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Mechanism of Tennis Racket Spin Performance*

(Ultra-High-Speed Video Analysis of Spin Performance Improvement by Lubrication of String Intersections)

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Abstract
Players often say that some strings provide a better grip and more spin than others, but ball spin did not depend on string type, gauge, or tension in pervious laboratory experiments. There was no research work on spin to uncover what is really happening during an actual tennis impact because of the difficulty of performing the appropriate experiments. The present paper clarified the mechanism of top spin and its improvement by lubrication of strings through the use of high-speed video analysis. It also provided a more detailed explanation of spin behavior by comparing a racket with lubricated strings with the famous "spaghetti" strung racket, which was banned in 1978 by the International Tennis Federation because it used plastic spaghetti tubing over the strings to reduce friction, resulting in excessive ball spin. As the main strings stretch and slide sideways more, the ball is given additional spin due to the restoring force parallel to the string face when the main strings spring back and the ball is released from the strings. Herein, we also showed that the additional spin results in a reduction of shock vibrations of the wrist joint during impact.

Key words: Sports Engineering, Tennis Racket, Impact, Ball Spin, Strings, Spaghetti Strings, Lubricant, High Speed Video Analysis, Shock Vibrations, Tennis Elbow

1. Introduction

Many players confirm through experience that some strings "bite" the ball better than others[1]. Appropriate spin (rotation) is required for ball control; a ball with a well-applied spin will bounce sharply and farther after it hits the ground. The spin of the ball at impact is an extremely important element in tennis, and so a research topic of significant interest for a long time has been the question of how spin is affected by such factors as the type, material, tension, and gauge (strand diameter) of strings, of which there are now several hundred commercially available. However, due to the complexity of the phenomenon, prior research has almost all focused on frontal collisions[2],[3]. Therefore, despite a great deal having been revealed concerning rebound characteristics, the relationship between the physical properties of rackets and strings, and spin performance has remained unclear.

For some time now, the hypothesis frequently put forward has been that greater friction

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between the ball and strings leads to easier application of spin, and yet even in recent studies involving oblique collisions with a fixed racket head[(4),(5)], no clear relationship has been observed between friction properties, the type of strings, or the tension with which they are strung (initial tension) and spin performance.

It is an empirical fact that many players, including the world's top professionals, can feel the difference in play caused by using different string. Furthermore, top-spin methods have become commonplace as rackets have become lighter. Accordingly, measurement of the spin behavior of the ball when struck by a player was required in order to clarify the effects of differences in strings on spin[(1),(4),(5)]. However, there are experimental difficulties in the reproducibility of aspects such as the player's (tester's) swing, the position of the racket at the moment of impact, and the position of the ball on the racket surface. Also, there has been virtually no report concerning the spin behavior at the actual moment of impact for tennis.

In the present paper we shed light for the first time on the puzzle surrounding the spin performance of rackets by means of high-speed video analysis at 10,000 fps. Contrary to the conventional assumption that greater friction on the strings results in more spin, we clarify that low friction enables the main and cross strings to slide across one another and the intersections to slip, thus producing spin through the restoring force generated when the main strings stretch sideways and spring back. Lubrication of the string intersections with a silicon oil [international patent application filed and ITF (International Tennis Federation) approval applied for by Mr. Okimoto] results in the main strings sliding to the side and springing back more readily and therefore easier application of rotation. As the spin rate is increased, the contact time also grows. In addition, we show using simulations based on experimental identification of the ball and racket that a longer contact time leads to reduced shock vibrations transmitted to the racket and hand and discuss the correspondence with questionnaire results and the feel when hitting according to the racket tester.

Rackets with what is known as "spaghetti strings" (patent application filed in 1977)[(6),(7)] were banned by the ITF in 1978 on the basis of their ability to apply excessive spin due to the use of spaghetti-like plastic tubes to reduce friction (see Figure 12(a)). Rackets in which the main and cross strings are not alternately interwoven are now prohibited by the rules. We compare our racket with the string intersections lubricated with the results of spin measurements of these "spaghetti rackets" using high-speed video analysis[(6),(7)], and based on the results, we indicate the possibility that it is easier to apply spin with low-surface friction strings like polyester than it is with strings with high surface friction that are commercially available as "spin gut". This overturns conventional theories on spin friction and design.

2. Ultra-high-speed video analysis of top-spin performance improvement due to lubricated string intersections

Figure 1 shows the top-spin technique of the tester hitting a ball thrown by hand. These are high-speed video images taken from an oblique angle at 10,000 fps. Figs. 1(a) and (b) are representative frames prior to impact, Figs. 1(c) and (d) show the time at which the ball and strings are in contact (for the top-spin shown, approximately 3–4 ms), and Figs. 1(e) and (f) show from after the ball has left the string surface. There is almost no change in the angle of the racket surface while the ball and racket are in contact, which proves that spin control using the racket is impossible over this time interval.

Figure 2 shows images from a high-speed video taken to analyze spin behavior. Figure 2(a) was taken from directly to the side of the racket at the moment of impact and is used mainly for analysis of the ball's spin (rotation) rate and linear velocity right after its release from the strings. Figure 2(b) was taken from directly behind the racket at the moment of impact and is used mainly to observe the movement of the ball and strings from the point when they come into contact until their separation, as well as to calculate the contact time between the ball and strings.

Figure 3 shows images of the 10,000 fps high-speed video taken at impact from directly to the side. It shows representative frames from which the approximate trajectory of the racket head during the swing and the angle of impact can be discerned.

Figure 4 shows representative frames of the 10,000 fps imaging taken from directly behind at impact for ordinary strings [Fig. 4(a)] and the same strings with lubricant applied [Fig. 4(b)]. These tests were conducted after stringing at 50 lbs by a professional stringer and a 7-day period of use at 3 h/day. The position of the racket at the moment of impact and the position of the ball on the surface of the racket are in rough agreement between the two sets of images. The contact time (period from the point when the ball and strings come into contact until their separation) is 3.4 ms for the ordinary strings and 4.1 ms for the lubricated strings. When lubricant is applied (made to permeate the intersections between the main and cross strings), it is possible to see that the main strings slide sideways along the cross strings and then spring back once the ball is released. In the ordinary, unlubricated case, even after the ball is released, some of the main strings remain displaced to the side.

Figure 5 shows an enlargement of some of the frames of Figure 4(b) to clarify the behavior when the ball is hit with top spin by a racket with lubricated strings. Figure 5(b) shows directly after the ball and strings have come into contact. As shown in Figure 5(c) (1.7 ms after contact), the main strings slide perpendicularly much more than ordinary unlubricated strings before springing back once the ball is released (Figure 5(d): 4.1 ms after contact). In the case of the ordinary unlubricated strings, as shown in Figure 4(a), the amount of perpendicular sliding by the main strings is low. The easier it is for the main and

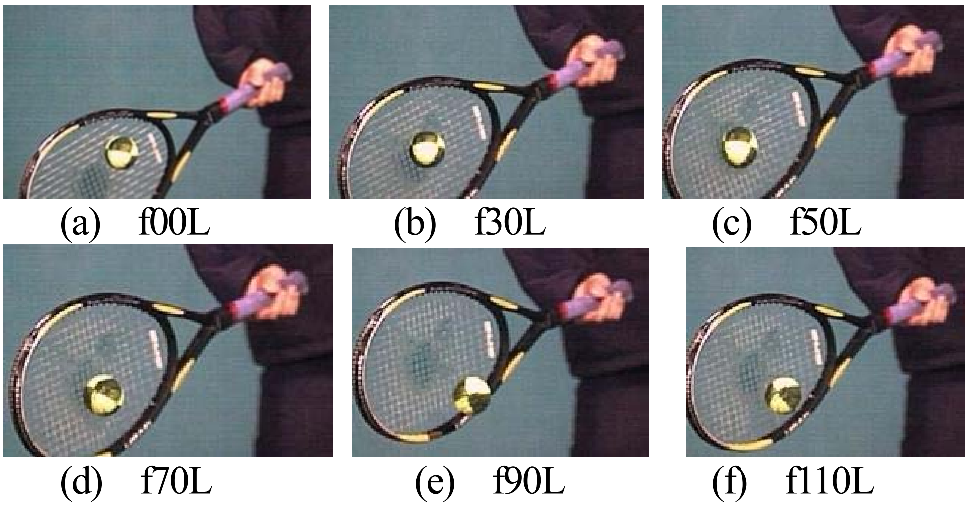


Fig.1 Oblique view of topspin impact (trial T2) of a tester in this experiment

(a) From the side (b) From backside

Fig.2 High-speed video for impact top-spin analysis

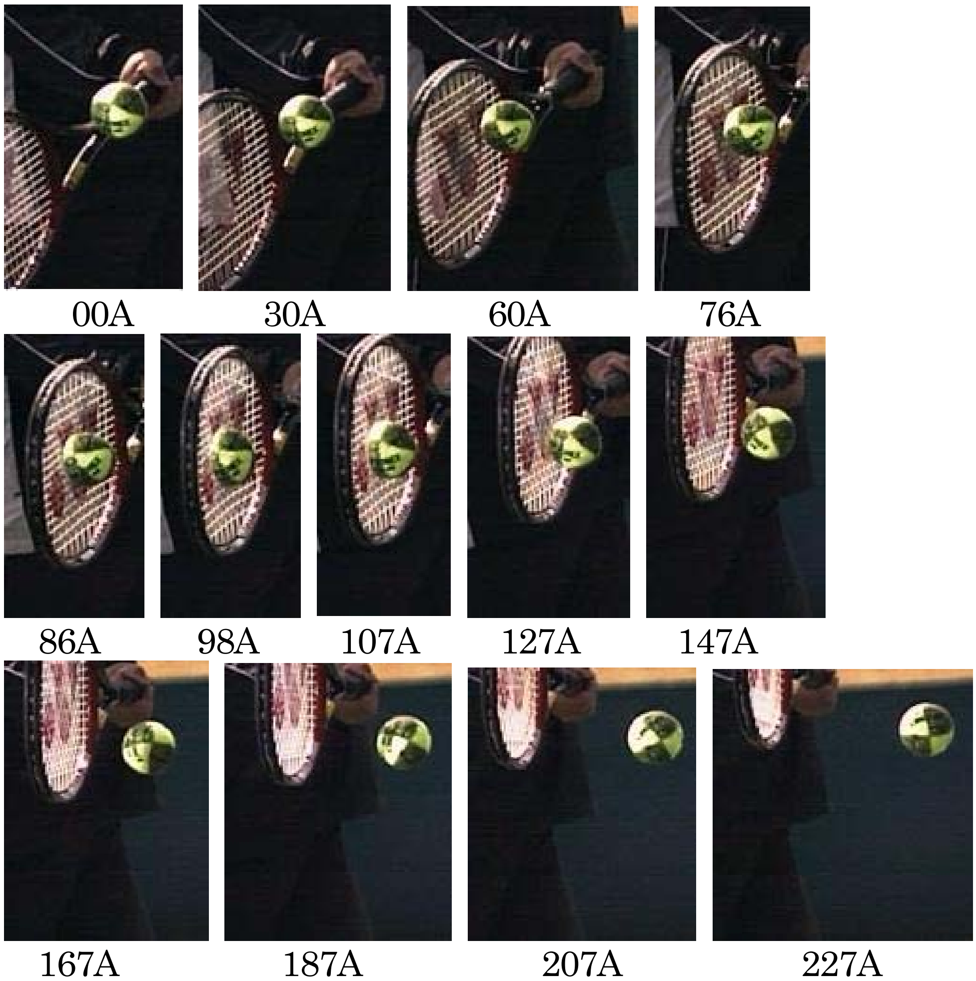


Fig. 3 Side-angle views of top-spin impact (trial 205) of a tester at 104 fps. Pre-impact: 00AL–76A, contact: 86A–107A, post-impact: 127A–

cross strings to slide against each other, the more the strings bite into the ball, and as mentioned in Section 3, the greater is the restoring force from the main strings on the string surface [the arrow in Figure 5(c)]. This is thought to make the application of rotation to the ball easier when the main strings spring back into position.

Figure 6 compares the ordinary, unlubricated case with the trials when the effects of string intersection lubrication were most evident (Figures 3, 4, and 5) in terms of the following factors: (a) the spin rate of the ball directly after its release from the strings (2.1 times greater with lubrication), (b) the contact time between the ball and the strings (23% greater with lubrication), and (c) the linear velocity of the ball directly after its release from the strings (23% slower with lubrication). Figure 7 shows the mean values and standard errors from three trials, where the standard error is the standard deviation divided by $\sqrt{n}$ (n: sample size), and indicates, from the sample averages, which range the true values are most likely to lie in. In terms of average values, the spin rate was 30% greater, the contact time was 16% longer, and the post-impact ball velocity was 6% slower in the lubricated case versus the unlubricated case.

3. Tangential force and rotary torque applied to the ball

If the tennis ball is regarded as a spherical shell, then the moment of inertia of rotation is $I_B = (2/3)\, R_B^{\;2}\, m_B = 431.7$ cm^{2}g. Here, we take the tennis ball diameter $D = 2R_B \approx 6.7$ cm

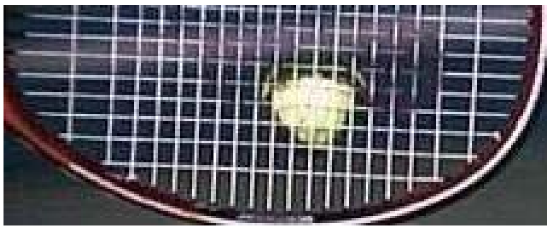
(a) Without strings lubrication (trial T405) (b) With strings lubrication (trial 506)

Fig. 4 Effect of string lubrication on ball spin behavior (impact views from the back at 10^4 fps). (a) Without string lubrication (b) With string lubrication

(a) (T506 f000) Before impact

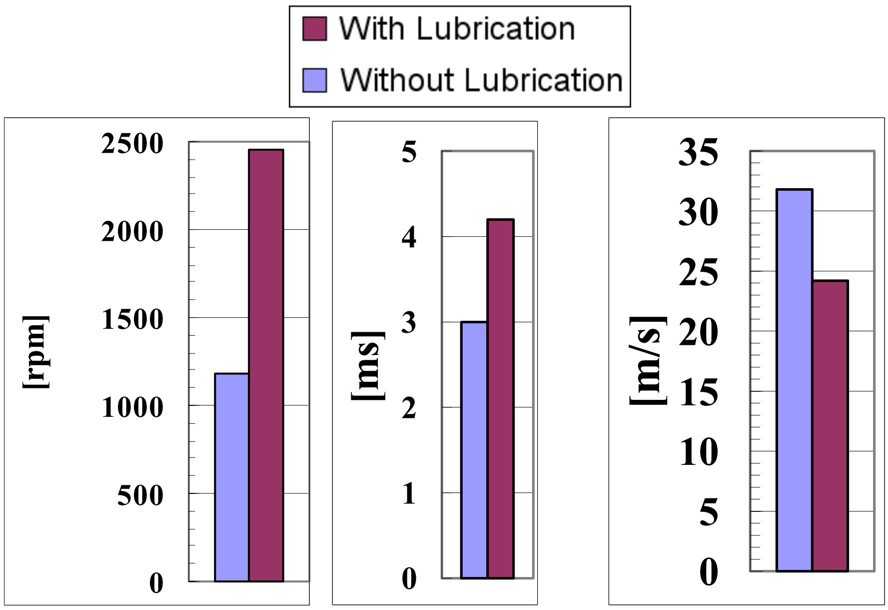
(b) (T506_f142_L4) Start contact: 0.0 ms

(c) (T506_ f159_L4) 1.7 ms after contact



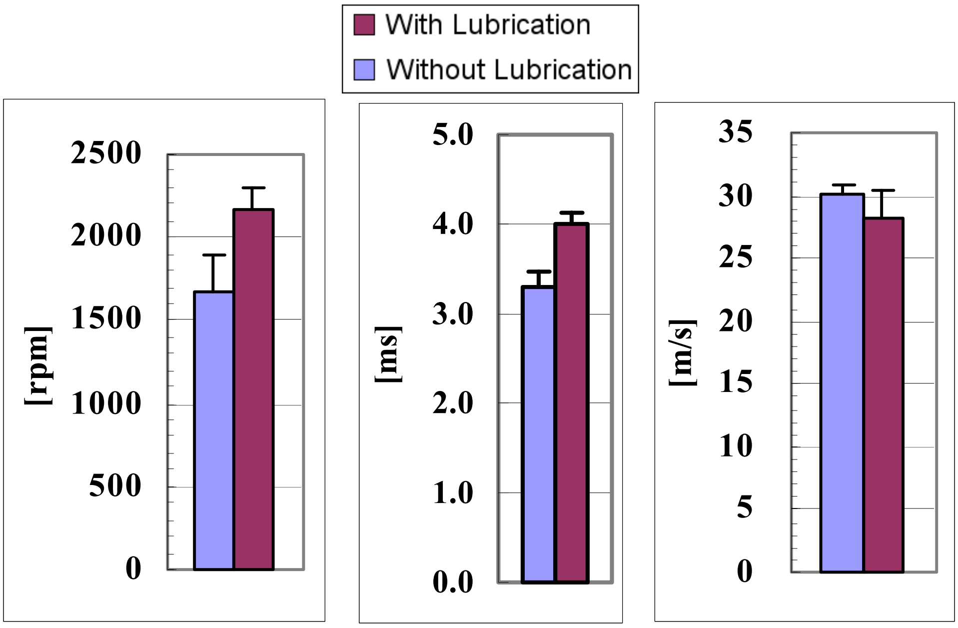
(d) (T506_f183_L4) End contact: 4.1 ms after contact

Fig. 5 Ball spin behavior and mechanism of spin rate increase by lubrication of string intersections. Main strings stretch and slide sideways and spring back when the ball is released from the strings. (Impact views from the back).



(a) Ball spin rate ω (b) Contact time T_C (c) Post-impact ball velocity V_B

Fig. 6 Typical example of the effect of string lubrication on ball spin rate and contact time.



(a) Ball spin rate ω (b) Contact time T_C (c) Post-impact ball velocity V_B

Fig. 7 Effect of string lubrication on the ball spin performance (mean and standard error).

and the mass $m_B \approx 57.7$ g. In the case of lubricated string intersections (Trial 205), a post-impact ball velocity V_B = 24.2 m/s and rate of rotation (spin rate) ω = 2460 rpm are applied. The speed of the thrown ball (incident velocity) was slow, so we take $\omega_0 \approx 0$. If we take the rotary torque applied to the ball to be τ (average torque: τ_{MEAN}) and the tangential force applying the spin to the ball as $F_{T,MEAN}$, then we have $F_{T,MEAN} = \int \tau \, dt / (R_B T_C) = 7.9$ N. The tangential force is not large, but it is at right angles to the linear motion of the ball, and so rotation is easily applied. In the case of no lubrication (Trial 103), $F_{T,MEAN}$ was 5.3 N.

4. Mechanism of improved feel when hitting the ball due to increased spin

The impulse waveform is approximated as shown in Eq. (1). If the hitting position on the string surface and the impact velocity are given, then the waveform can be predicted as shown in Fig. 8 (hit in the center of the string surface as an example). The Fourier spectrum is given by Eq. (2).

$$F(t) = F_{max} \sin(\pi t/T_C) \ (0 \le t \le T_C) \tag{1}$$

$$S(f) = 2F_{max} T_C |\cos(\pi f T_C)| / [\pi |1 - (2fT_C)^2|] \tag{2}$$

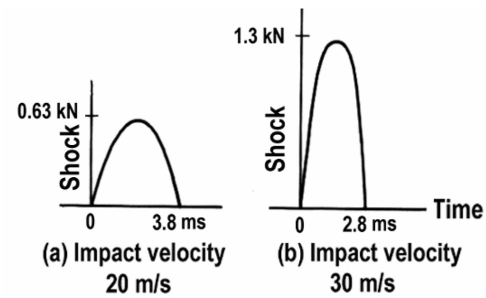


Fig. 8 Predicted shock over time when a ball strikes the center on the string face of the racket at a velocity of (a) 20 and (b) 30 m/s.

The k-th mode response amplitude component X_{ijk} at point i on the racket due to collision at point j on the racket surface can be approximated as below. Here, f_k is the natural frequency.

$$X_{ijk} = r_{ijk} S_j(f_k) \tag{3}$$

The k-th vibration mode component r_{ijk} at response point j when a unit shock force acts at an arbitrary strike point i is identified based on experimental modal analysis. As the contact time T_C increases, the Fourier spectrum value of the collision force decreases(8)-(12).

Figure 9 shows the geometry of the racket used. Figure 10 is the predicted effect of string intersection lubrication on the fundamental vibration amplitude of the racket(12)-(15).

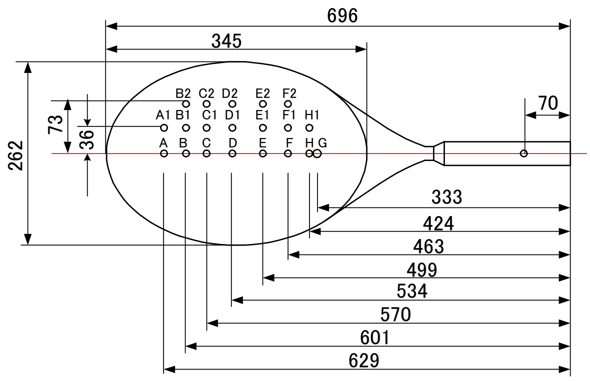
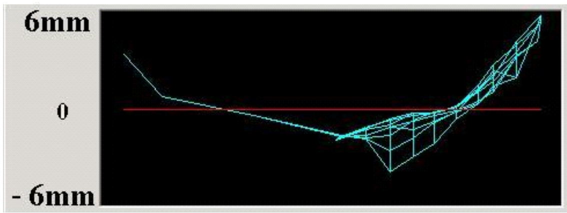
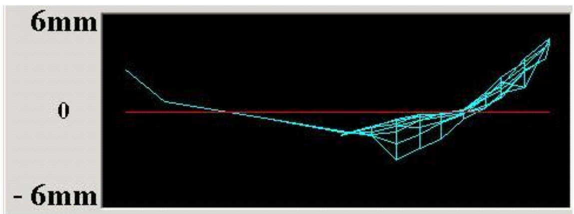


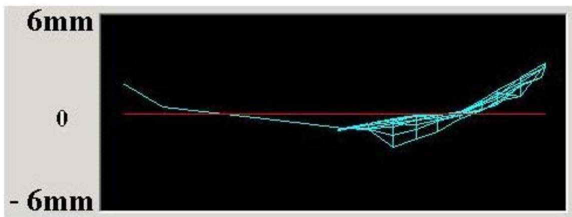
Fig. 9 Geometry of Racket MP-1.



(a) Contact time T_C = 2.6 ms
(Flat drive without lubrication)



(b) Contact time T_C = 3.4 ms
(Top-spin without lubrication)



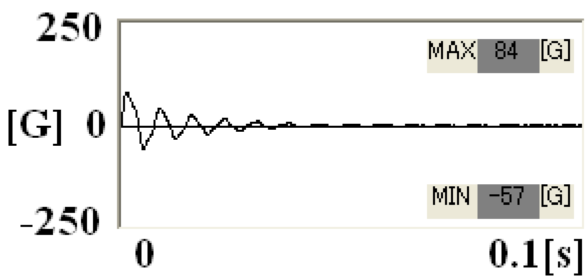
(c) Contact time T_C = 4.1 ms
(Top-spin with lubrication)

Fig. 10 Predicted effect of contact time on the racket vibration. Impact velocity: 30 m/s, hitting location: top side 95 mm from the tip of racket (B in Fig. 9).

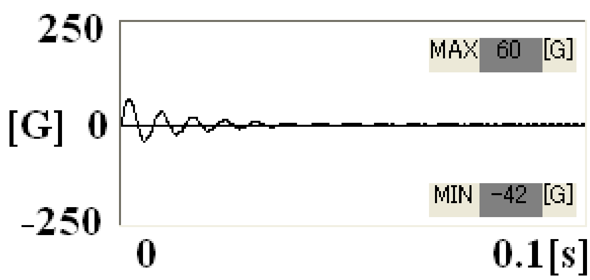
Figure 11 is the predicted waveform of the shock vibration in the wrist joint[(13)–(15)]; the position of the collision with the ball is the edge of the racket surface (hit point B in Figure 9). Figures 10 and 11(a) show the case of a flat, frontal collision at a impact velocity of 30 m/s, whereas in 11(b) and (c), the values for contact time and impulse

$$\int f(t)\,\mathrm{d}\,t = F_{\mathrm{MEAN}}\cdot T_{\mathrm{C}} = \pi\, F_{\mathrm{MEAN}}/2 = m_{\mathrm{B}}\,(V_{\mathrm{B}} - V_{\mathrm{B}\,0}) \tag{4}$$

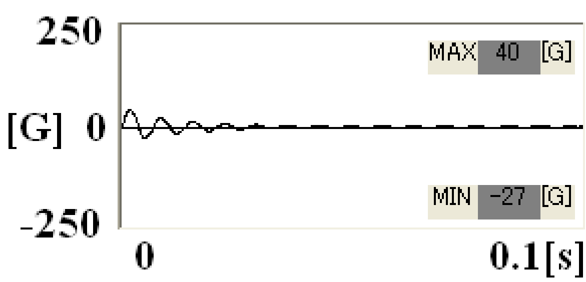
as calculated from image analysis, are applied. The calculated frontal impulses between the ball and strings in Figs. 11(b) and (c) were respectively 0.85 and 0.65 times that in Fig. 11(a). When the spin rate increases and the contact time grows as a result of the restoring force parallel to the string surface after the main strings slide perpendicularly, the frame vibration decreases. It also appears that the deformation of the ball and strings also decreases and only the part of the string surface in contact with the ball sinks in. This is thought to correspond with the feel when hitting the ball according to the tester with respect to "increased sensation of biting into the ball", "an increased sense of hold", and "a gentler feel when hitting the ball".



(a) Contact time $T_C = 2.6$ ms
(Flat drive without lubrication)



(b) Contact time $T_C = 3.4$ ms
(Top spin without lubrication)

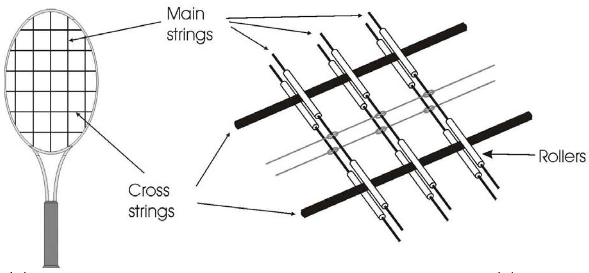


(c) Contact time $T_C = 4.1$ ms
(Top spin with lubrication)

Fig. 11 Predicted 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 (B in Fig. 9).

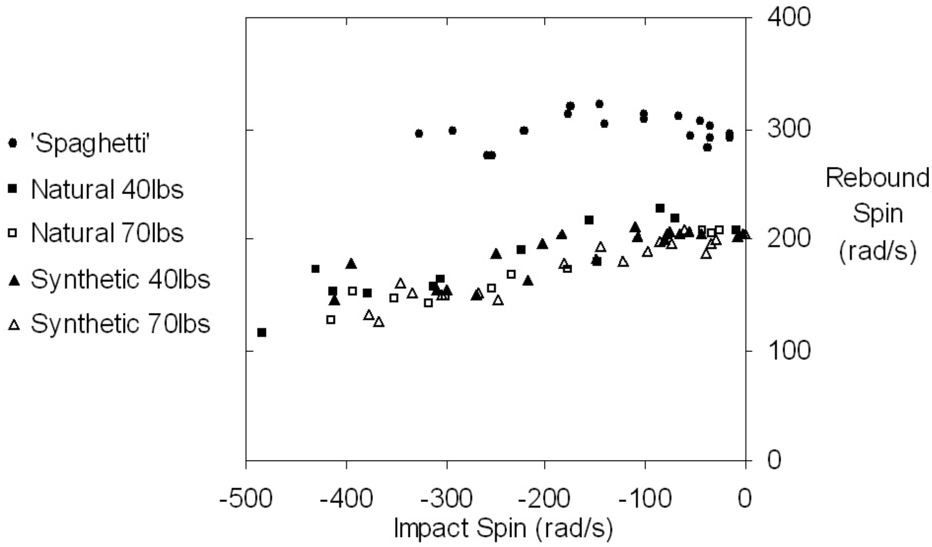
5. Similarity between the spin increase from string intersection lubrication and spaghetti strings

Using a spaghetti racket, a player ranked 200th managed to defeat the 4th ranked player, and the US, French, and Australian Open winner Guillermo Vilas retired during his final against Ilie Năstase, who was using spaghetti strings. Results such as these sparked controversy and the use of spaghetti rackets was banned. Rackets in which the main and cross strings are not alternately interwoven are now against the rules[3]. Figures 12(a) and (b) show examples of spaghetti rackets, which are strung as follows: each of the 16 main strings is doubled up, passing 2 per hole through the grommet holes. Each is then fed through hollow plastic rollers, sandwiching the thick cross strings (of which there are 5) on either side, thus forming three planes. Shown in Figure 12(c) are the spin measurements performed by Goodwill & Haake of balls made to collide with the string surface of fixed racket heads at an oblique angle. The spin rate is approximately double that of ordinary strings. The rollers move like bearings, making it easier for the main strings to slide upon the cross string surface. The negative values on the horizontal axis indicate back spin[6],[7]. There was considerable variation in the four types of stringing used, natural gut and synthetic strings at 40 and 70 lbs, but practically no differences in spin rate[7]. The increased spin rate using a spaghetti racket was due to the fact that the main and cross strings can easily slide.



(a) Illustration of a “spaghetti” strung racket.

(b) Photograph of a “spaghetti” strung racket.



(c) Comparison of the measured spin rate between the conventionally strung rackets and the “spaghetti” strung racket

Fig. 12 Comparison of the spin generated by rackets conventionally strung using natural gut and synthetic gut, and those strung using the “spaghetti” stringing system [reprinted by permission of Goodwill & Haake[7]].

6. Discussion of string tension and spin

Figure 13 shows the equivalent spring stiffness of the string, ball, and the composed ball/string system, respectively K_G, K_B, and K_{GB}, versus the amount of deformation X. These results were derived from measurements of the restoring force and deformation characteristics of the ball and composed ball/string system. Spring stiffness K_G is generally referred to as surface pressure. Within the scope of actual use, stronger hard spring characteristics are demonstrated in association with increased ball and string deformation. An impact model for the ball and strings can be represented as in Figure 14[(8)–(12)]. The level of the initial tension with which strings are strung, as shown in Figure 15, differs within the same strings, depending on whether they are strung beforehand either slightly strongly or weakly, and yet, in a real impact with impact velocity of 20 m/s or more, both the contact time and the collision force acting between the ball and strings barely differ[(2),(3)]. Accordingly, even if the difference in tension (initial tension) is great, there is no large difference in the frictional force between the main and cross strings, and therefore, there is ultimately little difference in spin either.

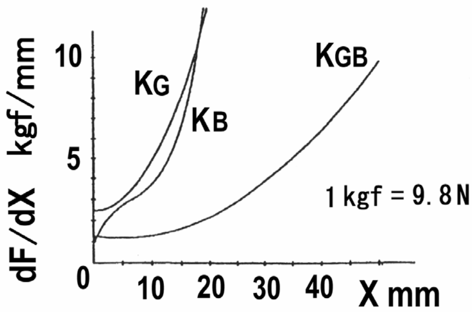


Fig.13 Stiffness vs. deformation of a ball, strings, and a composed ball/string system assuming that a ball deforms only at the side in contact with the strings [(2)(3)].

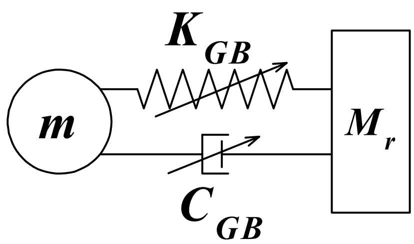
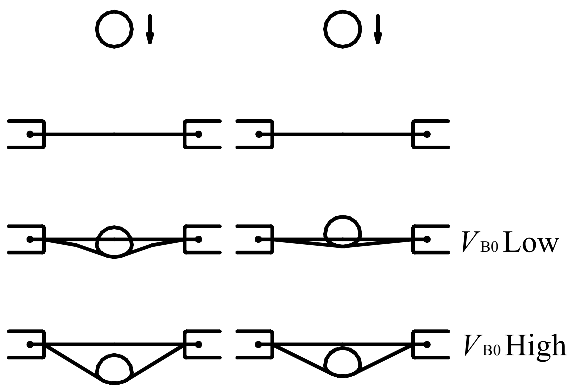


Fig. 14 Impact model of a ball-strings system.



(a) Low tension **(b) High tension**

Fig. 15 Stiffness of the string bed vs. impact velocity relative to the string tension as a parameter.

7. The principle of "spin gut": The lower the friction on the strings the more spin is generated

Polyester gut is hard, and does not readily adhere to other fibers, and therefore it can only be made as a monofilament. It is described as durable but hard to string, with no flexibility and substantial shock. It has not been on the market for very long yet. However, due to its economic advantage (that it is difficult to break), junior players in Europe have started to use it on en-tout-cas courts, and they continue to use it after they become top professionals. Furthermore, thanks to the assumption that even when hit with force, it is difficult to overshoot the ball, it has started to gain in popularity, and the success of players using polyester has helped it to become mainstream. The strings used by Nadal, a top player in the world renowned for his shots with strong spin, are polyester, not spin gut.

The reason for the spin increase from rackets with lubricated strings and spaghetti rackets is the fact that the main strings slide easily. Therefore, contrary to conventional wisdom, the smooth surfaced, hard polyester strings may possibly be superior in terms of spin performance, even than the high-friction nylon "spin gut" with bumpy surfaces. Even if they feel hard, if spin is applied, the flight of the ball is suppressed, leading to excellent controllability, and in reality, a decrease in the shock vibration transmitted to the hand. Polyester has become mainstream due to the potential for a sea change in the conventional concept of spin gut design. A future topic for study is to reveal the spin performance of different types of strings by means of high-speed video analysis.

8. Conclusion

(1) Contrary to the conventional assumption that greater friction on the strings results in more spin, we have revealed that, with low friction, the main and cross strings slide across one another, and the intersections slip; in this case, the spin rate is increased due to the restoring force when the main strings stretch sideways and spring back.

(2) We discovered that when string intersections are lubricated, it becomes easier to apply spin to the ball.

(3) As the spin rate is increased, the contact time grows.

(4) We showed by simulations based on experimental identification of the ball and racket that as the contact time grows, the shock vibration transmitted to the racket and hand decreases.

(5) "Spaghetti string" rackets (the use of which was banned some time ago because they could apply excessive spin by using plastic tubing to reduce friction) and rackets with lubricated string intersections have very similar spin mechanisms.

(6) We indicated the possibility that it is easier to apply spin with low-friction strings such as polyester than with the nylon strings known as "spin gut" which have high surface friction.

The fact that polyester has become mainstream in international tennis means the potential for a sea change in the conventional concept of spin gut design. We hope that the knowledge gained from this research will prove useful in the design of rackets and strings, and for the selection and use of equipment by players.

To conclude, we would like to express our sincerest gratitude to Dr. S. Haake, Dr. S. Goodwill and the International Sports Engineering Association for their consent to the inclusion of Figure 12. We also received the kind cooperation of Noriyoshi Hiraoka, Masayuki Hamaguchi, Haruki Taguchi, and Masaki Yamamoto of NAC Image Technology Inc., and we wish to express our deepest thanks to the following for their support and assistance: Ryoso Tomosue (Yasuda Women's University) of the Japan Society on Tennis Science, Shuichi

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