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Prediction of the shock vibrations at the wrist joint with the new large ball compared to the conventional ball impacted to the tennis racket during forehand stroke

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A recent rule change by the ITF has allowed larger balls (7- 8 % increase in diameter while keeping the same mass) to be used in tournaments. The intention of introducing the larger ball is to slow down the flight through the air thus reducing the dominance of the 'big-servers' on fast surfaces such as grass. A previous paper of the authors investigated the effect of the larger ball on the impact shock vibrations at the player's wrist joint and the racket handle during the forehand ground stroke and at the player's elbow joint during the service stroke by recording the waveforms of accelerations. This result showed that the waveforms of shock vibrations with the normal ball and the larger ball are very similar. Since the drag force of the larger ball is larger than that of the normal ball, the shock vibrations of a larger ball should be smaller. This paper has predicted the waveforms of shock vibrations at the wrist joint with the new large ball compared to the conventional ball during forehand stroke. The simulated results agree well with experimental results. The contact time of the larger ball is slightly longer and the impact force is slightly smaller. There is little difference in the deformation of the string and the ball between the larger ball and the normal ball.

INTRODUCTION

A recent rule change by the ITF has allowed larger balls (7 - 8 % increase in diameter while keeping the same mass) to be used in tournaments. The intention of introducing the larger ball is to slow down the flight through the air thus reducing the dominance of the 'big-servers' on fast surfaces such as grass. Kawazoe *et al*. (2002) investigated experimentally the effect of the larger ball on the impact shock vibrations at the player's wrist joint and the racket handle during the forehand ground stroke and at the player's elbow joint during the service stroke. Result showed that the waveforms of shock vibrations with the normal ball and the larger ball are very similar. Since the drag force of larger ball is larger than that of the normal ball, the shock vibrations of a larger ball should be smaller. This paper predicts and makes clear the mechanism of the shock vibrations at the wrist joint with the new large ball compared to the conventional ball impacted to the tennis racket during forehand ground stroke.

RESTORING FORCE - DEFORMATION CHARACTERISTICS AND ENERGY LOSS OF BALL AND STRINGS

Figure 1 shows the diameters of the normal ball and larger ball. The mass of both balls are about 58 g. Two rackets (SG made by Prince) with the same physical properties were used in this test, and each racket was strung at 45 lbs and 65 lbs. The mass of strung racket is 338 g, total length 685 mm, racket face area 694 cm^2, the balance (centre of gravity from grip end) 327 mm, moment of inertia 15.0 $g \cdot m^2$ about the centre of gravity, moment of inertia 37.3 $g \cdot m^2$ about grip portion 70 mm from grip end, moment of inertia 0.935 $g \cdot m^2$ about the longitudinal axis. Figure 2 shows the location of accelerometers at the wrist joint and the racket handle in the forehand ground stroke.

Figure 3 shows schematically the measurement for obtaining the applied force-deformation curves, where the ball is deformed between two flat surfaces as shown in (a) and the ball plus strings is deformed with a racket head clamped as shown in (b). Figure 4 shows the restoring force - displacement characteristics, where S indicates the standard (normal) ball and L indicates the larger ball. In this work, it is assumed that the deformation of the larger ball is 8 % larger than the measured deformation of the conventional normal ball against the same applied force. Assuming that a ball with concentrated mass deforms only at the side in contact with the strings (Kawazoe; 1992, 1994), the curves of restoring force F_B v. ball deformation, restoring force F_G v. string deformation, and the restoring force F_{GB} v. deformation of the composed ball/strings system can be obtained. These restoring characteristics are determined in order to satisfy a number of experimental data using the least squares method. The curves of the corresponding stiffness K_B, K_G and K_{GB} are derived by differentiation of the equations of restoring force with respect to deformation. The stiffness K_B of a ball, K_G of strings and K_{GB} of a composed ball/strings system exhibit strong non-linearity.

Furthermore, it is also assumed that the coefficient of restitution (COR) e_{BG} of the larger ball is the same as the measured one of the normal ball impacted to the string bed with the head clamped shown in figure 5. The measured coefficient of restitution e_{BG} can be regarded as the energy loss of the ball and strings due to the impact (Kawazoe, 1992). The coefficient e_{BG} is almost independent of ball velocity and strings tension. This is due to an increase of equivalent spring stiffness K_{GB} with an increase of the damping coefficient C_{GB} of the compound system as the impact velocity increases.

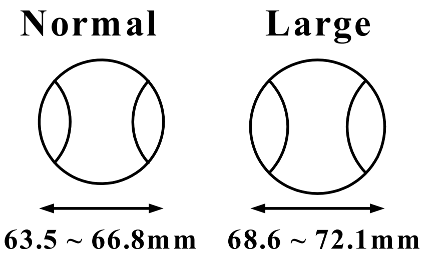


Figure 1. New large ball and conventional normal ball (standard).

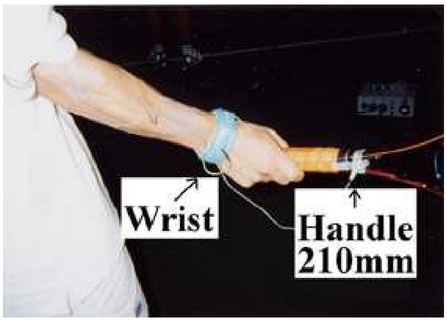


Figure 2. Location of accelerometers at the wrist joint in forehand ground stroke and the racket handle.

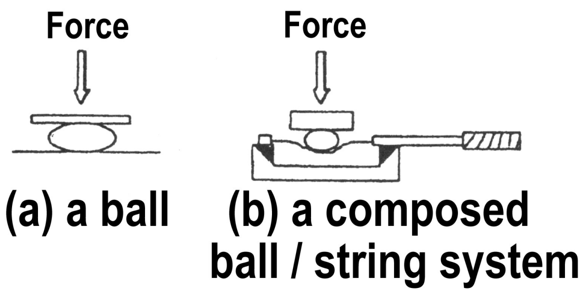


Figure 3. Illustrated Measurement of restoring force vs. displacement characteristics.

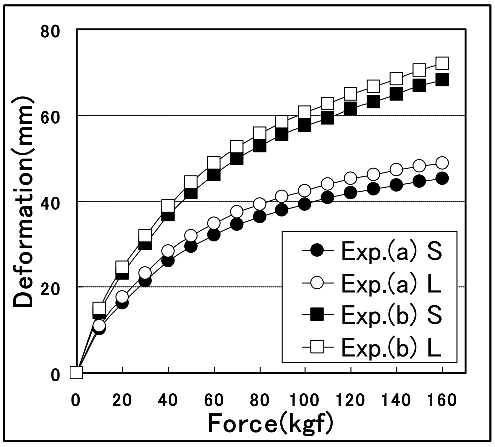


Figure 4. Measured restoring force vs. displacement characteristics. S: standard (normal) ball, L: larger ball

METHOD TO PREDICT THE SHOCK VIBRATIONS AT THE WRIST JOINT

Figure 6 shows the impact model of a ball-string system, where *Mr* is the reduced mass at the impact locations on the string face. Figure 7 shows the string mesh (left side) and impact locations on the string face (right side). It is assumed that the ball contacts to the string face at the four cross points.

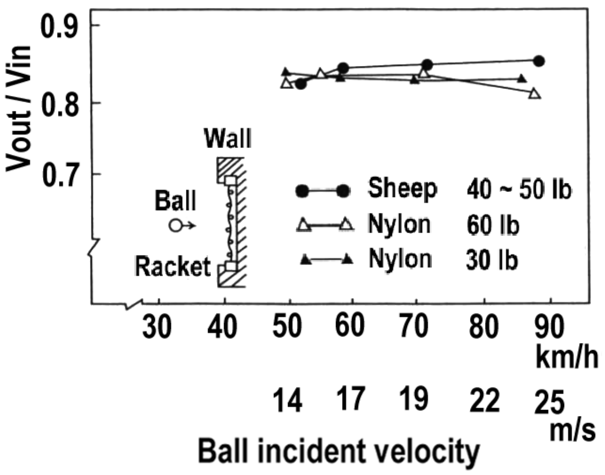


Figure 5. Measured COR (e_{BG}) between a ball and strings with frame clamped.

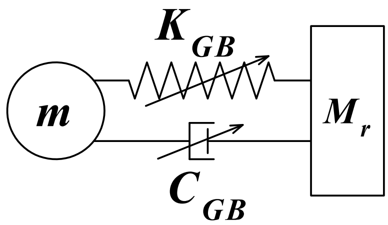


Figure 6. Impact model of a ball - string system.

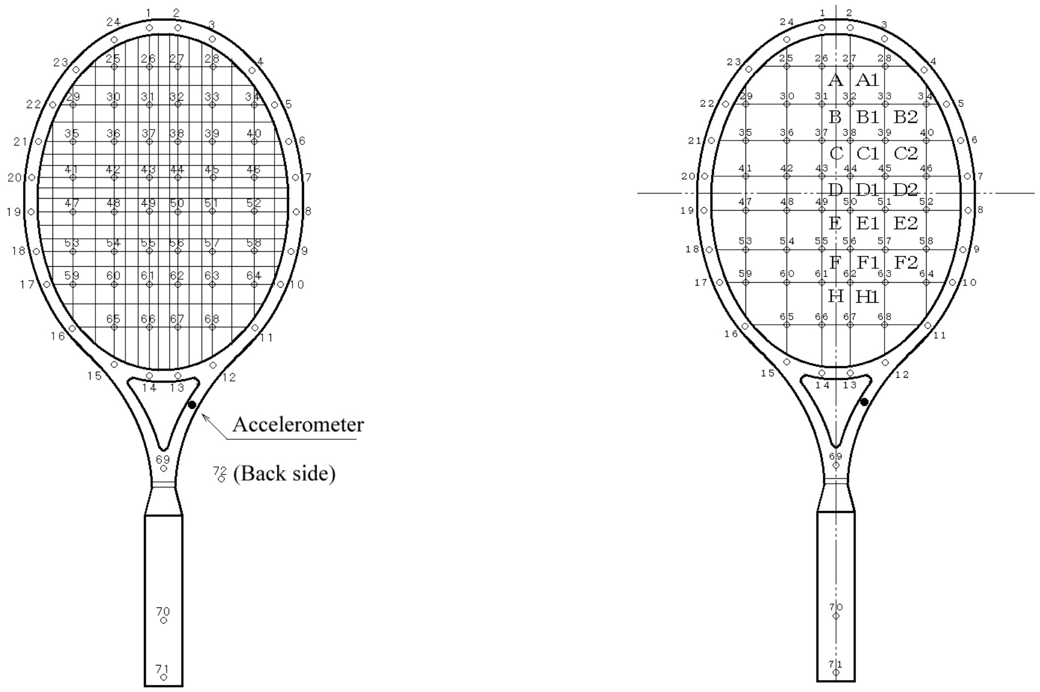


Figure 7. String mesh (left side) and impact locations on the string face (right side).

Figure 8 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 alter its velocity, despite the presence of the shock force S_3. The shock forces S_0, S_1, S_2, and S_3 are assumed to be one order of magnitude higher than those due to gravity and muscular action.

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 *et al.* 1991, Kawazoe *et al.,* 2000). Figure 9 shows the measured rebound power coefficients *e* of a racket with equivalent mass of an arm compared to a handled racket.

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 centre of gravity are given. The reduced mass M_r at the impact location with a racket-arm system can be derived as

$$M_r = 1/[1/(M_R + M_H) + c^2/I_G] = (M_R + M_H)I_G/[I_G + (M_R + M_H)c^2] \quad (1)$$

where

$$c = c_o + (L_{Go} - L_H)M_H/(M_R + M_H) \quad (2)$$

$$I_G = I_{Go} + M_R \triangle G^2 + M_H(L_{Go} - L_H - \triangle G)^2 \quad (3)$$

$$\triangle G = (L_{Go} - L_H)M_H/(M_R + M_H) \quad (4)$$

and L_{Go} denotes the distance between the centre of mass and the grip end of the racket, I_{Go} the moment of inertia with respect to the centre of gravity of the racket, c_o the distance between the centre of gravity and the impact location of the racket, and L_H the distance of the point P_1 of the hand grip from the grip end. The moment of inertia with respect to the center of gravity and the distance of the center of gravity from the impact location of the racket-arm system are indicated by I_G and *c,* respectively. Figure 10 shows the predicted reduced mass of the racket-arm system compared to the freely suspended racket against impact locations on the string face ($M_H =$ 1.0 kg: with arm, $M_H =$ 0 kg: without arm). There is no big difference between them.

The vibration characteristics of a racket can be identified using the experimental modal analysis (Kawazoe, 1989; 1997) 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

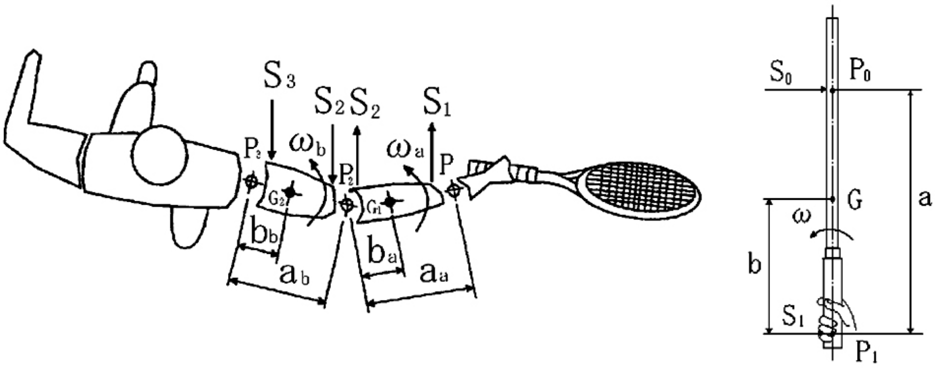


Figure 8. Impact model for the prediction of the shock force transmitted to the arm joints from a racket.

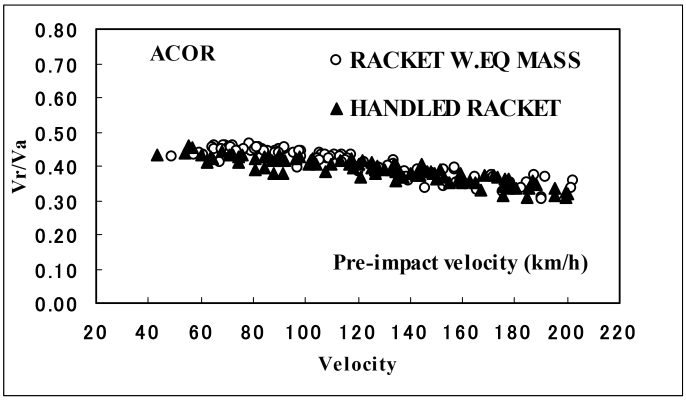


Figure 9. Rebound power coefficients e of a handled racket and a racket with equivalent mass of an arm.

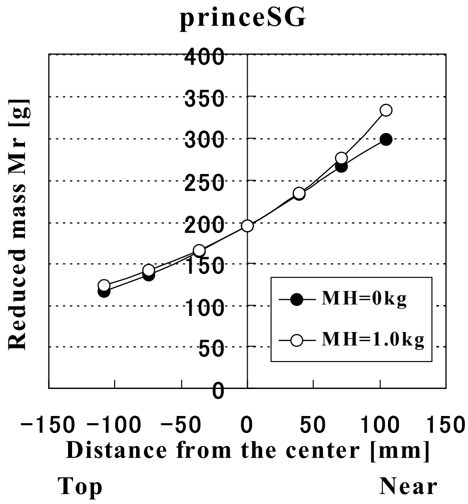


Figure 10. Reduced mass of the racket arm system

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 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, 1993; 1994).

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 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; 1994). Furthermore, the force-time curve of impact between a ball and a racket considering the vibrations of a racket frame can be approximated as:

$$S_0(t) = S_{0\,max}\ \sin(\pi t / T_c) \quad (0 \leqq t \leqq T_c) \tag{5}$$

where

$$S_{0\,max} = (\pi / (2\,T_c))\,(V_{BO} - V_{RO})\,(1 + e_r)\,m_B / (1 + m_B / M_r). \tag{6}$$

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.

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

$$A_{nv}(t) = S_0(t)\,[\,1 / (M_R + M_H) - (a / I_G)\,X] \tag{7}$$

where X denotes the distance between the centre of mass of racket-arm system and the location of hand grip, a the distance between the centre of mass of racket-arm system and the impact location of the racket, I_G the moment of inertia around the centre 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 $S_{0\,max}$.

The vibration acceleration component $A_{i\,j,k}(t)$ of the k-th mode at the location i of handgrip is represented as:

$$A_{i\,j,k}(t) = -(2\pi f_k)^2 r_{ij\,k} S_{0j}(2\pi f_k) exp(-2\pi f_k \zeta_k t)\, sin(2\pi f_k t) \qquad (8)$$

where j denotes the impact location between ball and racket on the string face, ζ_k the damping ratio of the k-th mode, $S_{0j}(2\pi f_k)$ the Fourier spectrum of equation (5). The summation of equations (7) and (8) represents the shock vibrations at the handgrip.

VARIOUS IMPACT FACTORS WITH THE LARGER BALL COMPARED TO THE CONVENTIONAL BALL

Figure 11 - 14 are the predicted results of maximum impact force, contact time, the deformation of the strings and the deformation of the ball against impact velocities at the centre on the string face. The contact time of the larger ball is slightly longer and the impact force is slightly smaller. Accordingly there is no big difference in the deformation of the string and the ball between the larger ball and the normal ball.

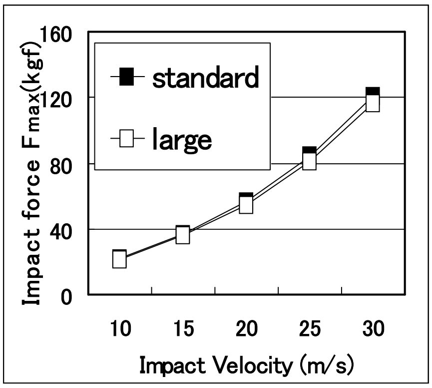


Figure 11. Predicted impact force against impact velocity at the center on the string face (45 lbs).

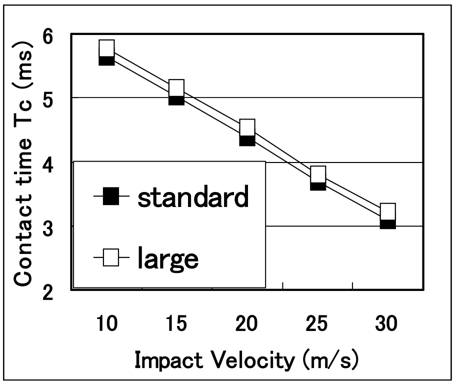


Figure 12. Predicted contact times against impact velocity at the center on the string face (45 lbs).

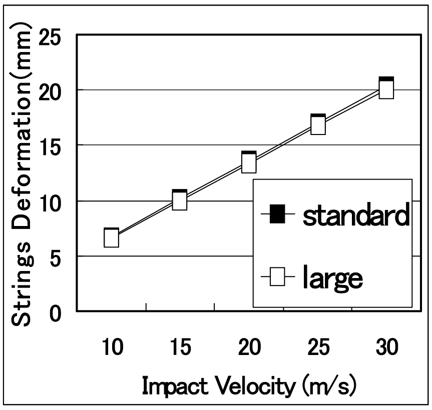


Figure 13. Predicted string deformation against impact velocity (45 lbs).

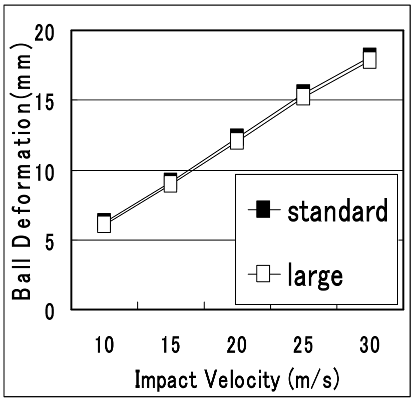
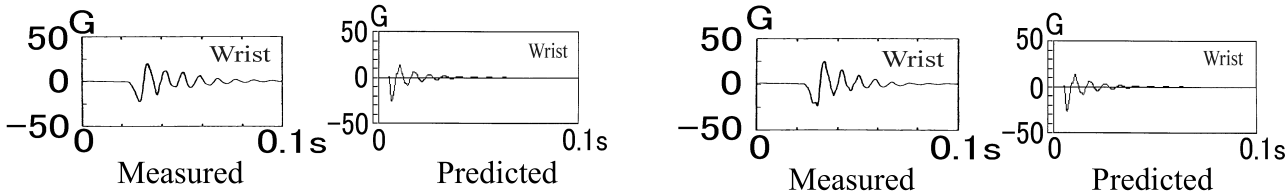


Figure 14. Predicted ball deformation against impact velocity (45 lbs).

PREDICTED RESULTS OF THE SHOCK VIBRATIONS AT THE WRIST JOINT

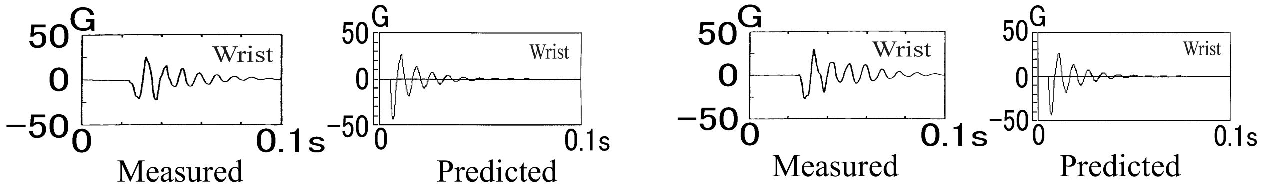
The damping ratio of a hand-held racket during actual impact has been estimated as about 2.5 times that of the one identified by the experimental modal analysis with small vibration amplitude. Furthermore, the damping of the waveform at the wrist joint has been 3 times that at the grip portion of the racket handle. Figure 15 shows the comparison between the predicted shock vibrations at the wrist joint and the measured ones with (a) the normal ball and (b) the larger ball in the off-centre impact during the ground stroke, where the racket is strung at 45 lbs. Figure 16 shows the results when the racket is strung at 65 lbs. The predicted waveform of the shock vibrations with the wrist joint agrees fairly well with the measured one during actual forehand stroke by a tournament player.

Figure 17 shows the peak value between the maximum and minimum of acceleration waveform. Figure 18 shows the predicted peak values of shock vibrations at the wrist joint with the larger ball compared to the normal ball against the locations of string face strung at 65 lbs when the impact velocity is 30 m・s^{-1}. The shock vibrations at the wrist joint with the larger ball are almost the same as those of normal ball. Since the drag force of the larger ball is larger than that of the normal ball,



(a) Normal ball (impact velocity: 21±1 m・s^{-1}) (b) Larger ball (impact velocity: 19±1 m・s^{-1})

Figure 15. Shock vibrations at the wrist joint when hitting a flat forehand drive off-centre (top side) of racket face strung at 45 lbs.



(a) Normal ball (impact velocity: 21±1 m・s^{-1}) (b) Larger ball (impact velocity: 21±1 m・s^{-1})

Figure 16. Shock vibrations at the wrist joint when hitting flat forehand drive at the off-center (Top side) of racket face strung at 65 lbs.

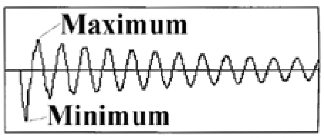


Figure 17. Peak value.

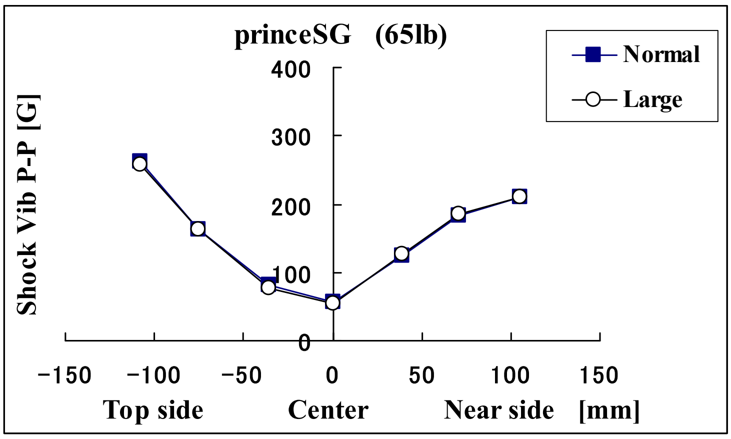


Figure 18. Peak values of shock vibrations at the wrist joint with the larger ball compared to the normal ball against the locations of string face strung at 65 lbs when the impact velocity is 30 m・s^{-1}.

the shock vibrations at the wrist joint with the larger ball should be smaller.

CONCLUSIONS

(1) The simulated results agreed fairly well with the experimental results.
(2) The waveforms of the shock vibrations at the wrist joint when using the larger ball are almost the same as those when using the normal ball independent of the string tensions. Since the drag force of the larger ball is larger than that of the normal ball, the shock vibrations of a larger ball should be smaller.
(3) The contact time of the larger ball is slightly longer and the impact force is slightly smaller. Accordingly there is no big difference in the deformation of the string and the ball between the larger ball and the normal ball.

ACKNOWLEDGEMENT

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