$) is defined as the rebound power coefficient e written as Eq.(4), because the coefficient e is often used to estimate the rebound power performance of a racket experimentally in the laboratory. A comparison between the measured e and the predicted e when a ball hits a freely-suspended racket (about 30 m/s) showed a good agreement between

(a) Is-10(Head)

(b) Piezoelectric fibers

Fig.1 Racket with active piezoelectric fibers.

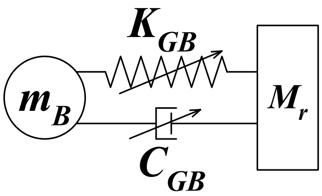


Fig.2 Non-linear impact model of a ball-string system.

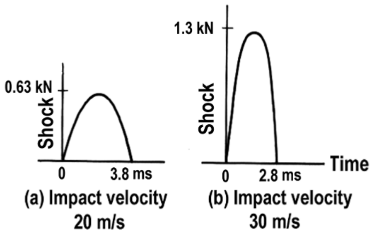
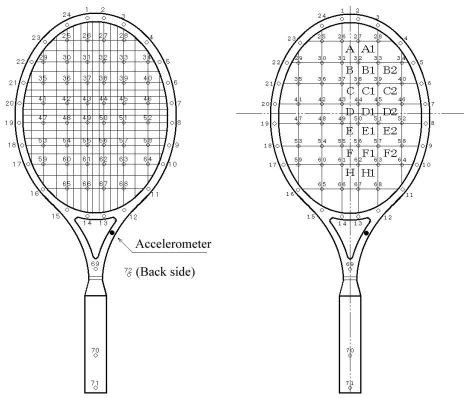


Fig.4 Calculated shock shape when a ball strikes the center on the String face.



(a) (b)

Fig.3 String meshes for vibration model and impact locations for impact simulation.

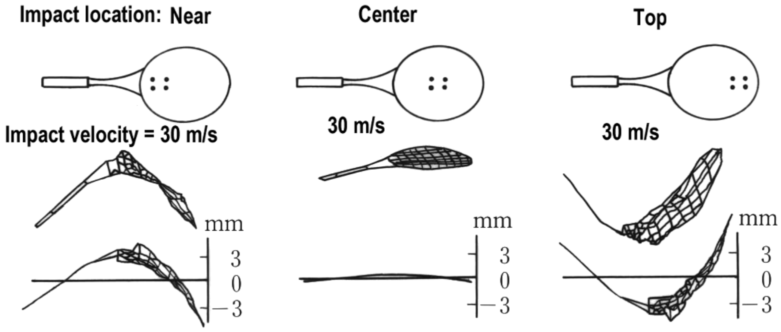


Fig.5 Predicted initial amplitude of 1st mode component of racket frame vibrations.

them (Kawazoe, 1993).

$$e = -V_B \;/\; V_{BO} \;=\; (\,e_r\; - m_B/M_r)\;/(1+ m_B/M_r\,) \qquad (4)$$

PREDICTION OF POST-IMPACT BALL VELOCITY

The power of the racket could be estimated by the post-impact ball velocity V_B when a player hits the ball. The V_B can be expressed as Eq.(5). The pre-impact racket head velocity V_{RO} is given by $L_X\,(\,\pi N_s\,/\,I_s\,)^{1/2}$, where L_X denotes the horizontal distance between the player's shoulder joint and the impact location on the racket face, N_s the constant torque about the shoulder joint, and I_s the moment of inertia of arm/racket system about the shoulder joint. Figure 6 shows a simple forehand ground stroke swing model (Kawazoe, 1997b; Kawazoe *et al.* 1997).

$$V_B \;=\; -\,V_{Bo}\;\; e \;\;+ V_{Ro}\,(\,1 + e\;) \qquad (5)$$

BALL CONTROL AND RACKET STABILITY

Control is simply being able to put the ball where desired, but it is the most difficult to analyze. Designing equipment to optimize control for all types of players is nearly impossible. Tennis players have a wide variety of styles from smooth stroking to whippy and wristy. These style differences require different equipment to optimize control. However, one characteristic required for control is stability. Stability refers to the ability at impact to maintain its swing path without deviation. Stability is also defined as the ability to resist off center hits. It is desirable to maximize stability (Davis, 1997). We can estimate the racket stability by the amount of twist or turn about the long axis when the ball hits the strings at the location away from the long axis of a racket as shown in Fig.7. The amount of racket twist vs. distance of the impact location from the long axis, assuming that there is no friction between the hand and the racket grip shows that the twist angle of light weighted racket is larger thanthat of conventional heavier weighted racket at the near side from the center on the racket face away from the long axis; however, there is no big difference at the topside away from long axis between them. Since the hitting areas for the ground stroker and the service are usually at the topside from the center, there is no big disadvantage for the light weighted racket for the ground stroker and the server.

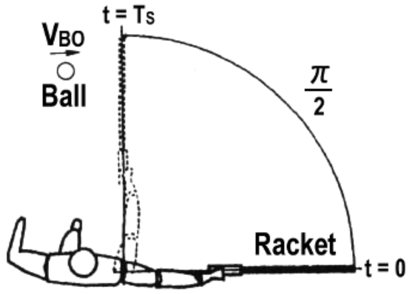


Fig.6 Forehand stroke model

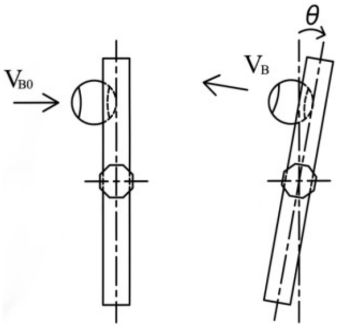


Fig.7 Twist or turn about the long axis when the ball hits the strings.

ESTIMATION OF THE PERFORMANCE IN TERMS OF POWER

Now we can predict the various factors associated with the tennis impact when the impact velocity or swing model and the impact locations on the racket face are given. Furthermore we can estimate the performance of the various rackets with different physical properties. Table 1 shows the physical properties of three representative rackets (Intelligent fiber Is-10, Lightest racket TSL, Highest power racket EOS120A among available passive rackets), where the mass M_R of racket includes strings, I_{GY} denotes the moment of inertia about the center of mass, I_{GR} the moment of inertia about the grip 70 mm from grip end and I_{GX} the moment of inertia about the longitudinal axis of racket head. Table 2 shows the result of experimental vibration modal analysis and Fig.8 shows the modal shapes of intelligent fiber racket Is-10. The 1st mode frequency of racket Is-10 is higher than those of the other rackets considering the other frequencies. It is the reason that the piezo-electricity is embedded at the antinode of 1st vibration mode of racket frame.

Figure 9 shows the comparison of the predicted coefficients of restitution e_r between three rackets during forehand stroke. It is seen that er of intelligent fiber racket is higher than that of a lightest racket TSL and quite high even at the top side off-center on the string face, because the energy loss due to frame vibrations are rather small. The intelligent fiber racket also gave larger rebound power coefficients particularly at the topside. Figure 10 shows the predicted post-impact ball velocity VB at each hitting location along the longitudinal centerline on the racket face. Figure 11 shows the difference in sweet area in terms of racket power or VB between three rackets compared to a wooden racket (375 g). It is seen that VB of intelligent fiber racket is higher than that of a lightest racket TSL and quite high even at the top off-center on the string face. The post-impact ball velocity VB of racket is-10 is 5 % larger at the center hitting and 14 % larger at the top off-center hitting compared to wooden racket. Although this new type racket surely provides higher coefficient of restitution on the whole area of string face and also gives larger rebound power coefficients at the topside and bigger powers on the whole area of string face but the difference was not so large.

Table 1 Physical properties

Racket	IS−10	TSL	EOS120A
Total length	700 mm	710 mm	690 mm
Face area	740 cm^2	742 cm^2	760 cm^2
Mass	241 g	224 g	292 g
Center of gravity from grip end	382 mm	379 mm	363 mm
Moment of intertia I_{GY} about Y axis	11.2 gm^2	11.0 gm^2	14.0 gm^2
Moment of intertia I_{GR} about grip	36.7 gm^2	32.4 gm^2	39.0 gm^2
Moment of intertia I_{GX} about X axis	1.51 gm^2	1.21 gm^2	1.78 gm^2
1st frequency	205 Hz	200 Hz	137 Hz
Strings tension	55 lb	55 Ib	79 Ib
Reduced mass (center)	179 g	152 g	206 g

Table 2 Frequencies of vibration modes of 3 rackets (Hz)

	Is-10	TSL	EOS120A
1st	205 Hz	200 Hz	137 Hz
2nd	400 Hz	474 Hz	322 Hz
3rd	493 Hz	557 Hz	391 Hz
4th	532 Hz	581 Hz	605 Hz

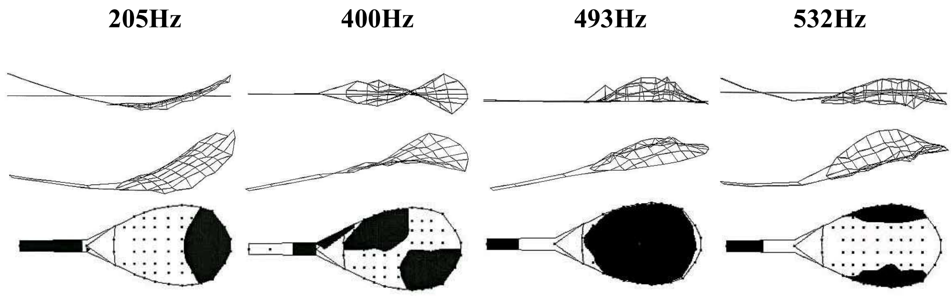


Fig.8 Experimentally identified vibration modes (Is-10)

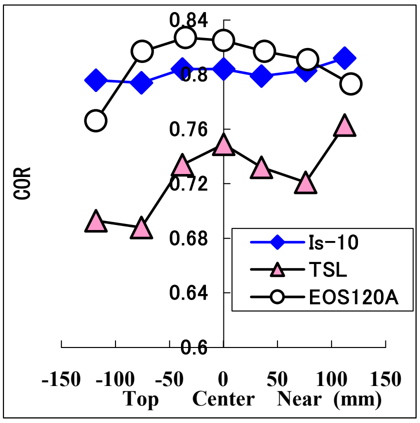


Fig.9 Predicted coefficient of restitution e_r (Ns =56.9Nm, V_{B0} =10 m/s)

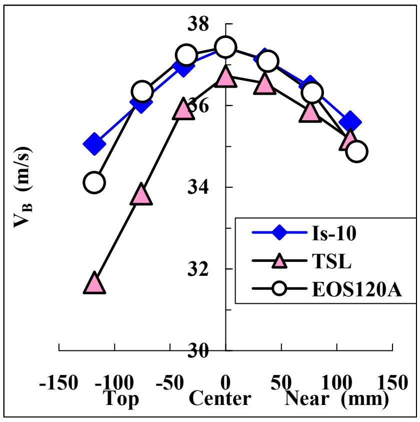
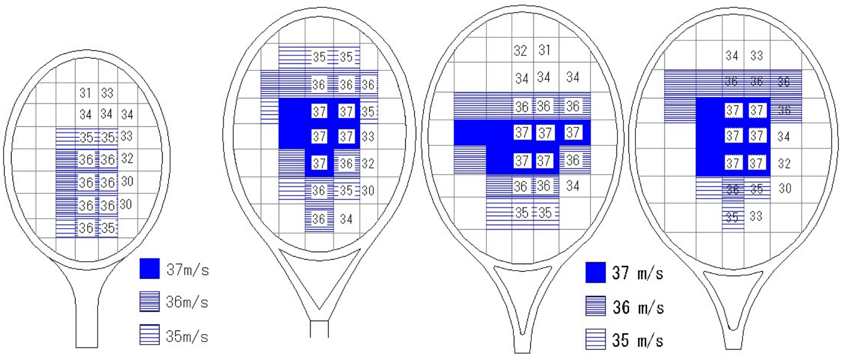


Fig.10 Predicted post-impact ball velocity V_B (Ns=56.9Nm, V_{BO} =10m/s)



(a) Wood (70 in^2) 375 g (b) Piezo-fiber Is-10(115 in^2) 241 g (c) Lightest weight TSL(115 in^2) 224 g (d) High power EOS(120 in^2) 292 g

Fig.11 Predicted sweet area in terms of post-impact ball velocity V_B
(Shoulder torque Ns = 56.9Nm, coming ball velocity V_{BO} = 10m/s)

CONCLUSIONS

The predicted results with forehand stroke model could explain the difference in mechanism of performance between the new type racket with active piezoelectric fibers and the conventional passive representative rackets. It showed that this new type racket provides higher coefficient of restitution on the whole area of string face and also gives larger rebound power coefficients particularly at the topside and bigger powers on the whole area of string face but the difference was not so large. It seems that the racket-related improvements in play are relatively small and the players themselves continue to improve, accordingly there is a gap between a perception and reality.

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