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Prediction of the Impact Shock Vibrations of the Player's Wrist Joint: Comparison between Two Super Large Sized Rackets with Different Frame Mass Distribution

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ABSTRACT: This paper investigates the tennis racket performance in terms of the feel or comfort. It predicts the effect of the mass and mass distribution of super-large sized rackets on the impact shock vibrations of racket handle and the player's wrist joint when a player hits flat forehand drive. The prediction is based on the identification of the racket characteristics, the damping of the racket-arm system, equivalent mass of the player's arm system and the approximate nonlinear impact analysis in tennis. The result of the comparison between the two super-large sized rackets with different mass and mass distribution shows that the shock vibration of the super-light racket is much larger than that of the conventional weight balanced type racket. It also shows that the sweet area in terms of the shock vibration shifts from the center to the topside on the racket face with a super-light racket compared to the conventional weight balanced type racket.

INTRODUCTION

The implementation of material composites has led to increased flexibility in the design and production of sporting goods. The increased freedom has enabled manufacturers to tailor goods to match the different physical characteristics and techniques of users. However, ball and racket impact in tennis is an instantaneous non-linear phenomenon creating frame vibrations and large deformations in the ball/string system in the racket. The problem is further complicated by the involvement of humans in the actual strokes. Therefore, there are many unknown factors involved in the mechanisms explaining how the racket frame influences the racket capabilities.

This paper investigates the tennis racket performance in terms of the feel or comfort. It predicts the effect of the mass and mass distribution of super-large sized rackets on the impact shock vibrations of racket handle and the player's wrist joint when a player hits flat forehand drive. The prediction is based on the identification of the racket characteristics, the damping of the racket-arm system, equivalent mass of the player's arm system and the approximate nonlinear impact analysis in tennis.

The racket called EOS120A is employed as a representative of super-light racket (mass: 292 g including the weight of strings, the center of gravity L_G: 363 mm), while the racket called EOS120H is selected as a representative of conventional weight and

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weight balanced racket (349 g, L_G: 363 mm). They are the super-large sized rackets made of carbon graphite with a head size of 120 square inches (Kawazoe 2000).

PREDICTION OF SHOCK ACCELERATIONS TRANSMITTED TO THE ARM JOINT FROM A RACKET IN THE IMPACT

IMPACT MODEL FOR THE PREDICTION OF SHOCK FORCE AT THE ARM JOINTS

Figure 1 shows the situation of experiment where a male tournament player hits flat forehand drive and Fig.2 shows the locations of attached accelerometers at the wrist joint and the elbow joint in the experiment. Figure 3 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 intensity of the impulse decreases with the distance from the point of impact with the ball, it can be assumed that the shoulder does not basically alter its velocity, despite the

Fig.1 Experiment where a male player hits flat forehand drive.

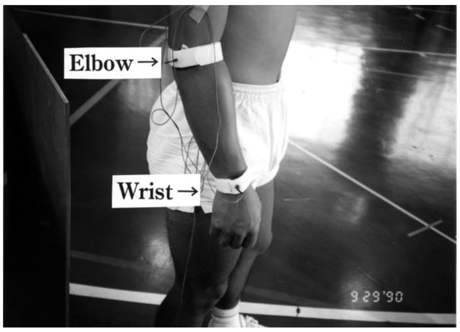

Fig.2Accelerometers attached at the wrist and the elbow.

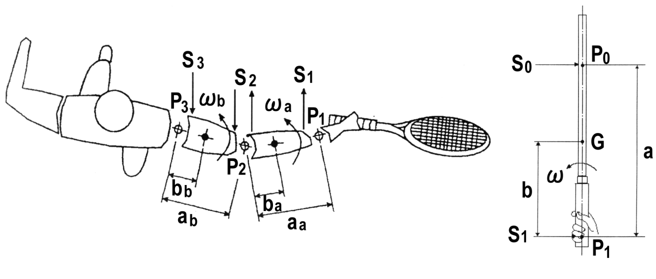

Fig.3 Impact model for the prediction of the shock force transmitted to the arm joints from a racket.

presence of the shock force S_3. Generally speaking, the shock forces S_0, S_1, S_2, and S_3 , which is mainly responsible for the sudden changes in velocity that take place in the brief interval of time considered, is one order of magnitude higher than the other forces in play during the same interval; consequently 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, the forearm being 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 impact between 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 point P_1 of the hand grip. If the impact force S_0 between a ball and the racket is given when the ball hits the racket, the shock force S_1 can be obtained (Casolo 1991, Kawazoe et al 2000).

DERIVATION OF THE RESTITUTION COEFFICIENT AND THE IMPACT FORCE BETWEEN A BALL AND A RACKET

The vibration characteristics of a racket can be identified using the experimental modal analysis (Kawazoe 1989, 1990) 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 k-th mode frequency f_k in the frequency region applies to the point j on the racket face, the amplitude X_{ijk} of k-th mode component at point i can be derived using the residue r_{ijk} of k-th mode between arbitrary point i and j (Kawazoe, 1993).

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) can be derived considering the energy loss E during impact. The main sources of energy loss is E_1 due to racket vibrations as well as E_2 due to the instantaneous large deformation of a ball and strings (Kawazoe 1993). Furthermore, the force-time curve of impact between a ball and a racket considering the vibrations of a racket frame can be approximated as

$$S_0(t) = S_{0\,max} \sin(\pi t / T_c) \quad (0 \leqq t \leqq T_c) \tag{1}$$

where

$$S_{0\,max} = (\pi / (2\,T_c))\,(V_{BO} - V_{Ro})\,(1 + e_r)\,m_B / (1 + m_B / M_r). \tag{2}$$

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.

PREDICTION OF SHOCK ACCELERATIONS TRANSMITTED TO THE ARM JOINT FROM A RACKET IN THE IMPACT

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

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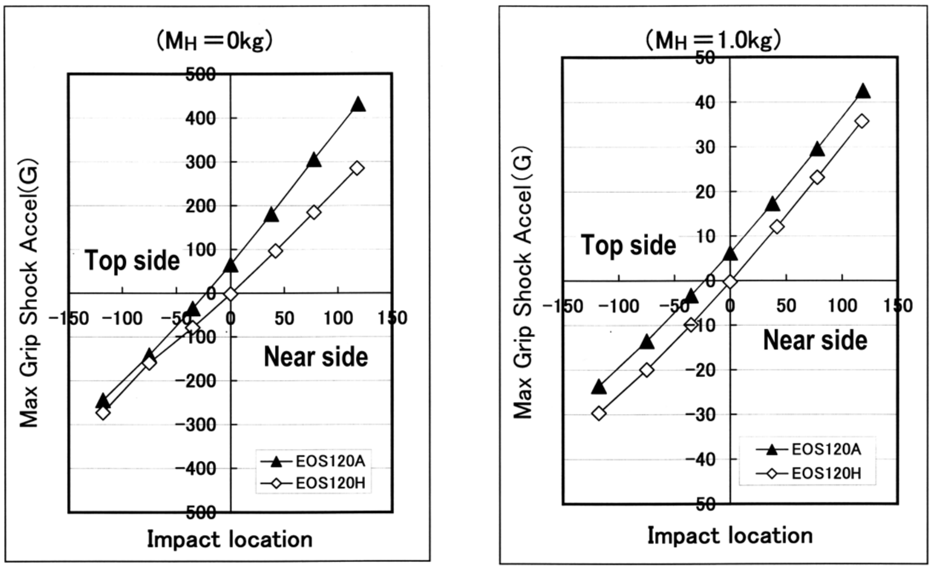
$$A_{nv}(t) = S_0(t)\,[\,1/(M_R + M_H) - (a/I_G)X] \qquad (3)$$

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, I_G the moment of inertia around the center of mass of racket-arm system, respectively. The maximum shock force $S_{1\,max}$ transmitted to a wrist joint corresponds to the maximum impact force $S_{0\,max}$.

Figure 4 shows the predicted maximum shock acceleration at the grip portion (a) freely suspended racket, (b) hand-held racket.



(a) Freely suspended racket (b) Hand-held racket.

Fig.4 Predicted maximum shock acceleration at the grip (impact velocity: 30 m/s).

PREDICTION OF VIBRATION COMPONENTS AT THE RACKET HANDLE AND THE WRIST JOINT

The vibration acceleration component of k-th mode at the location i of handgrip is represented as

$$A_{ij,k}(t) = -(2\pi f_k)^2 r_{ijk} S_{0j}(2\pi f_k)\, exp(-2\pi f_k \zeta_k t)\, sin(2\pi f_k t) \qquad (4)$$

where j denotes the impact location between ball and racket on the string face, ζ_k the damping ratio of k-th mode, $S_{0j}(2\pi f_k)$ the fourier spectrum of Eq.(1). Figure 5 shows the predicted vibration amplitude components during impact at the grip of 70 mm from the grip end, where the four vibration modes of freely suspended rackets are considered. The vibration of the super-light racket at the grip is much larger than that of the conventional weight balanced type racket. It is because the location of grip (70 mm from the grip end) is more apart from the location of node on the handle of the first mode of super-light racket than that of the conventional weight balanced type racket.

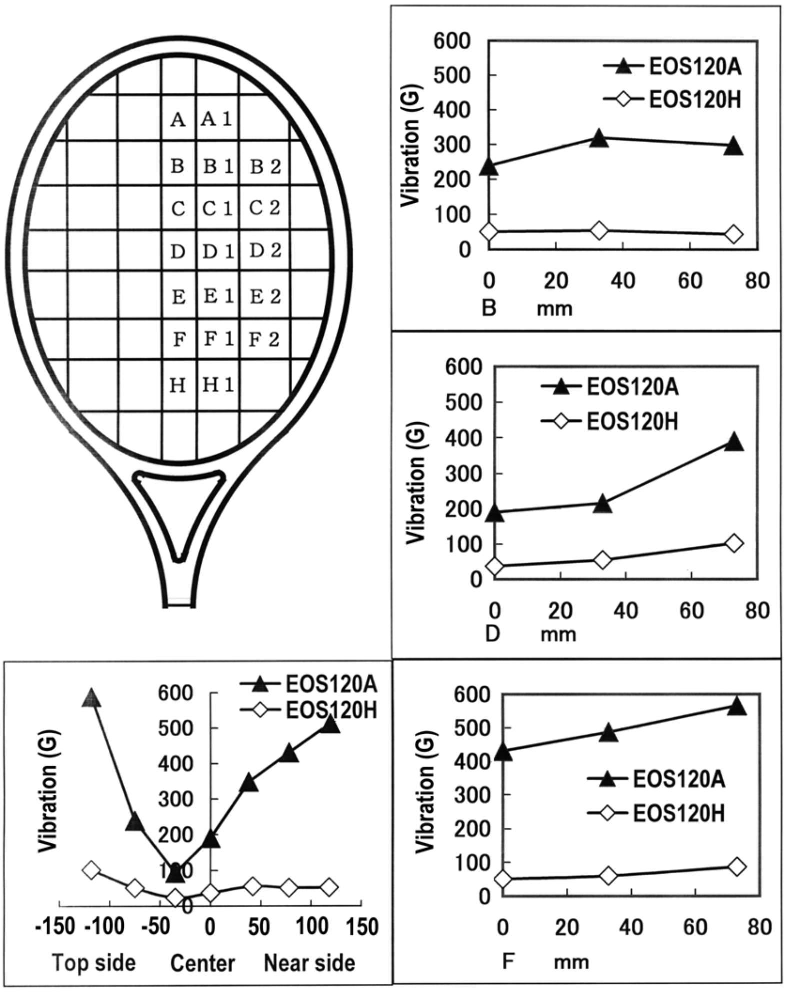


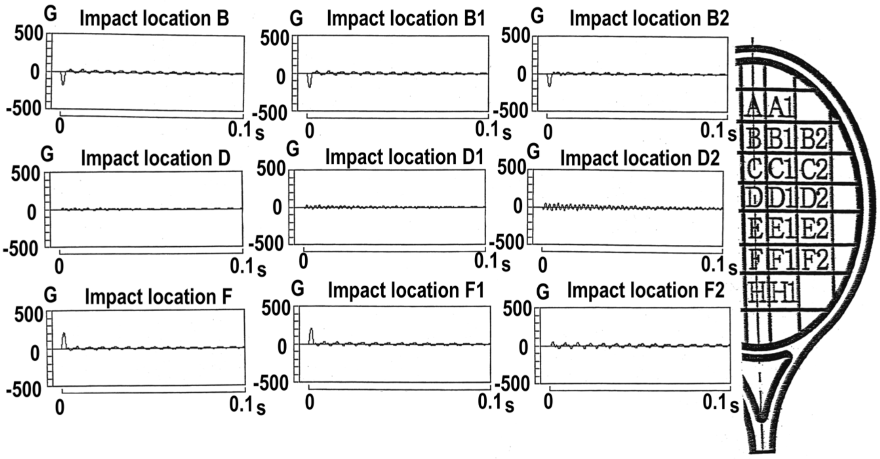
Fig.5 Predicted vibration components at the grip (impact velocity: 30 m/s).

It also shows that the sweet area with respect to the vibration is located around 30-mm topside from the center on the racket face with a super-light racket.

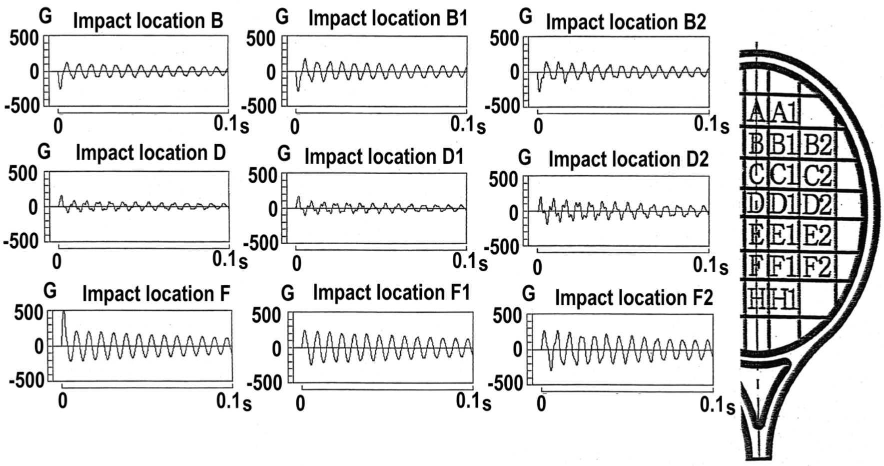
PREDICTION OF THE WAVEFORMS OF SHOCK VIBRATIONS AT THE GRIP

The summation of Eq.(3) and Eq.(4) represents the shock vibrations at the handgrip. Figure 6 shows the predicted waveform of the shock vibrations at the grip on comparing the two freely suspended rackets with different weight and weight balance when a ball strikes the various locations on the string face. The impact velocity between the ball and the racket is 30 m/s. The shock vibration of the super-light racket at the grip is much larger than that of the conventional weight balanced type racket.

PREDICTION OF THE WAVEFORMS OF SHOCK VIBRATIONS AT THE WRIST JOINT



(a) Racket EOS120H: 349 g



(b) Racket EOS120A: 292 g

Fig.6 Predicted waveform of the shock vibrations at the grip on comparing the two freely-suspended rackets with different weight and weight balance when a ball strikes the various locations on the string face. The impact velocity between the ball and the racket is 30 m/s.

The predicted waveform of the shock vibrations at the wrist joint agrees fairly well with the measured ones during actual forehand stroke by a player (Kawazoe et al 1997, 2000). *Figure* 7 shows the predicted shock vibrations of a wrist joint. The damping ratio of a hand-held racket in the actual impact is estimated as about 2.5 times that of the one identified by the experimental modal analysis with small vibration amplitude. Furthermore, the damping of the waveform at the wrist joint was 3 times that at the grip portion of the racket handle. The shock vibrations of super-light racket are much larger than those of conventional weighted and weight balanced racket; the conventional weighted and weight balanced super- large racket is predicted to be very comfort when the ball is hit with.

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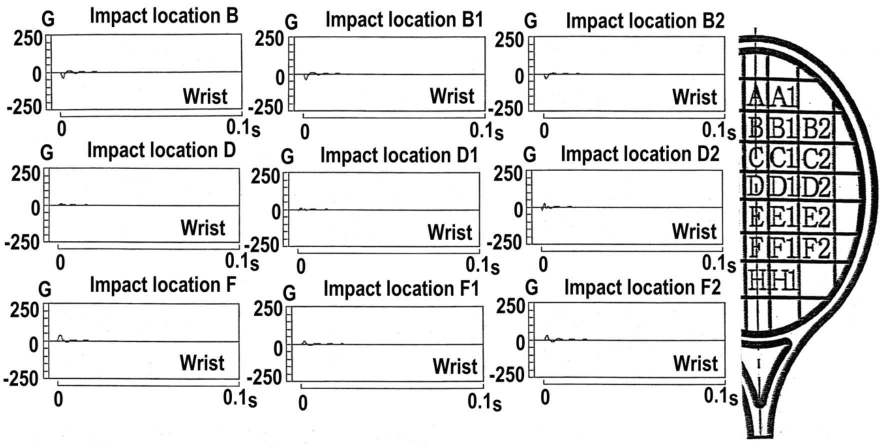
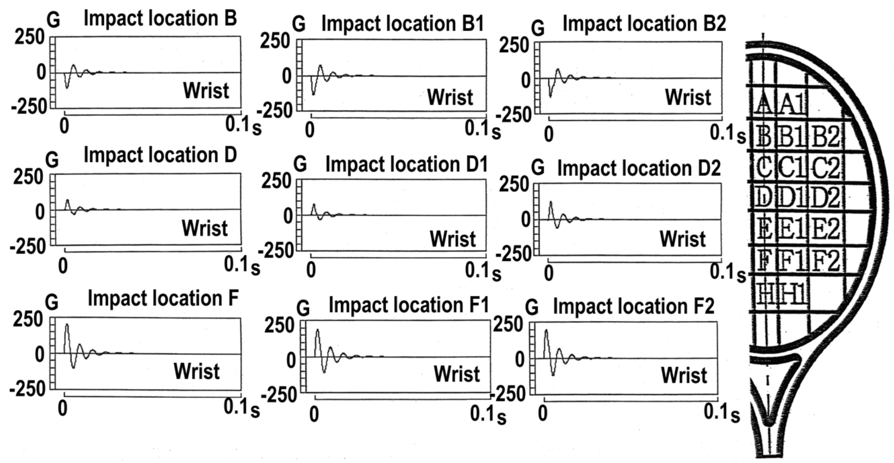


(a) Racket EOS120H: 349 g



(b) Racket EOS120A: 292 g

Fig. 7 Predicted waveform of the shock vibrations of the player's wrist joint on comparing the two rackets with with different weight and weight balance when a ball strikes the various locations on the string face. The impact velocity between the ball and the racket is 30 m/s.

CONCLUSIONS

This paper has investigated the tennis racket performance in terms of the feel or comfort. It predicted the effect of the mass and mass distribution of super-large sized rackets on the impact shock vibrations of racket handle and the player's wrist joint when a player hits flat forehand drive. The prediction is based on the identification of the racket characteristics, the damping of the racket-arm system, equivalent mass of the player's arm system and the approximate nonlinear impact analysis in tennis. The result of the comparison between the two super-large sized rackets with different mass and mass distribution shows that the shock vibration of the super-light racket is much larger than that of the conventional weight balanced type racket. It is seen that the vibration of the super-light racket at the grip is much larger than that of the conventional weight balanced type racket. It is because the location of grip (70 mm from the grip end) is more apart from the location of node on the handle of the first mode of super-light racket than that of the conventional weight balanced type racket. It is also seen that the sweet area with respect to the vibration is located around 30-mm topside from the center on the racket face with a super-light racket.

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