in Engineering of Sport 5, Volume 1, pp.393-399 (2004)

Performance prediction and estimation system for tennis racket in terms of player's wrist joint shock vibrations

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ABSTRACT: It is quite difficult to see how the physical property of equipment has an effect on the performance of a player. This paper introduced a computer aided prediction and estimation system for wrist joint shock vibrations during flat forehand stroke in tennis when the impact velocity and the impact location on the racket face are given. This system can estimate the feel or comfort of various rackets with various specifications and physical properties, even with recent innovative complex structures. The predicted results showed that although the new type racket with active piezoelectric fibers provides higher coefficient of restitution on the whole area of string face and also gives bigger powers on the whole area of string face according to the author's separate paper, it is not so effective on the shock vibrations of the racket handle and the wrist joint compared to the conventional passive rackets. There seem to be much room for further improvement in the shock vibrations relevant to the feel or comfort transmitted to the arm joint through the racket handle.

INTRODUCTION

Since the sport should be learned from the experience, it is the subjective thing. Thus, it is very difficult to see how the physical property of equipment has an effect on the performance of a player. The terms used in describing the performance of a tennis racket are still based on the feel or perception of an experienced tester or a player even today. However, the optimum racket depends on the physical and technical levels of each user. Accordingly, there are a number of unknowns regarding the relationship between the performance estimated by a player and the physical properties of a tennis racket.

This paper introduces a computer aided prediction and estimation system for wrist joint shock vibrations during forehand stroke in tennis when the impact velocity and the impact location on the racket face are given. The analysis is based on the identification of the racket characteristics, the damping of the racket-arm system and the equivalent mass of the player's arm system with the approximate nonlinear analysis of the impact in tennis. The predicted waveform of shock vibrations of the player's wrist joint agrees fairly well with the measured one. This system can estimate the feel or comfort of various rackets with various specifications and physical properties, even with recent innovative complex structures. The predicted results will explain the difference in mechanism of shock vibrations at the wrist joint between the new type racket with active piezoelectric fibers (Kotze *et al.*, 2003) and the conventional representative passive rackets.

PREDICTION OF SHOCK VIBRATIONS AT THE WRIST JOINT

Figure 1 shows the locations of attached accelerometers at the wrist joint and the elbow joint in the experiment where a male tournament player hits flat forehand drive. Figure 2 shows an impact model for the prediction of shock forces transmitted to the arm joints from a racket. The impact force S_0 at P_0 causes a shock force S_1 on the player's hand P_1, a shock force S_2 on the elbow P_2, and finally a shock force S_3 on the player's shoulder P_3 during the impact at which the player hits the ball with his racket. Since the shock forces S_0, S_1, S_2, and S_3 is considered to be one order of magnitude higher than the other forces in play during the impact, the gravity force and muscular action are not taken into account. Accordingly, we consider the racket to be freely hinged to the forearm of the player,

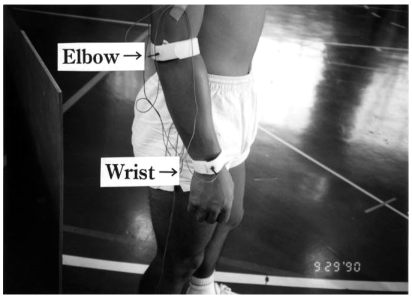


Fig.1 Accelerometers attached at the wrist and the elbow.

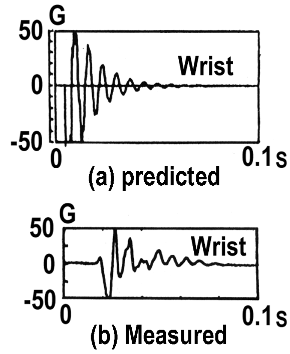


Fig.3 Predicted shock vibrations of a wrist joint compared to the measured.

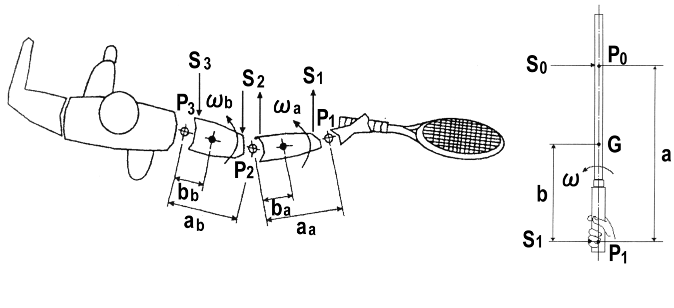


Fig.2 Impact model for the prediction of the shock force transmitted to the arm joints from a racket.

the forearm freely hinged to the arm and the arm freely hinged to the player's body. We can deduce that the inertia effect of the arm and the forearm can be attributed to a mass M_H concentrated in the hand. Therefore, the analysis of the impact between the ball and racket can be carried out by assuming that the racket is free in space, as long as the mass M_H is applied at the point that the hand grips the racket. If the impact force between a ball and the racket is given when the ball hits the racket, the shock force can be obtained (Casolo et al., 1991; Kawazoe, 1994a, 1994b, 1997b, 2000). The reduced mass M_r of a racket at the impact location on the string face can be derived from the principle of the conservation of angular momentum when the moment of inertia and the distance between an impact location and a center of gravity of the racket-arm system are given.

The vibration characteristics of a racket can be identified using experimental modal analysis (Kawazoe, 1989, 1997a) and the racket vibrations can be simulated by applying the approximate impact force-time curve to the hitting portion on the string face of the identified vibration model of the racket. When the impact force component of the *k*-th mode frequency f_k in the frequency region applies to the point *j* on the racket face, the amplitude $X_{ij\,k}$ of the *k*-th mode component at point *i* can be derived using the residue $r_{ij\,k}$ of the *k*-th mode between arbitrary point *i* and *j* (Kawazoe, 1992, 1993, 1994a).

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 a racket frame, when an impact location on the string face and the impact velocity are given.

The coefficient of restitution e_r (COR) between a ball and a racket can be derived by considering the energy loss due to the instantaneous large deformation of a ball and strings and that due to the racket vibrations (Kawazoe, 1993, 1994a). Furthermore, the force-time curve of the impact between a ball and a racket considering the vibrations of a racket frame can be approximated. The contact time T_C during impact can be determined against the pre-impact velocity (V_{BO} - V_{RO}) between a ball and a racket assuming the contact time to be half the natural period of a whole system composed of the mass m_B of a ball, the equivalent stiffness K_{GB} of ball/strings, and the reduced mass M_r of the racket-arm system.

The shock acceleration $A_{mv}(t)$ at the hand grip considering the equivalent mass M_H of the arm system can be represented as:

$$A_{mv}(t) = S_0(t)\,[\,1/(M_R + M_H) - (a/I_G)X] \qquad (1)$$

where X denotes the distance between the center of mass of racket-arm system and the location of hand grip, a the distance between the center of mass of racket-arm system and the impact location of the racket, and I_G the moment of inertia around the center of mass of racket-arm system, respectively. The maximum shock force S_{1max} transmitted to a wrist joint corresponds to the maximum impact force $S_{0\,max}$. The vibration acceleration component $A_{i\,j,\,k}(t)$ of the *k*-th mode at the location *i* of the hand grip is represented as:

$$A_{i\,j,\,k}(t) = -(2\pi f_k)^2 r_{ij\,k} S_{0j}(2\pi f_k) exp(-2\pi f_k \zeta_k t)\, sin(2\pi f_k t) \qquad (2)$$

where *j* denotes the impact location between ball and racket on the string face, ζ_k the damping ratio of the *k*-th mode, and $S_{0j}(2\pi f_k)$ the Fourier spectrum of impact-force curve between a ball and strings. The summation of equation (1) and equation (2) represents the shock vibrations at the hand grip. The damping ratio of a hand-held racket during actual impact has been estimated as about 2.5 times that of the one identified by the experimental modal analysis with small vibrations amplitude. Furthermore, the damping of the waveform at the wrist joint has been 3 times that at the grip portion of the racket handle. Figure 3 shows the predicted shock vibrations of a wrist joint compared to the measured ones. The predicted waveform of shock vibrations of the player's wrist joint agrees fairly well with the measured one.

ESTIMATION OF THE SWEET SPOTS RELEVANT TO THE FEEL

Now we can predict the shock vibrations at the grip and the wrist joint during the impact and can estimate the sweet spots relevant to the feel for the various rackets with different physical properties (Kawazoe *et al.*, 1997, 2003a, 2003b, 2003c).

Table 1 shows the specifications and the main physical properties of the physical properties of three representative rackets (Intelligent fiber Is-10, Lightest racket TSL and Highest power racket EOS120A among available passive rackets), where the mass of a racket includes strings, I_{GY} denotes the inertial moment about the center of mass, I_{GR} the inertial moment about the grip 70 mm from grip end and I_{GX} the inertial moment about the longitudinal axis of a racket. Intelligent fiber Is-10 is 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). Table 2 shows the vibration frequencies and Table 3 shows the damping ratios obtained from the experimental vibration modal analysis. The 1st mode damping ratio of racket Is-10 is larger than those of the other rackets (Kawazoe 2004).

Figure 4 shows the predicted shock vibration accelerations at the wrist joint and Fig. 5 shows the estimated peak-peak values at the wrist joint from the predicted shock vibrations waveforms when the ball strikes the each hitting location along the longitudinal axis on the string face of hand-held rackets. The predicted results shows that although the new type racket with active piezoelectric fibers provides higher coefficient of restitution on the whole area of string face and also gives bigger powers on the whole area of string face according to the author's separate paper, it is not so effective on the shock vibrations of the racket handle

Table 1 Specification and physical properties

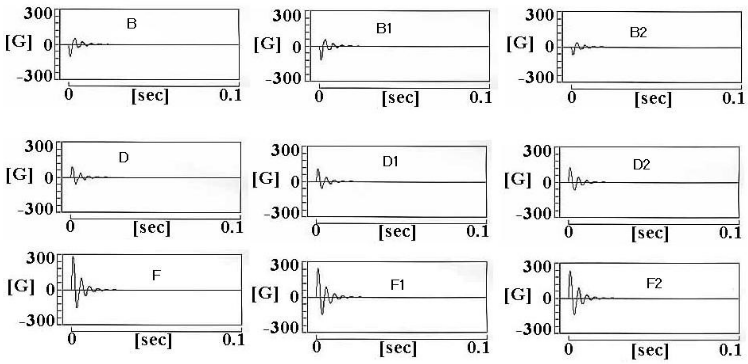
Racket	IS－10	TSL	EOS120A
Total length	700 mm	710 mm	690 mm
Face area	740 cm^2	742 cm^2	760 cm^2
Mass	241 g	224 g	292 g
Center of gravity from grip end	382 mm	379 mm	363 mm
Moment of intertia I_{GY} about Y axis	11.2 gm^2	11.0 gm^2	14.0 gm^2
Moment of intertia I_{GR} about grip	36.7 gm^2	32.4 gm^2	39.0 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

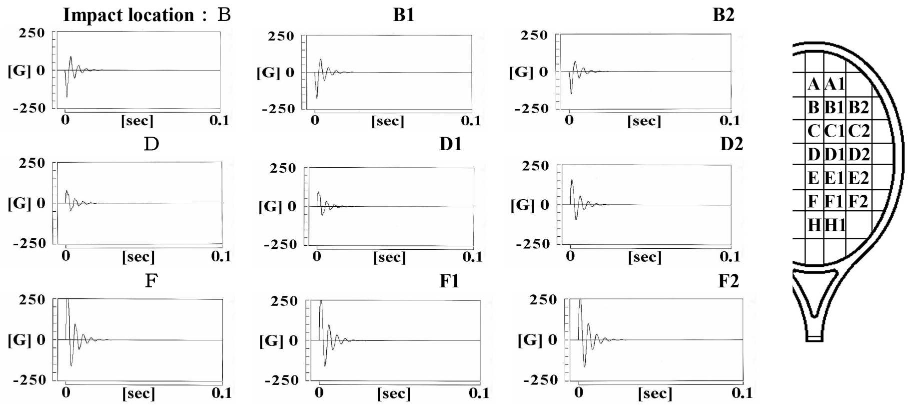
	Is-10	TSL	EOS120A
1st	205 Hz	200 Hz	137 Hz
2nd	400 Hz	474 Hz	322 Hz
3rd	493 Hz	557 Hz	391 Hz
4th	532 Hz	581 Hz	605 Hz

Table 3 Damping ratios

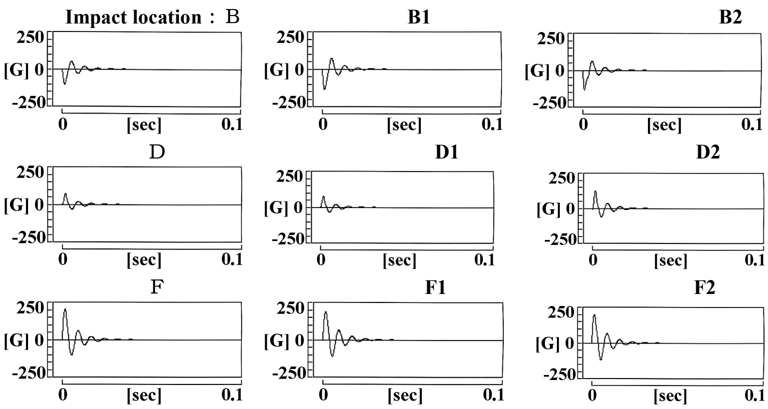
	Is-10	TSL	EOS120A
1st	0.014	0.011	0.008
2nd	0.012	0.011	0.013
3rd	0.003	0.005	0.006
4th	0.013	0.004	0.002



(a) Racket IS-10 (241 g)

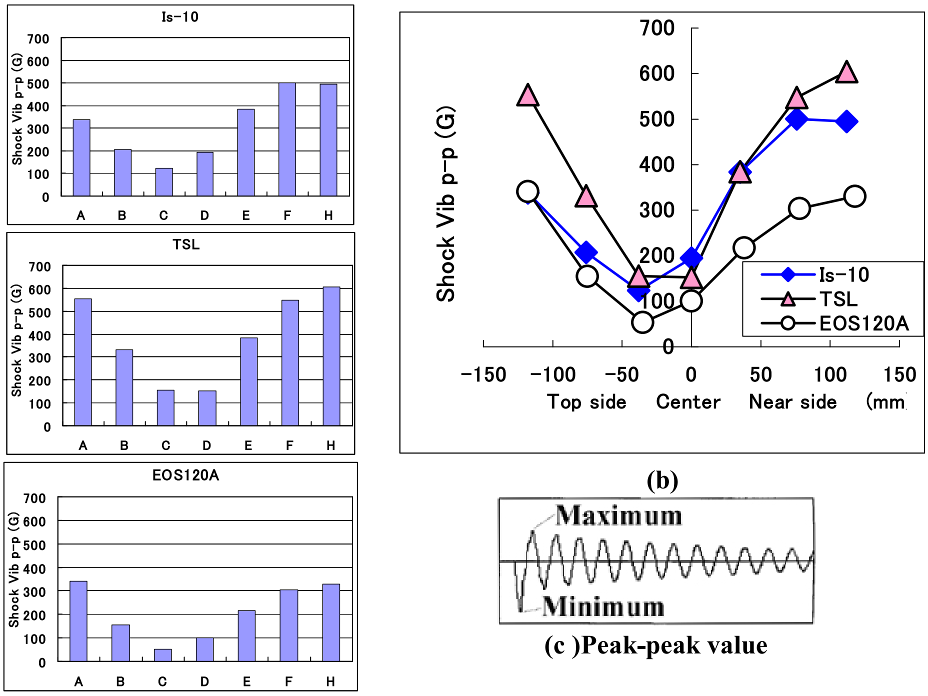


(b) Racket TSL (224 g)



(c) Racket EOS120A (292 g)

Fig.4 Predicted shock vibrations at the wrist joint when hitting a ball with flat forehand drive at the various impact locations of racket face (impact velocity: 30 m/s).



(a)

Fig.5 Predicted shock vibrations at the wrist joint when hitting a ball with flat forehand drive at the various impact locations of racket face (impact velocity: 30m/s).

and the wrist joint compared to the conventional passive rackets. There seem to be much room for further improvement in the shock vibrations relevant to the feel or comfort transmitted to the arm joint through the racket handle.

CONCLUSIONS

The computer aided prediction and estimation system for wrist joint shock vibrations during flat forehand stroke in tennis introduced in this paper can estimate the feel or comfort of various rackets with various specifications and physical properties, even with recent innovative complex structures. The predicted results showed that although the new type racket with active piezoelectric fibers provides higher coefficient of restitution on the whole area of string face and also gives bigger powers on the whole area of string face according to the author's separate paper, it is not so effective on the shock vibrations of the racket handle and the wrist joint compared to the conventional passive rackets. There seem to be much room for further improvement in the shock vibrations relevant to the feel or comfort transmitted to the arm joint through the racket handle.

ACKNOWLEDGEMENT

This work was supported by a Grant-in-Aid for Science Research of the Ministry of Education, Culture, Sports, Science and Technology of Japan, and a part of this work was also supported by the International Tennis Federation (ITF) and the High-Tech Research Center of Saitama Institute of Technology.

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