Tennis Top Spin Comparison between New, Used and Lubricated Used Strings by High Speed Video Analysis with Impact Simulation

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This paper made clear the mechanism of actual top spin and its improvement by lubrication of used and notched strings at the intersections using 10,000 frames/sec high-speed video analysis. Contrary to the hypothetical conventional spin theory, as the main (longitudinal) strings stretch and slide side ways more and they spring back by lubrication of notched strings, the ball is given more spin when the ball is released from the strings. The notches at string intersections reduce the spin rate of the ball. More spin produce longer contact time between ball and strings, resulting in the reduction of shock vibrations of the wrist joint during impact according to the impact simulation based on the experimental identification of racket-arm system. Furthermore, it showed that the spin rate of a newly strung racket without notch is much larger than that of a racket with lubricated used strings. The lubricant materials are most effective to the notched used strings.

1. INTRODUCTION

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.

The restitution characteristics between a ball and racket as well as the shock vibrations at the wrist joint can be calculated for a simple forehand swing model at any given swing speed and at any impact location on the string plane if the ball strikes the strings at normal incidence [1)-16)].

However, the ball spin is the mystery. Very little is known about the relationship between the ball spin and the string characteristics both for researchers and players.

Players often say that some strings provide a better grip and more spin than others, but ball spin did not depend on string tension, gauge or type and the scatter of data was larger than the difference of strings in the past laboratory experiment for oblique impacts on a head-clamped racket or a freely suspended racket. Even recent measurements made by several authors on rebound spin [17)-23)] showed that there still be no significant difference in ball spin off natural and synthetic gut strings, off thin and thick strings, off loose and tight strings, contrary to common belief.

There was no research work on the topspin to uncover what is really happening during actual tennis impact owing to difficult experiment, although the topspin hitting is very popular among amateur players in these days.

This paper will make clear the mechanism of actual top spin and its improvement by lubrication of used notched strings at the intersections using 10,000 frames/sec high-speed video analysis. It also shows that more spin results in more reduction of shock vibrations of the wrist joint during impact according to the impact simulation based on the experimental identification of racket-arm system. Furthermore, it shows that the spin rate of newly strung racket without notch is much larger than that

of lubricated used racket.

2. MECHANISM OF TENNIS TOP SPIN AND PERFORMANCE IMPROVEMENT BY LUBRICATION OF NOTCHED USED STRINGS

Figure 1 shows the notches of used gut (natural strings) at the intersections of string face of racket. Figure 2 shows the oblique view of topspin impact by a professional racket tester in the experiment using the ultra high-speed video analysis. Figure 3 shows an example of frames of ultra high-speed video operating 10,000 frames/sec for topspin impact analysis, where (a) side view for velocity analysis of spin angular motion and rectilinear motion of a ball and (b) behind view for analysis of contact time and spin behaviors.

Figure 4 shows the geometry of Racket MP-1 used in the experiment and Table 1 shows its specification and fundamental physical property.

Figure 5 shows the ball spin behaviors viewed from behind the racket, in which (a) with the notched used strings and (b) with the lubricated strings at the intersections. The long main strings stretch and slide side ways more across the short cross strings and mains spring back by lubrication at the string intersections in Fig.5(b) compared to the notched used strings in Fig.5(a), where the mains do not move much and do not recover to their original position. The contact time (dwell time) for the lubricated strings is longer (4.1 ms) than that for the notched used strings (3.4 ms) [24]-[25].

Figure 6 shows the high-speed video frames from behind the racket to see and analyze the effect of the lubrication of the notched used strings at the intersections on the ball spin during topspin forehand stroke, using high-speed video operating at 10,000 frames per sec. Figure 6(a) shows the topspin using a racket with notched strings at the intersections which was used 3 hours a day for a week. Figure 6(b) shows the topspin using the same racket with the lubricated strings at the intersections. The main strings (longitudinally strung) stretch and slide side ways more and they spring back by lubrication of string intersections in Fig. 6(b) compared to the topspin with notched strings in Fig.6(a), which does not move much and does not recover to their original position. The contact time (dwell time) with lubrication in Fig.6(b) is longer than that of ordinary used strings in Fig.6(a).

Figure 7 shows the frames from side views, where Fig.7(a) shows the ordinary used strings and Fig.7(b) shows the strings with oil lubrication. As the main strings stretch and slide side ways more
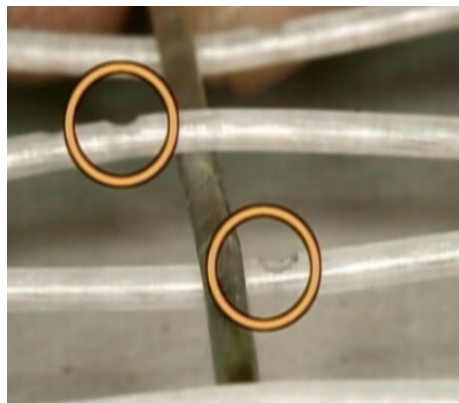

Fig.1 Notches of used gut (natural strings) at the intersections of string face of racket.

| (a) f00L | (b) f30L | (c) f50L | (d) f70L | (e) f90L | (f) f110L |

Fig.2　Oblique view of topspin impact of a tester in this experiment.

(a) From the side　　　　　　　　**(b) From the backside**
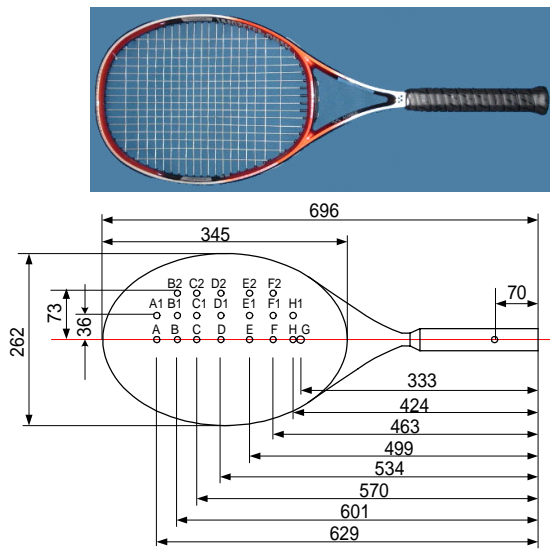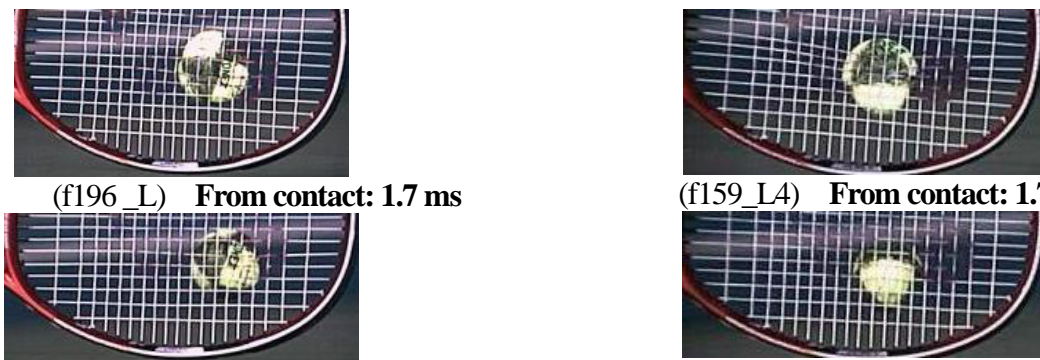
Fig.3 High speed video for impact topspin analysis.

Fig.4 Geometry of Racket MP-1.

Table 1 physical property of tennis racket

Racket	MP-1
	Muscle Power 1
Total length	**696 mm**
Face area	**581** ²
Mass	**310**
Center of gravity from grip end	**333 mm**
Moment of intertia I_{GY} about Y axis	**14.9gm²**
Moment of intertia I_{GR} about grip	**36.4 gm²**
Moment of intertia I_{GX} about X axis	**0.954gm²**
1st frequency	**146 Hz**
Strings tension	**50lb**

(f196 _L)　　**From contact: 1.7 ms**

(f213_L)　　**End of contact: 3.4 ms**

(a) Without strings lubrication T405

(f159_L4)　　**From contact: 1.7 ms**

(f183_L4)　　**End of contact: 4.1 m**

(b) With strings lubrication　T506

Fig.5 Mechanism of top spin improvement by lubrication of used notched strings at the intersections of the string face (Impact views from behind the racket).

and they spring back by lubrication of strings intersections in Fig.7(b), the ball is given more spin (2460 rpm) when the ball is released from the strings compared to the ordinary used strings (1180 rpm).

　　Figure 8 shows the mechanism of spin rate increase by lubrication of string intersections. Main strings stretch and slide side ways and spring back when the ball is released from the strings. The ball is given more extra spin when the main strings can slide freely over the cross strings, bite into the ball (the ball sinks into the strings) and spring back to their original position by reducing friction with oil lubrication of the notched string intersections, where the elastic force in a direction parallel to the string surface make a ball spin.

(f179_L) Start contact 0.0 ms

(f185_L) 0.6 ms

(f190_L) 1.1 ms

(f196 _L) 1.7 ms

(f200_L) 2.1 ms

(f204_L) 2.5 ms

(f209) 3.0 ms

(f211) 3.2 ms

(f213_L) End contact 3.4 ms

(f142_L4) Start contact 0.0 ms

(f148_L4) 0.6 ms

(f153_L4) 1.1 ms

(f159_L4) 1.7 ms

(f163_L4) 2.1 ms

(f167_L4) 2.5 ms

(f172_L4) 3.0 ms

(f174_L4) 3.2 ms

(f176_L4) 3.4 ms

(f180_L4) 3.8 ms

(f183_L4) End contact: 4.1 ms

(a) Without strings lubrication (trial T405)

(b) With strings lubrication (trial 506)

Fig.6 Effect of lubrication of used strings on the ball spin behaviors (impact views from back side direction with frames per 10^{-4} s). (a) Without lubrication (b) With lubrication of used strings

Trial 103(f40　)
Start contact

0.0 ms:

1.0 ms

2.0 ms

3.0 ms:
End of contact

(a-1)
Without lubrication

Trial 205(f77　)
Start contact

0.0 ms:
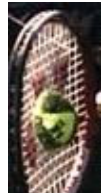
1.0 ms

2.0 ms

3.0 ms

4.0 ms

4.2 ms:
End of contact

(b-1)
With lubrication

Trial 103
Ball release
V_B=31.8 m/s

3.1 ms:

After release
(f81　)

(1 ms)

(2 ms)

(4 ms)

(6 ms)
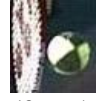
(8 ms)
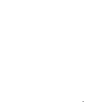
(10 ms)

(12 ms)

(14 ms)

(a-2)
Without lubrication

Trial 205
Ball release
V_B=24.2 ms

4.3 ms:

After release
(f130　)

(1 ms)

(2 ms)

(4 ms)

(6 ms)
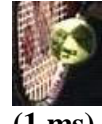
(8 ms)

(10 ms)

(12 ms)
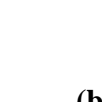
(14 ms)

(b-2)
With lubrication

Ball spin rate ω
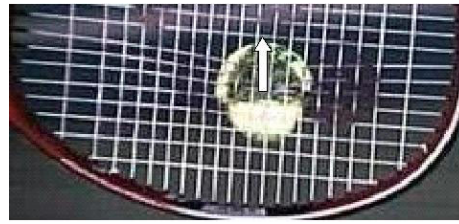**(c)**

Fig.7　Effect of lubrication of used strings on the ball spin (Impact views from side direction)

(T506_ f159_L4)   **1.7 ms after contact**

Fig.8 Ball spin behavior and mechanism of spin rate increase by lubrication of string intersections. Main strings stretch and slide side ways and spring back when the ball is released from the strings. (Impact views from back side direction).

3. COMPARISON OF TOP SPIN PERFORMANCE BETWEEN NEW, USED AND LUBRICATED USED STRINGS BY HIGH SPEED VIDEO ANALYSIS

Figure 9 shows the top spin behavior with a newly strung tennis racket, where (a) shows the ball behavior during contact and (b) shows the top spin behavior after the release of a ball from the string bed.

Figure 10 shows the comparison of top spin performance, that is the ball spin rate, the contact time and the post-impact ball velocity, between the new strings without notches, the notched used strings and the lubricated used strings, which is derived from the average and standard error of three times trials. The ball is given less spin rate (40 % decrease) with the notched used strings compared to that with the new strings. However, the ball is given more extra spin (30 % increase) by oil lubrication at the string intersections compared to that with the notched used strings. Furthermore, more spin with the lubricated used strings produces longer contact time between a ball and strings (21 % increase), reducing the post-impact ball velocity (6 % decrease) compared to those with the notched used strings.

The lubricant material is most effective to the notched strings, because it increases the ball spin rate.
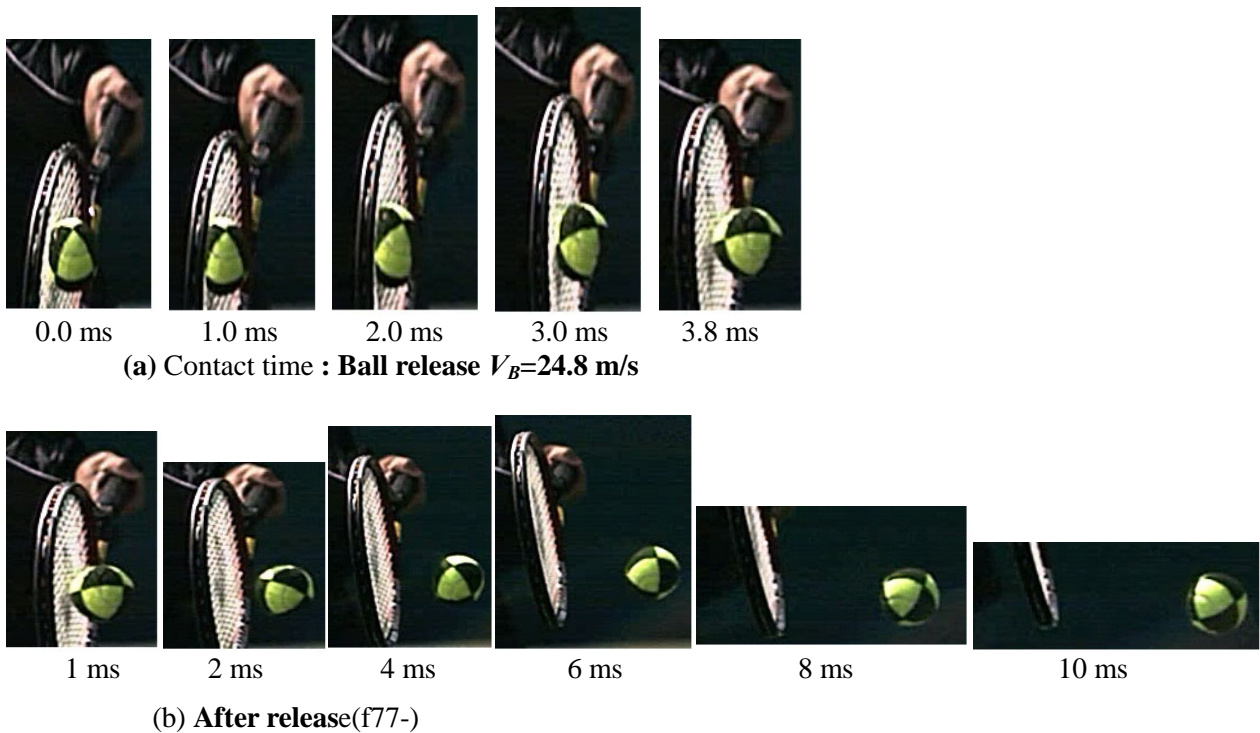

0.0 ms   1.0 ms   2.0 ms   3.0 ms   3.8 ms
(a) Contact time **: Ball release V_B=24.8 m/s**

1 ms   2 ms   4 ms   6 ms   8 ms   10 ms

(b) **After releas**e(f77-)

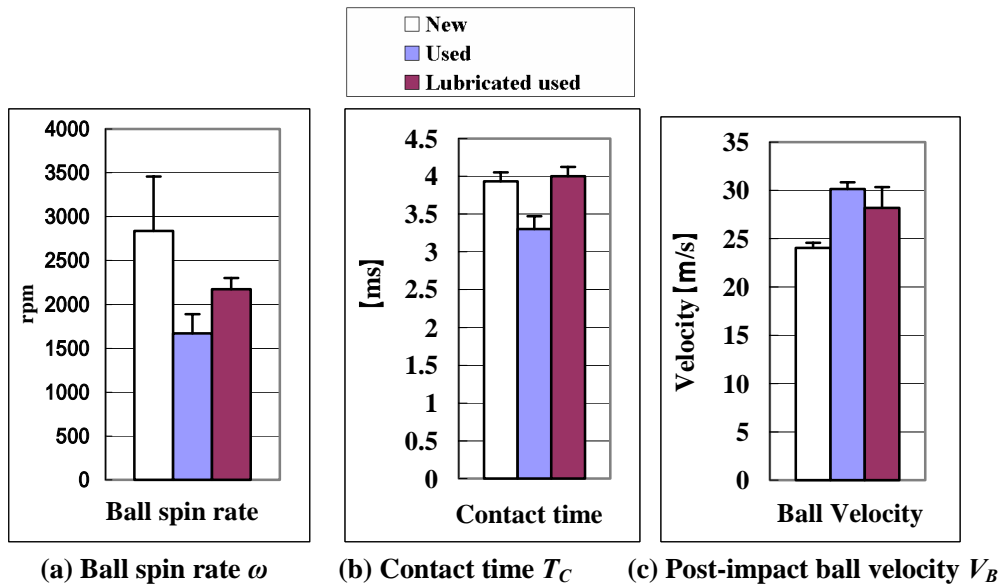Fig.9 Top spin behavior with a newly strung tennis racket (Trial 003:f39   )

Fig.10 Spin performance vs. string conditions with average and standard error.

4. COMPARISON OF TOP SPIN PERFORMANCE WITH THE SHOCK VIBRATION AT THE WRIST JOINT OF A PLAYER BASED ON THE IMPACT SIMULATION

Figure 11 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 12 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, 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 [4)-6),8)-10)]. 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 [1),6),7)] 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 [2),4)].

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 [3), 4)]. 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:

$$A_{mv}(t) = S_0(t)[\quad /(M_R + M_H) \quad (a/I) \quad] \qquad (1)$$

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 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 $A_{\quad,}(t)$ of the k-th mode at the location i of the hand grip is represented as:

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

where j denotes the impact location between ball and racket on the string face, the damping ratio of the k-th mode, and $S_{0j}(2 \quad f_k)$ the Fourier spectrum of impact-force curve between a ball and strings. The summation of eq.(1) and eq.(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 13 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.
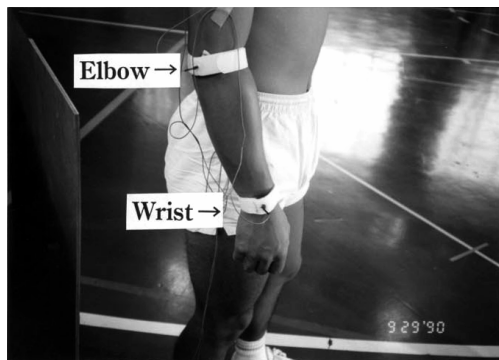

Fig.11 Location of the wrist joint where the accelerations of the shock vibrations are predicted.
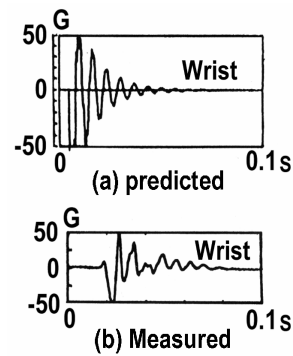

Fig.13 Predicted shock vibrations of a wrist joint compared to the measured.
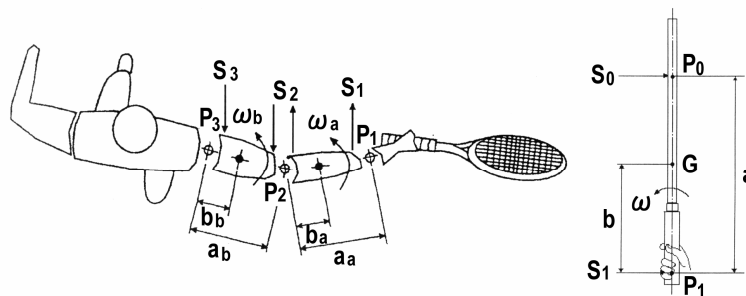

Fig.12 Impact model for the prediction of the shock force transmitted to the arm joints from a racket.

Figure14 shows the simple forehand ground stroke swing model in this study. Figure15 shows the impact model of a ball-string system, where M_r is the reduced mass at the impact locations on the string face. Figure16 shows the string mesh (left side) for identification of vibration characteristics of a racket and the impact locations on the string face (right side) for computer simulation. It is assumed that the ball contacts to the string face at the four cross points.

Figure 17 shows the predicted effects of the spin rate   and the contact time T_C on the fundamental racket frame vibration, where the impact velocity: 30 m/s under the same hitting location on the string plane: top side 95 mm from the tip of racket. Figure 18 shows the predicted effect of the spin rate   and the contact time T_C on the shock vibrations at the wrist joint.

More spin produces longer contact time between ball and strings, resulting in the reduction of shock vibrations of the wrist joint and a feel of softer impact [24)-26)].
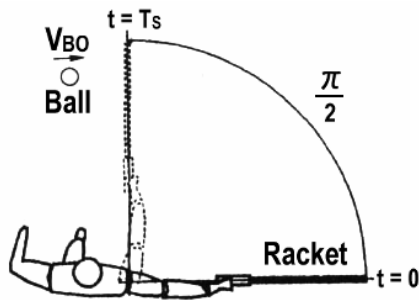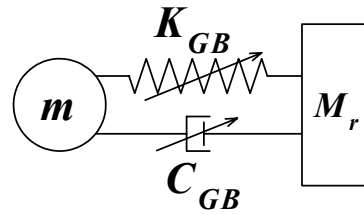

Fig.14 Simple forehand ground stroke swing model.

Fig.15 Impact model of a ball-string system, where Mr is the reduced mass at the impact locations on the string face.
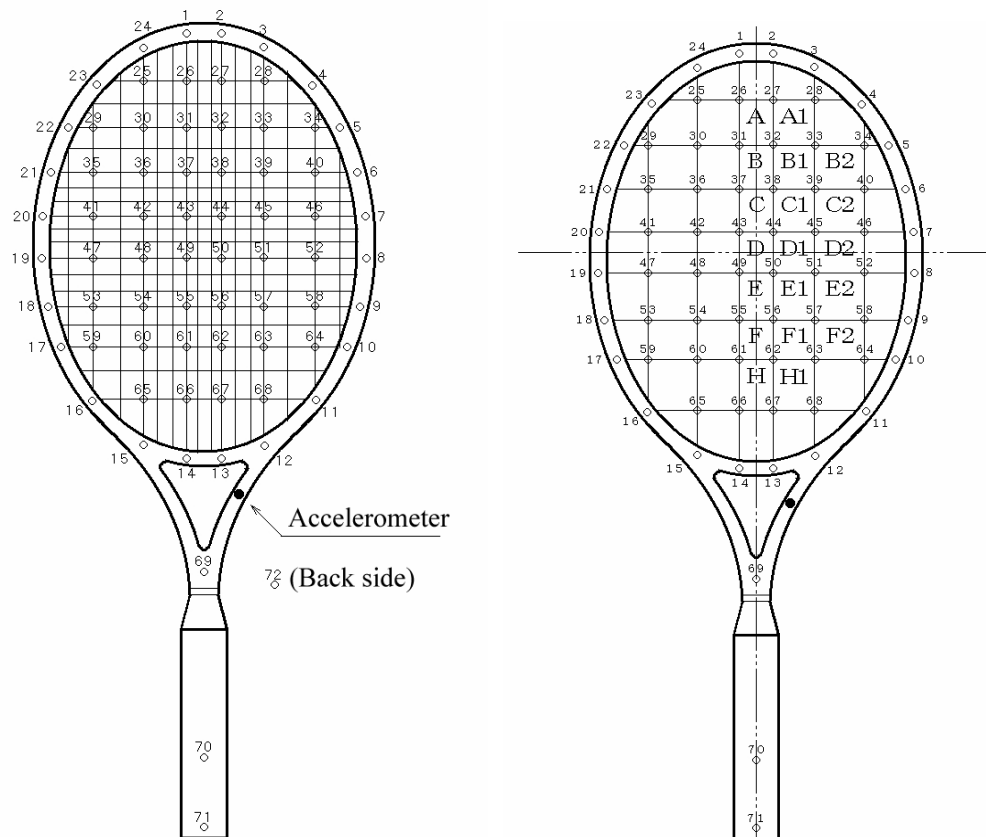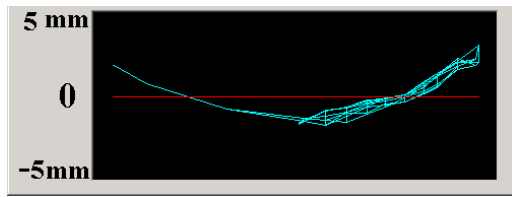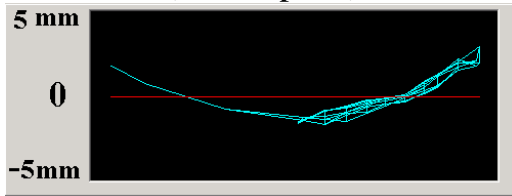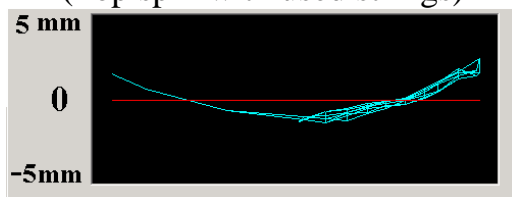

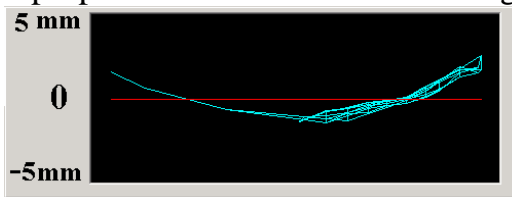Fig.16 String mesh (left side) and impact locations on the string face (right side).

(a) $T_C = 2.6$ [ms], $\omega = 60$ rpm
(Flat impact)

(b) $T_C = 3.4$ [ms], $\omega = 1180$ rpm
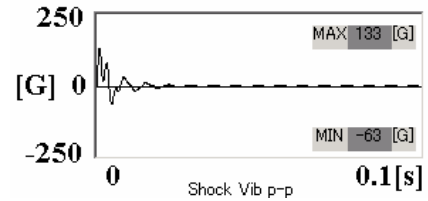(Top spin with used strings)

(c) $T_C = 4.1$ [ms], $\omega = 2460$ rpm
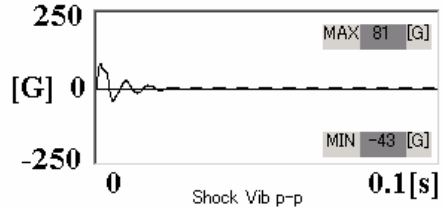(Top Spin with lubricated used strings)

(d) $Tc = 3.9$[ms], $\omega = 2836$ rpm
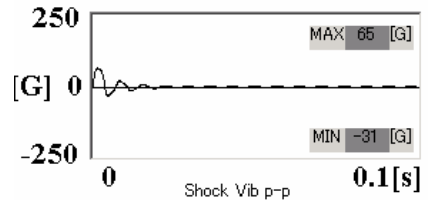(Top Spin with new strings)

Fig.17 Effect of contact time T_C on the fundamental racket frame vibration. Impact velocity: 30 m/s, hitting location: top side 95 mm from the tip of racket.
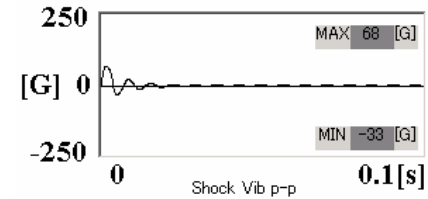

(a) Contact time $T_C = 2.6$ [ms]
(Flat impact)

(b) Contact time $T_C = 3.4$ [ms]
(Top spin with used strings)

(c) Contact time $T_C = 4.1$ [ms]
(Top Spin with lubricated used strings)

(d) Contact time $Tc = 3.9$ ms
(Top Spin with new strings)

Fig.18 Calculated effect of contact time on the wrist joint shock vibrations. Impact velocity: 30 m/s, hitting location: top side 95 mm from the tip of racket.

5. CONCLUSIONS

This paper made clear the mechanism of actual top spin and its improvement by lubrication of used and notched strings at the intersections using 10,000 frames/sec high-speed video analysis.

Contrary to the hypothetical conventional spin theory, as the main (longitudinal) strings stretch and slide side ways more and they spring back by lubrication of notched strings, the ball is given more spin when the ball is released from the strings. The notches at string intersections reduce the spin rate of the ball. More spin produce longer contact time between ball and strings, resulting in the reduction of shock vibrations of the wrist joint during impact according to the impact simulation based on the experimental identification of racket-arm system.

The ball is given less spin rate (40 % decrease) with the notched used strings compared to that with the new strings. However, the ball is given more extra spin (30 % increase) by oil lubrication at the string intersections compared to that with the notched used strings. Furthermore, more spin with

the lubricated used strings produces longer contact time between a ball and strings (21 % increase), reducing the post-impact ball velocity (6 % decrease) compared to those with the notched used strings.

The lubricant material is most effective to the notched strings, because it increases the ball spin rate. Thus, the design concept of strings spin performance should be taken a turn of 180 degrees in future. Actually, almost top pros in the world are recently using the stiff and slippery strings like polyesters.

ACKNOWLEDGEMENTS

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