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Performance prediction of tennis rackets with different racket head size: impact shock vibrations of a racket grip and a player's wrist joint

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ABSTRACT: This paper predicts the effect of racket head size on the racket performance in terms of the impact shock vibrations of racket handle and the player's wrist joint. It is based on the experimental identification of the racket-arm dynamics and the simple nonlinear impact analysis, clarifying the mechanism of a difference in performance of different head-size tennis rackets. The result shows that the shock vibration of larger sized racket is bigger than that of smaller sized one. It also shows that the sweet area in terms of the shock vibrations shifts from the center to the top side on the face with an increase of head-size of super-light racket.

INTRODUCTION

Material composites have increased the degree of freedom of design and manufacturing for sports products. At the current stage, very specific designs are targetted to match the physical and technical levels of each user.

However, ball and racket impact in tennis is an instantaneous non-linear phenomenon creating large deformations in the ball/strings and vibrations in the racket. The problem is further complicated by the involvement of humans in the actual strokes. These problems make analysis extremely difficult. Therefore, there are many unknown factors involved in the mechanisms explaining how the specifications and physical properties of the racket frame influence the racket capabilities.

In terms of the power of racket, the distribution of the coefficient of restitution between a ball and a freely-suspended racket was predicted, and it was shown that the predicted ratios of ball rebound velocity to ball incident velocity at any given impact location agree well with experimental results (Kawazoe 1989,1992,1993,1994,1997). In this model, the impact forces and contact times have been determined using impact analysis on a rigid frame and a one degree of freedom model for a compound ball/strings system, considering the non-linear restoring characteristics and the energy loss of ball/strings . By applying these results to a vibrational model for a racket identified experimentally, the racket response was determined. Although the predicted rebound capability was slightly higher for the hand-held racket compared to the freely-suspended racket at the off-center of the string face, there is no big difference. The model provides an explanation for the mechanism of impact phenomena related to restitution characteristics and the post-impact ball velocity (Kawazoe et al.,1996, Kawazoe 1997).

On the other hand, in terms of the feel or comfort of the arm or hand in an impact, it has been investigated how the racket physical properties affect the impact shock vibrations of the racket handle, the wrist joint and the elbow joint in the actual forehand drives (Kawazoe et al., 1997), where physical explanations were given for the measured acceleration of the racket handle (210 mm from the grip end) and the wrist joint on the basis of the identification of the racket characteristics, the damping of the racket-arm system, the equivalent mass of the arm system and the approximate nonlinear impact analysis. It was shown that the shock vibrations of the wrist joint are transmitted from the racket with an impulse at the impact location and several vibration mode components of a racket frame and strings. The predicted wave forms of the shock vibrations of the racket handle and the wrist joint agree fairly well with the measured ones during actual forehand stroke by a player, although the mechanism of the shock vibrations of the elbow joint is left unclarified.

This paper predicts the effect of racket head size on the racket performance in terms of the impact shock vibrations of racket handle and the player's wrist joint on the basis of the author's previous work.

SHOCK VIBRATIONS PREDICTION OF A RACKET HANDLE AND A WRIST JOINT IN THE FOREHAND GROUND STROKE

The impact forces and contact times between a ball and a racket can be determined using the derived restitution coefficient and the reduced mass at the impact location of a racket-arm system. By applying these results to a vibrational model for a racket-arm system identified experimentally, the response of a racket and a wrist joint can be derived (Kawazoe 1989,1992,1993,1994,1997, Kawazoe et al.,1997).

Figure 1 shows the impact points of a racket using hammering method for identification of vibration characteristics. The black circle represents the attachment point of the accelerometer. The alphabetical signs in Fig. 2 show the impact locations between a ball and a racket on the racket face, where the shock vibrations should be predicted. Figure 3 shows the example of predicted initial amplitude components of racket vibrations when a ball strikes off-center of a racket face (Impact location B2) with a velocity of 40 m/s. The first mode component is the bending vibration with 2 nodes, the 2nd the twisting with 2 nodes, the 3rd the bending with 3 nodes, and the 4th mode the membrane vibration of strings. Although the frequency drops slightly for the hand-held racket compared to the freely suspended racket, the positions of nodes on the string surface are nearly identical. With a primary vibration, the position of the node on the handle for the hand-held racket shift somewhat to the held position. Although the initial amplitude is somewhat larger and the damping of frame vibration is remarkably larger for the hand-held racket compared to the freely suspended racket, the initial amplitude distribution is similar in both cases.

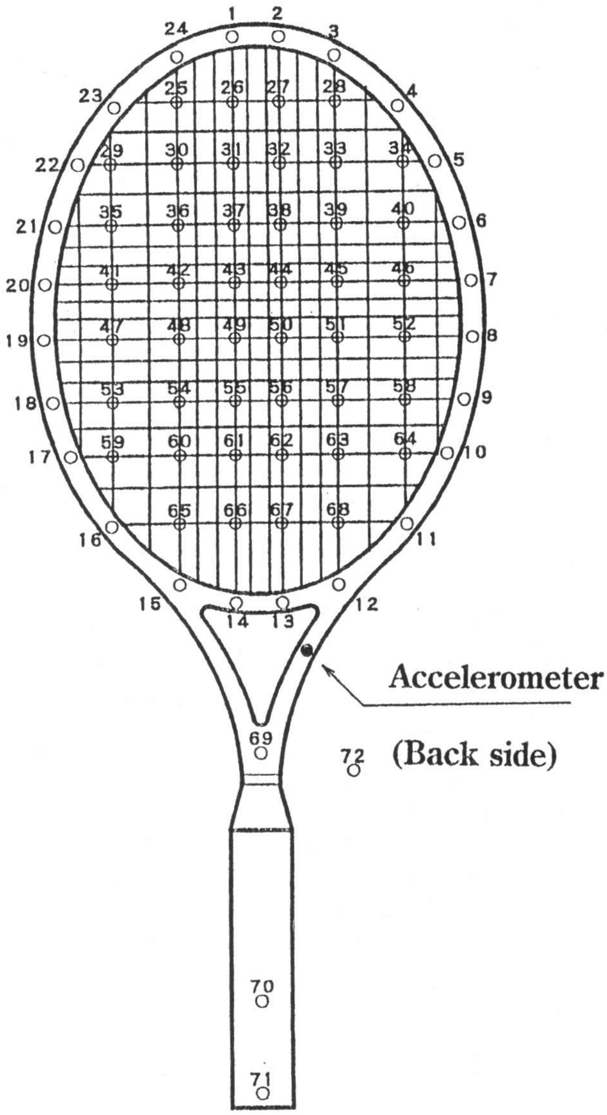


Fig. 1 The impact points of a racket using hammering method for identification of vibration characteristics.

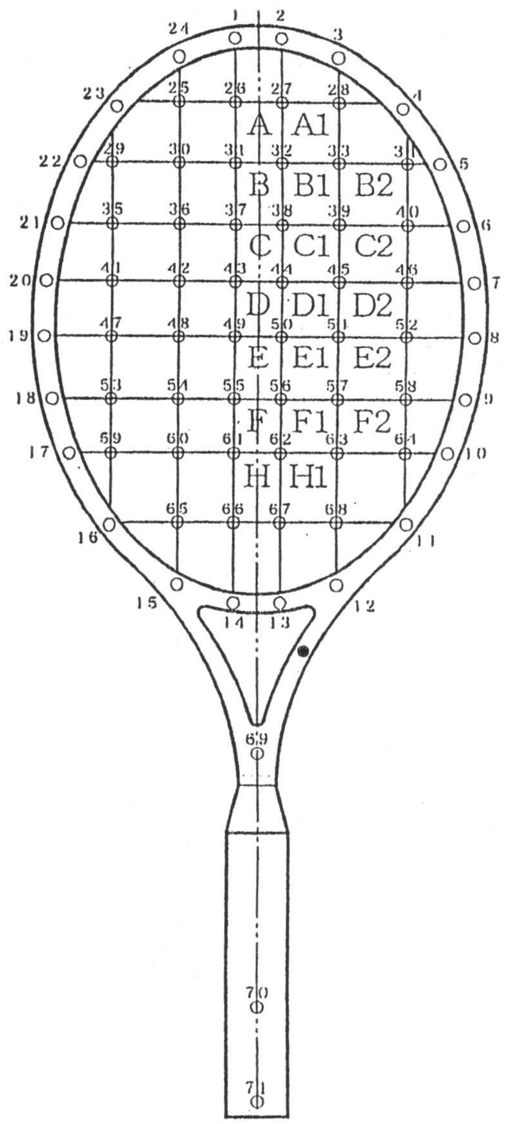


Fig. 2 The impact locations between a ball and a racket, where the shock vibrations be predicted.

EFFECT OF RACKET HEAD SIZE ON THE SHOCK VIBRATIONS OF A RACKET GRIP AND A WRIST JOINT

Figure 4 shows the maximum shock acceleration of a racket grip (70 mm from the grip end) when a ball strikes a freely suspended racket with different head size at a velocity of 30 m/s. Fig.4 is the case of conventional type of rackets with head size of 100 in ^{2} and 110 in ^{2}. The racket EX-II, including strings, has a mass of 360 g, a total length of 680 mm, surface area of 628 cm^2,{roughly 100 in ^{2}}, a center of gravity at 308 mm from the grip end, the inertial moment around the center of gravity of 13.1 gm ^{2}, around the longitudinal axis of 1.293 gm ^{2}, the string tension of 246 N{55 lbs}, and the primary mode frequency of 122 Hz, while the racket EX-110 has a mass of 365 g, a total length of 680 mm, surface area of 110 in ^{2}, a center of gravity at 325 mm, the inertial moment of 16.9 gm ^{2} and 1.683 gm ^{2}, the string tension of 63 lbs, and the primary frequency of 132 Hz. Figure 5 shows the maximum shock acceleration of a racket grip when a ball

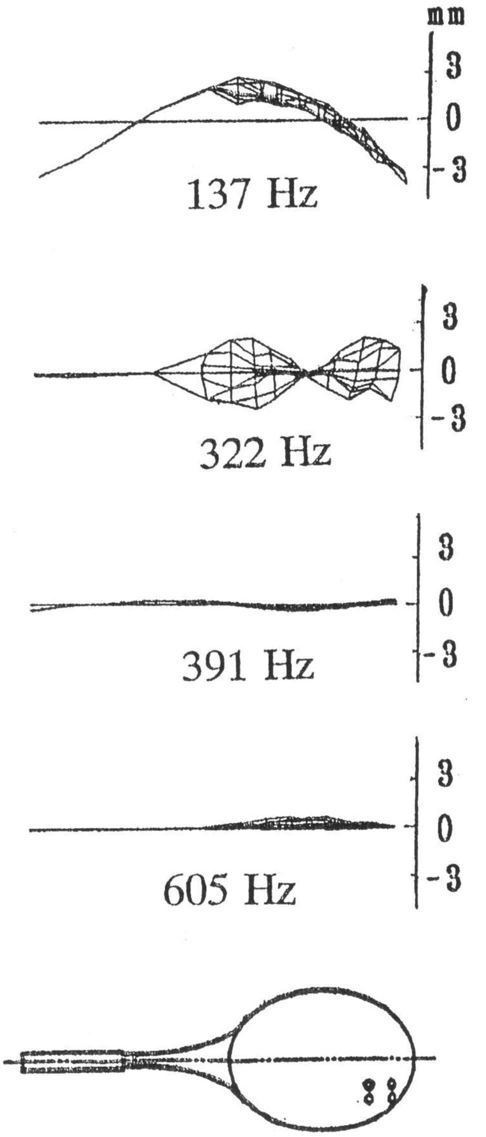


Fig.3 Example of predicted initial amplitude components of racket vibrations when a ball strikes off-center of a racket face (Impact location B2).

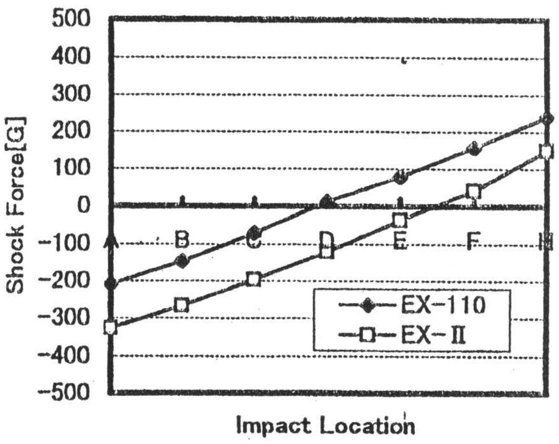


Fig.4 Predicted maximum shock acceleration at the grip (70 mm from grip end) of freely-suspended racket vs. impact location (Impact velocity: 30 m/s, EX-II:100 in^2, EX-110:110 in^2)

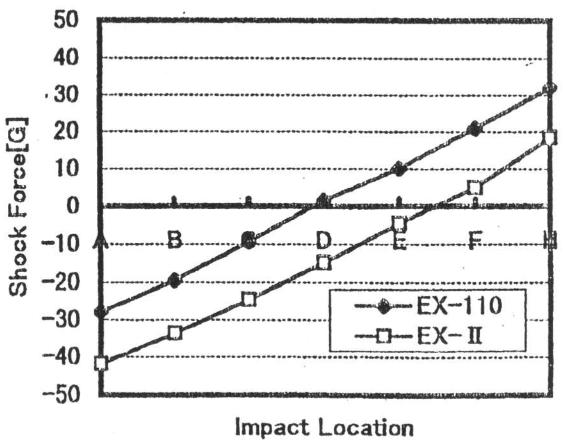


Fig.5 Predicted maximum shock acceleration at the grip (70 mm from grip end) with an equivalent mass of an arm vs. impact location (Impact velocity:30 m/s).

strikes a hand-held racket with different head size at a velocity of 30 m/s, where the shock is estimated by the approximate nonlinear impact analysis (Kawazoe, 1994). Fig.5 is the case of conventional type of rackets with head size of 100 in ^{2}(racket EX-II) and 110 in ^{2} (racket EX-110). The equivalent mass of an arm is estimated as MH=1.0 kg (Casolo et al.,1991, Kawazoe et al.,1996,1997). The equivalent mass of an arm reduces remarkably the maximum shock acceleration of a racket grip on comparing with Fig.4.

Figure 6 shows the summation of the predicted grip acceleration initial amplitude considering four vibration mode components when a player hits flat forehand drive, where a simple swing model is used. In this model it is assumed that a player initially at rest hits a coming ball with constant joint angles of the wrist and the elbow and a constant torque of the shoulder. The velocity of coming ball is 10 m/s and the torque given is 56.9 Nm, and the ball and the racket collides when the arm rotates by 90 degrees. Fig.6 is the case of conventional type of rackets with head size of 100 in ^{2} and 110 in ^{2}. The Initial amplitude of vibration acceleration of larger sized racket is bigger than that of smaller sized one.

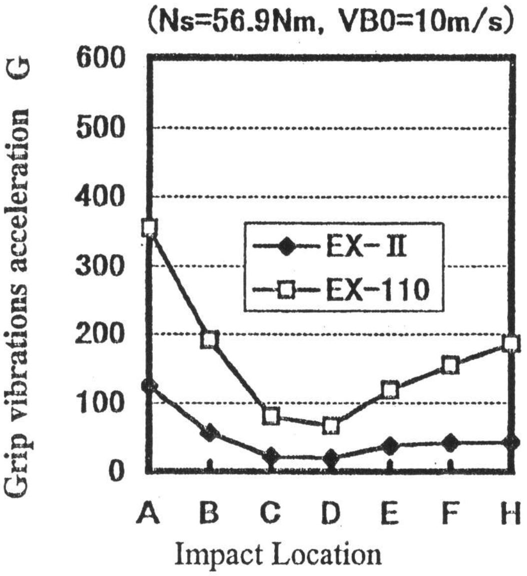
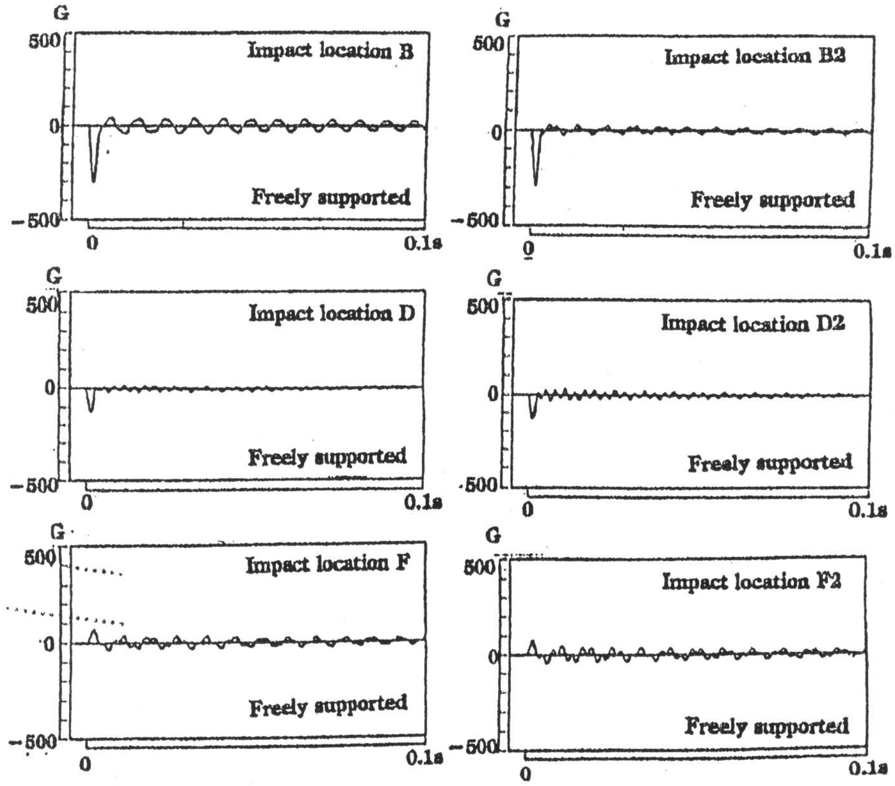
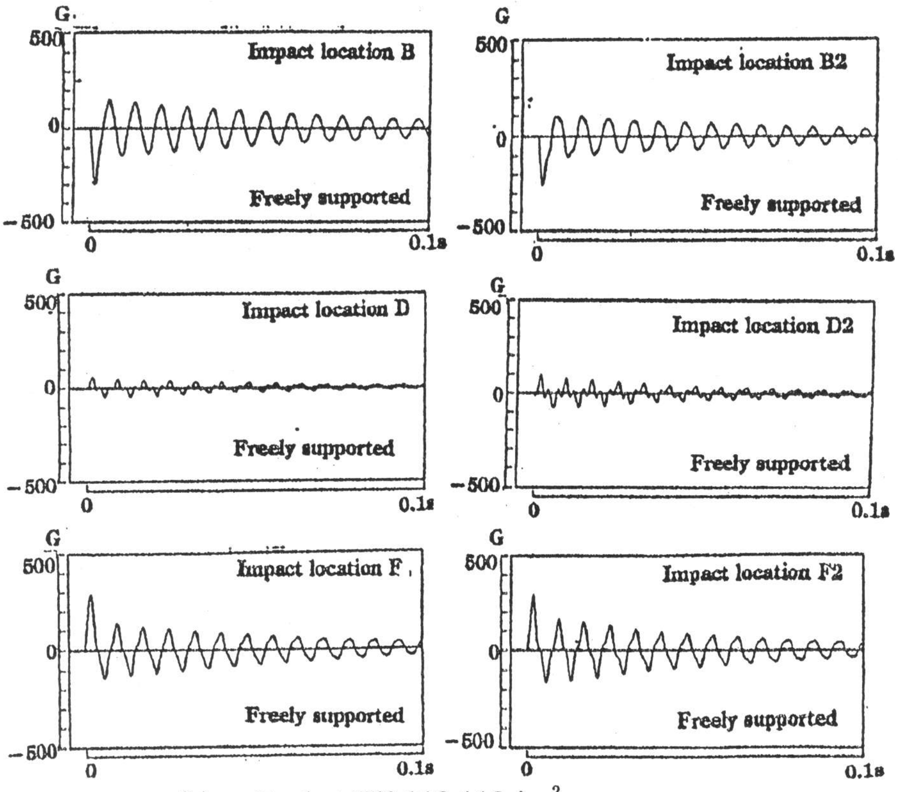


Fig.6 Summation of the predicted grip acceleration amplitude considering four vibration mode components when a player hits flat forehand drive, where a simple swing model is used (Racket EX-II:100 in ^{2}, EX-110:110 in ^{2}).

Figure 7 shows the predicted waveform of the shock vibrations at the grip on comparing the two freely-suspended rackets with different head size when a ball is struck at the various locations shown in Fig.2. The impact velocity between the ball and the racket is 30 m/s. Figure 8 shows the predicted shock vibrations of a wrist joint. The first largest peak in the impact was caused by the shock and vibrations of a racket frame, followed by the residual vibrations of the racket frame. The shock vibrations are composed of the shock acceleration and the racket frame vibration components, and each component has its own time history and magnitude depending on the impact velocity, impact location, grip location of racket handle and the physical properties of a racket. The damping ratio of a hand-held racket in

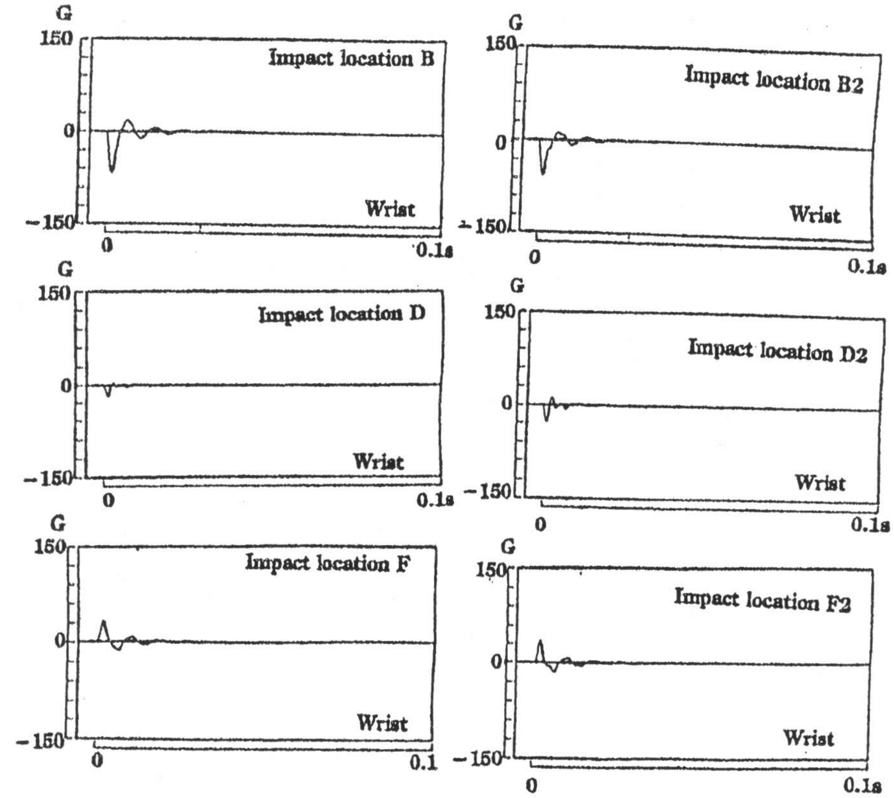


(a) Racket EX-II:100 in [2]

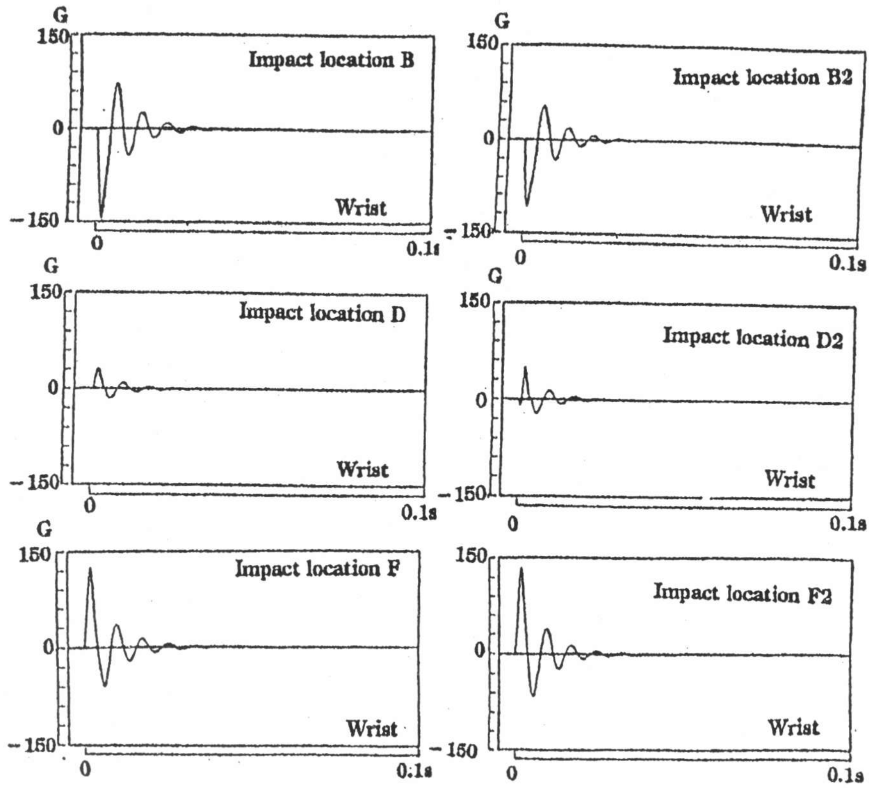


(b) Racket EX-110:110 in [2]

Fig.7 Predicted waveform of the shock vibrations at the grip on comparing the two freely-suspended rackets with different head size when a ball is struck at the various locations shown in Fig.2. The impact velocity between the ball and the racket is 30 m/s.



(a) Racket EX-II:100 in ^{2}



(b) Racket EX-110:110 in ^{2}

Fig.8 Predicted waveform of the shock vibrations of the player's wrist joint on comparing the two rackets with different head size when a ball is struck at the various locations shown in Fig.2. The impact velocity between the ball and the racket is 30 m/s.

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 wave form at the wrist joint was 3 times that at the grip portion of the racket handle.

Also with super-light rackets (EOS100:290 g,100 in ^{2}, EOS120A:292 g, 120 in ^{2}), the shock vibrations of larger sized racket were bigger than that of smaller sized one. Furthermore, the sweet area in terms of the shock vibrations shifts from the center to the top side on the strings face with an increase of head-size.

CONCLUSIONS

The result showed that the predicted shock vibration of the racket grip and the player's wrist joint are larger for the larger sized racket compared to that of smaller sized racket. It also showed that the sweet area in terms of the shock vibrations shifts from the center to the top side on the strings face with an increase of head-size of super-light racket.

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