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Experimental and theoretical criticism of the effectiveness of looser strings for the reduction of tennis elbow

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Lower string tension is to increase the dwell time of the ball on the strings and generate less impact on the arm. However, a previous paper showed experimentally that there is little difference in the waveforms at the wrist joint between a loosely strung and tightly strung racket for a flat forehand drive. There was also little difference between a loosely strung racket and a tightly strung racket, at the player's elbow joint and the racket handle, when he serves. The predicted waveforms have agreed fairly well with the measured ones. The predicted contact time for a loosely strung racket is longer compared to a tightly strung racket below impact velocities of 20 ms^{-1}, but almost the same above 20 ms^{-1}. The predicted deformation of the strings is larger, but the deformation of the ball and the impact force are almost the same, compared to the tightly strung racket. This is also the reason why a lower string tension does not result in a significant increase in rebound velocity.

INTRODUCTION

Currently, the terms used in describing the performance of a tennis racket are still based on the feel of an experienced tester or a player. Accordingly, there are many unknowns in the relationship between the performance estimated by a player and the physical properties of a tennis racket.

Although it is unknown how tennis elbow is caused, tennis elbow can be serious and can keep a player sidelined for many months. It is often said that the lower tensions of strings offer less impact on the arm, are better for the arm, and that is because they increase the dwell time of the ball on the strings (Pluim, 2000). A lot of engineering research has been conducted to determine an optimal tennis racket design, and numerous variables have been considered in order to assess the mechanical performance of the racket and string system along with their effect on the behaviour of a ball after impact (Groppel *et al.,* 1987a). It is well accepted that the string is quite important. Nevertheless, regarding the effects of string pre-tension, which means an initial tensile force prior to impact with the ball, the conventional research only demonstrates the complexity of the interaction of string and racket and suggests that more research should be conducted (Groppel *et al.*, 1987b). However, there are few publications containing experiments conducted at the actual impact velocities.

Kawazoe (1994a) has investigated the effects of string pre-tension on forces and duration of impact during the tennis stroke on the basis of a simple non-linear impact model (Kawazoe 1992a, 1993, 1994b, 1997). He pointed out the following: (1) although the impact force markedly increases with the impact velocity, it is not much affected by the string pre-tension; (2) the contact time decreases with increase of the impact velocity, but the string pre-tension does not have a marked influence on the contact time except at very low impact velocities; (3) according to the measured accelerations of the racket handle during actual forehand drives with the rackets strung at 35 lbs and strung at 60 lbs, there is no difference between them; (4) when the ball hits the centre of the string face, the difference of the predicted amplitudes of racket vibrations with different string pre-tensions is very small; (5) when the ball hits off-centre, the amplitude of a racket strung at higher tension is slightly larger than that of a racket strung at lower tension. According to the recent experimental research (Kawazoe *et al.*, 2002) on the effect of the string tensions on the impact shock vibrations of the arm of a tennis player, it was shown that there is little difference in the waveforms between a loosely strung racket and a tightly strung racket. In this study, the accelerations at the player's wrist joint and the racket handle were measured during the forehand groundstroke and at the player's elbow joint and the racket handle were measured during the serve in order to complement and validate the authors' previous research work.

This paper predicts and validates the mechanism of transmission of shock vibrations at the wrist joint with a loosely strung racket compared to a tightly strung racket during a forehand stroke.

EXPERIMENTAL RESULTS FOR DIFFERENT STRING TENSIONS AT REALISTIC IMPACT VELOCITIES

Figure 1 shows the effects of string tension on the measured coefficient of restitution e_{BG} when a ball strikes the strings with a racket head (string bed) clamped. The coefficient of restitution e_{BG} can be related to the energy loss of the ball and strings due to the impact (Kawazoe, 1992). String tension for most strings is between 200 N and 300 N; a string tension of 100 N is too loose for play. Impact velocity for most players during real play is between 20 m/s and 30 m/s and between 25 m/s and 35 m/s for an advanced player. The maximum pre-impact velocity (racket head velocity) during the serve of tour pros is over 40 m/s. Figure 2 shows the averaged coefficient of restitution e_{BG} between a ball and strings vs. string tension at impact velocities of 20 m/s and 30 m/s. This shows that the 40 % decrease in string tension from 300 N to 200 N results in only a 1.4 % increase in the restitution coefficient e_{BG} between a ball and strings at an impact velocity of 20 m/s, and results in almost no increase at 30 m/s. It is well accepted from experience and empirical studies, as Kotze *et al.* (2000) pointed out, that reducing the string tension reduces the deformation of the ball, and lower string tensions enable more powerful shots. Nevertheless, it is shown that the effect of the string tensions on the coefficient of restitution between a ball and strings at realistic impact velocities is very small.

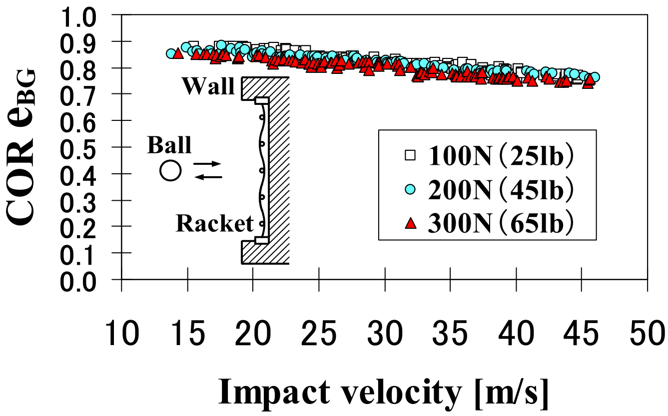


Figure 1. Measured coefficient of restitution e_{BG} between a ball and strings vs. impact velocity showing the effect of string tensions.

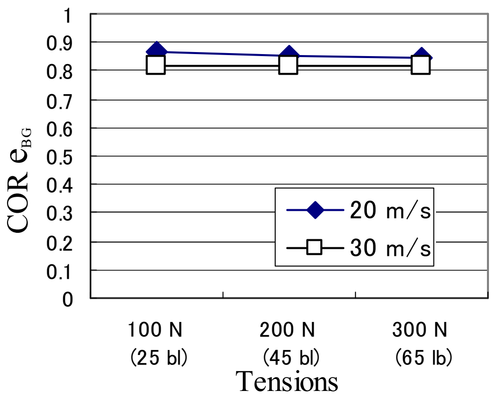


Figure 2. Averaged coefficient of restitution e_{BG} between a ball and strings vs. string tensions at the impact velocities of 20 m/s and 30 m/s.

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) and also shows the example of realistic restoring force-displacement curve corresponding to in-play, exhibiting the characteristics of strong non-linearity.

Figure 4 is an example of measured contact time vs. impact velocity with the rackets strung at different tensions (55 lbs and 75 lbs) showing that string tensions have no significant effect on the contact time in the actual impact velocity of over 20 m/s (Kawazoe 1994a).

Figure 5 shows the measured accelerations at the player's elbow joint and the racket handle (210 mm from the grip end) when a male tournament player hits a ball slightly above centre on the string face during service stroke. The impact velocity was derived from a high-speed video of the racket tip when a tester hits the ball. Although the shock vibrations of the elbow joint with the racket strung at 45 lbs seem to be marginally smaller than those with the racket strung at 65 lbs, the shock vibrations of the racket handle with the racket strung at 45 lbs are markedly larger than those with the racket strung at 65 lbs. This means that the lower tensions of strings do not always offer less impact on the arm and are not always better for the arm.

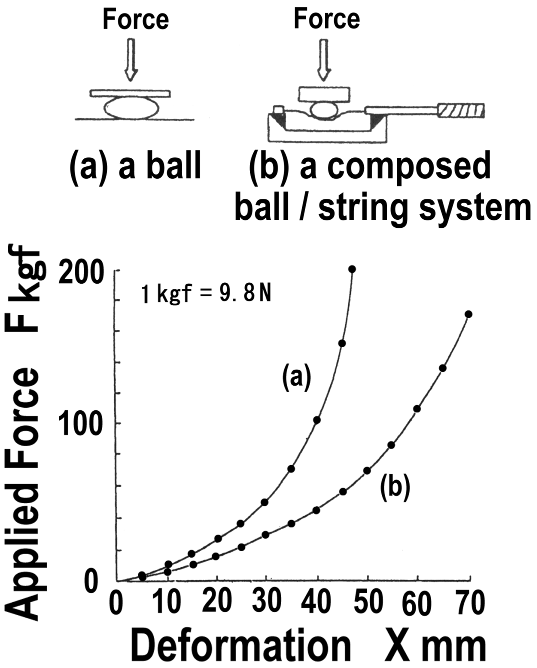


Figure 3 Applied force- deformation test and the results.

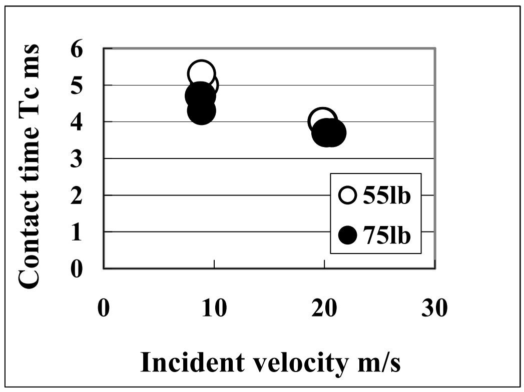
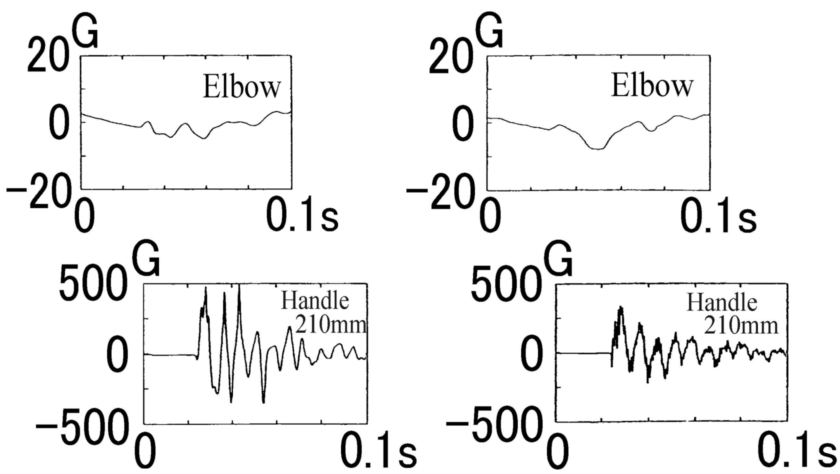


Figure 4. Measured contact time with different string tensions and different impact velocities.



(a) 45 lbs (impact velocity: 30±1 m/s) (b) 65 lbs (impact velocity: 32±1 m/s)

Figure 5. Measured shock vibrations at the elbow joint and the racket handle (210 mm from grip end) when hitting a normal ball with a service stroke at the centre of the racket face.

METHOD TO PREDICT THE SHOCK VIBRATIONS AT THE WRIST JOINT

Table 1 shows the physical properties of rackets used in this study. The acceleration of the shock vibrations at the player's wrist joint and at the racket handle was measured when a player hits flat forehand drive. The location of the accelerometer at the racket handle is 210 mm from the grip end. The waveforms of acceleration when struck at the off-centre (top side) and those at the centre were recorded during forehand stroke. Although we tested the effect of string tensions using three types of balls, we deal with only a normal ball here. We used two rackets named SG (made by Prince) in the test, and each racket was strung at 45 lbs and 65 lbs respectively. The sign I_{GY} denotes the moment of inertia about the centre of mass, the sign I_{GR} the moment of inertia about the grip portion 70 mm from the grip end, and the sign I_{GX} the moment of inertia about the longitudinal axis of racket head.

We used three rackets strung at 45 lbs, 55 lbs and 65 lbs in the prediction of the performance in terms of power and the shock vibrations of wrist joint based on the experimental identification of a ball, racket, arm and impact analysis (Kawazoe *et al.* 1997, 1998, 2000, 2002, 2003).

We consider the racket to be freely hinged to the forearm of the player, 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 *et al.* 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 centre of gravity are given. There is little difference in the predicted reduced mass between the racket-arm system and the freely suspended racket along the impact locations on the string face (Kawazoe *et al.* 2003).

The vibration characteristics of a racket can be identified using 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 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, 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.

Rackets	prince SG		
Tention	45lb	55lb	65lb
Total length [mm]	687	685	688
Mass[g]	337	338	339
Center of gravity [mm]	329	327	330
Face area [cm^2]	694		
Moment of inertia I_{GY} about Y axis [gm^2]	15.0		
Moment of inertia I_{GR} about grip (70 mm) [gm^2]	37.3		
Moment of inertia I_{GX} about X axis [gm^2]	0.935		

Table 1 Physical properties

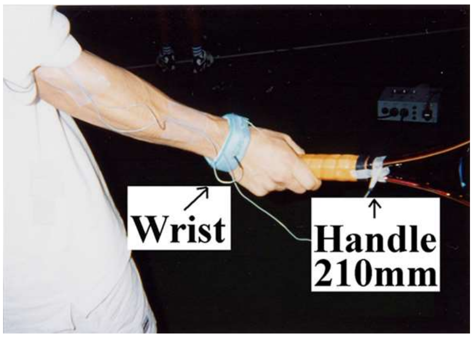


Figure 5. Location of accelerometers at the wrist joint and the racket handle in the forehand ground stroke.

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, 1994). 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 $A_{rv}(t)$ at the hand grip considering the equivalent mass M_H of the arm system can be represented as:

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

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, and I_G the moment of inertia around the centre 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_{0max}.

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

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

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.

PREDICTED EFFECT OF STRING TENSION ON VARIOUS FACTORS

Figure 7 shows the predicted stiffness of the string bed vs. impact velocity, while Figure 8 shows the predicted stiffness of the string bed vs. string deformation. Although the string stiffness markedly increases with the impact velocity, it is not much affected by the initial string tension.

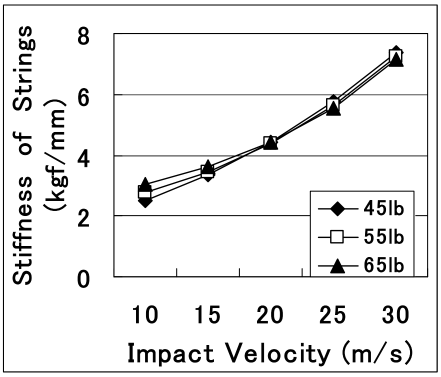


Figure 7. Predicted stiffness of the string bed vs. impact velocity relative to the string tension as a parameter.

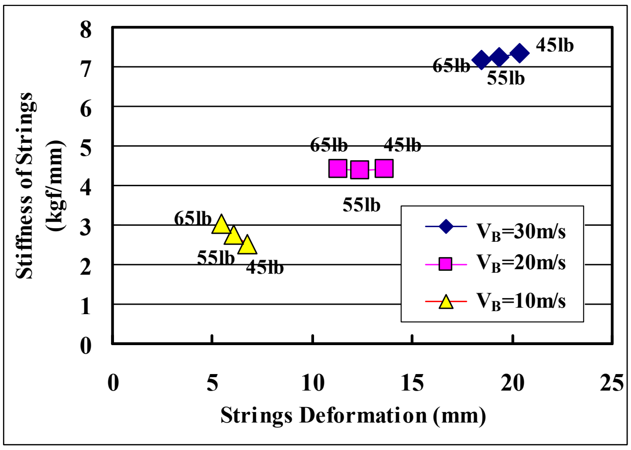


Figure 8. Predicted stiffness of the string bed vs. string deformation relative to the string tension as a parameter.

Figures 9 and 10 are the predicted string deformation and the ball deformation respectively, showing that a lower string tension results in an increase in string deformation but does not result in a decrease in ball deformation at realistic impact velocities. This is the reason why a lower string tension does not result in a significant increase in rebound velocity. Figure 11 is the predicted contact time, showing that the contact time decreases markedly with increasing the impact velocity and that the string tension does not have an effect on the contact time in an actual tennis play.

Figure 12 is the predicted contact time at very low impact velocities, which is very similar to Brody (1987). Although the predicted impact force also markedly increases with the impact velocity, it is not much affected by the initial string tension.

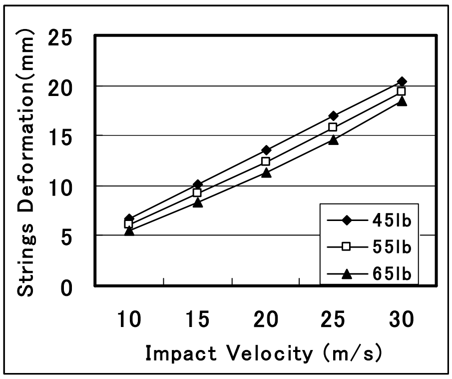


Figure 9. Predicted string deformation vs. impact velocity.

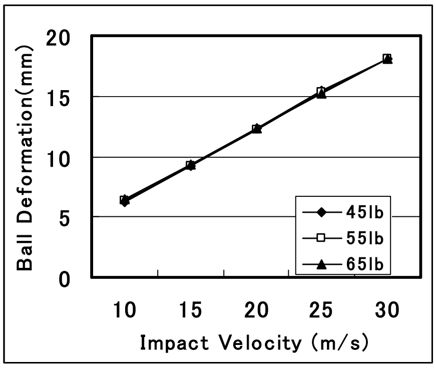


Figure 10. Predicted ball deformation vs. impact velocity.

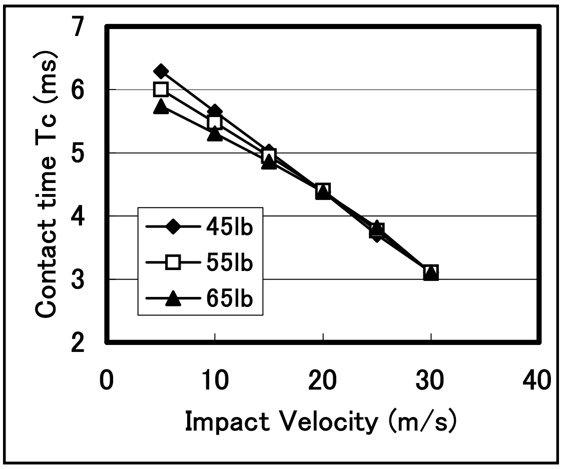


Figure 11. Predicted contact time vs. impact velocity relative to the string tension as a parameter.

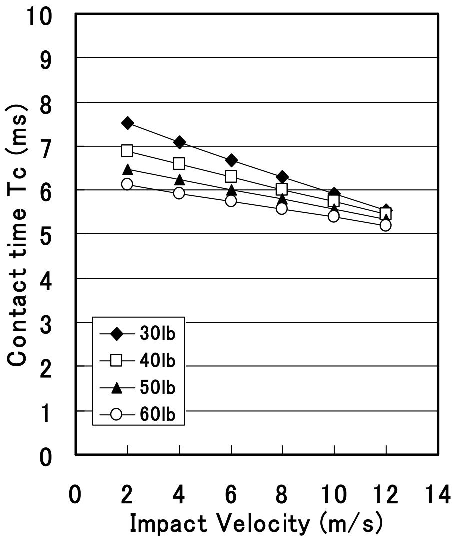
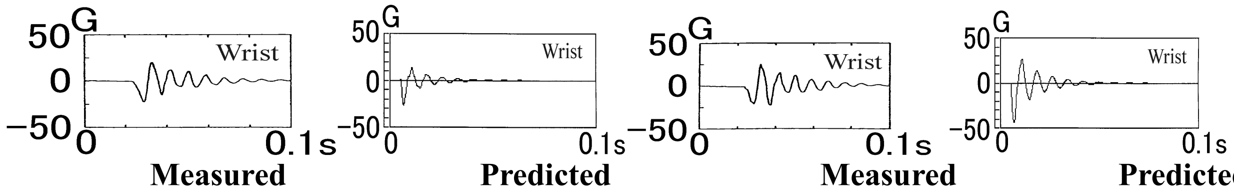


Figure 12. Predicted contact time vs. impact velocity at very low impact velocities.

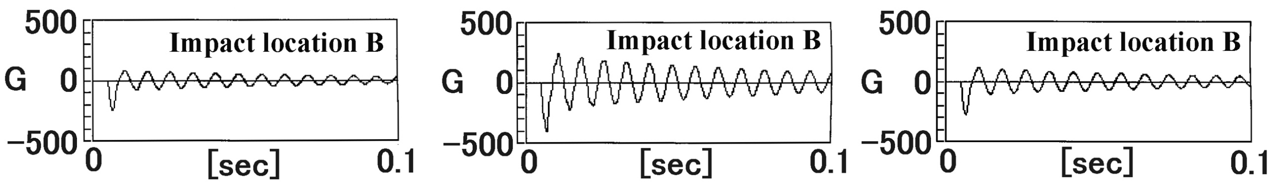
EFFECT OF STRING TENSION ON THE SHOCK VIBRATIONS AT THE WRIST JOINT

Figure 13 shows the comparison between the predicted shock vibrations and the measured ones at the wrist joint when hitting a ball with flat forehand drive at the off-centre (top side) of racket face. Figure 14 shows the predicted shock vibrations at the grip 70 mm from the grip end when a ball strikes the suspended racket at the off-centre (top side) along the longitudinal axis of racket face (impact velocity: 30 m/s). Figure 15 shows the predicted shock vibrations at the grip 70 mm from the grip end when a ball strikes the suspended racket at the off-centre (near side) along the longitudinal axis of racket face (impact velocity: 30 m/s). Figure 16 shows the shock vibrations peak values vs. locations of string face relative to the string tension as a parameter (impact velocity: 30 m/s). The predicted shock vibration of the racket strung at 45 lbs is slightly smaller than that of the racket strung at 65 lbs, while that of the racket strung at 55 lbs is the largest. This may be a matching problem between the natural frequency of frame bending vibration and that of strings membrane vibration.



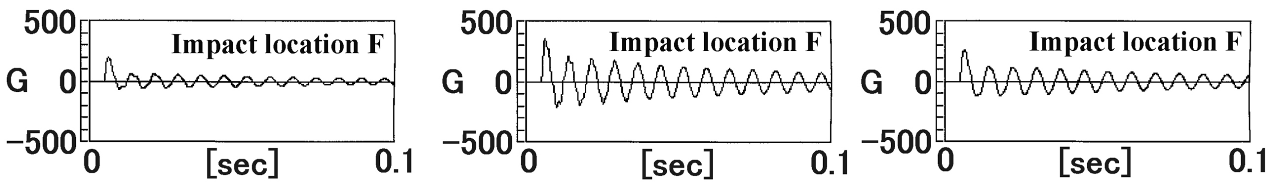
(a) 45 lbs (impact velocity: 21±1 m/s) (b) 65 lbs (impact velocity: 21±1 m/s)

Figure 13. Comparison between the predicted shock vibrations and the measured ones at the wrist joint when hitting a ball with flat forehand drive at the off-centre (top side) of racket face.



(a) 45 lbs (b) 55 lbs (c) 65 lbs

Figure 14. Predicted shock vibrations at the grip 70 mm from the grip end when a ball strikes the suspended racket at the off-centre (top side) along the longitudinal axis of racket face (impact velocity: 30 m/s).



(a) 45 lbs (b) 55 lbs (c) 65 lbs

Figure 15. Predicted Shock vibrations at the grip 70 mm from the grip end when a ball strikes the suspended racket at the off-centre (near side) along the longitudinal axis of racket face (impact velocity: 30 m/s).

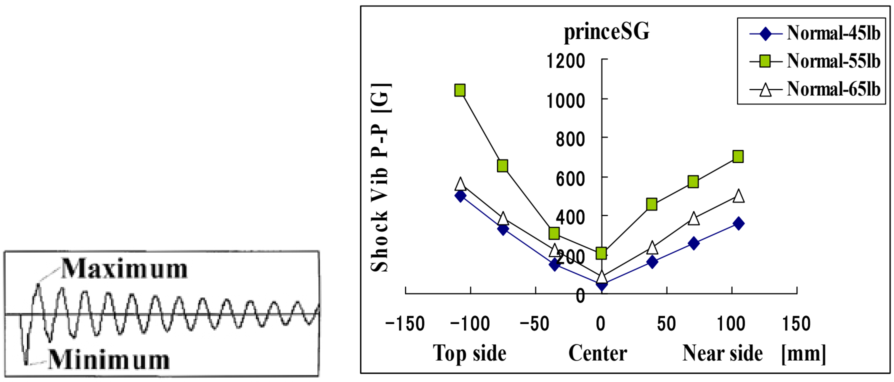


Figure 16. Shock vibrations peak values vs. locations of string face relative to the string tension as aparameter (impact velocity: 30 m/s). Peak value means the amplitude between the maximum and minimum of the acceleration waveform.

CONCLUSIONS

This paper has predicted the shock vibrations at the wrist joint with a loosely strung racket compared to a tightly strung racket during a forehand stroke. The simulated results have agreed fairly well with the experimental results. The predicted contact time for the loosely strung racket is longer compared to the tightly strung racket below 20 m/s of impact velocities, but both are almost the same at a more realistic impact velocity; above 20 m/s. The predicted deformation of the strings is larger, but the deformation of the ball and the impact force are almost the same, when compared to the tightly strung racket. This is also the reason why a lower string tension does not result in a significant increase in rebound velocity.

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