TENNIS RACKET TESTING

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The measuring of tennis ball-racket characteristics has been done for many years, but each project has generally been limited to a very narrow set of conditions. The projects done by the Tennis Industry magazine (1974-75) and Consumer Reports (1978) were subjective playing tests where teaching professionals judged racket weights, balance, flex, torque and vibration. Because judgements were often contradictory, it was stated in Consumer Reports: "Such contradictions only demonstrate that tennis racquets are best judged not in the laboratory but out on the court in the hands of players." The conclusion was also stated that, "the stiffer the racquet, the more control it provides; the more flexible the racquet, the more power it provides." Many others disagreed and evaluations were done in the laboratory. Sykes, Scott and Kellet (1971) presented three methods for determining center of percussion. Ramnath, Hedrick and Mikic (1979) did a series of articles for World Tennis measuring weight, balance, flex and torsion. They then gave their definition of the sweet spot using accelerometers and, also, compared various rackets. Baker and Wilson (1978), Baker and Putnam (1979), Brody (1979), Elliot, Blanksby and Ellis (1980), Hatze (1976), Kane, Hayes and Priest (1974) and Ohmichi, Miyashita and Mizuno (1979) did quantitative evaluations of rackets using strobe, high speed movies, strain guages with some rackets clamped and some free standing. Conclusions were contradictory about the firmness of the grip, ball velocity and the force on the hand. Elliot et al and Hatze used human subjects holding a stationary racket and Hatze measured the impact forces during the play of a top class player. Most researchers chose one particular ball velocity and a stationary racket clamped more solidly than a person can hold a racket. Hatze varied the ball velocity from 16.5 to 111 ft/s and concluded that a tight grip and off center hits produce greater stress on the player's hand. Bernhang, Dehner and Fogarty (1975) used EMG to assess the stress on the arm and related their results to the technique of hitting the ball. The research completed is supposed to help players select rackets, avoid injury to the arm and aid racket designers.

This paper summarizes published information (Plagenhoef 1970, 1971, 1979, 1980) and unreported research data obtained over 15 years. The projects include data from high speed films taken at Forest Hills and Longwood during match play and several laboratory tests using high speed film, strobe and force transducers. The studies include: 1. ball coefficient of restitution (e) on the strings of frames with the head clamped, 2. ball coefficient of restitution with the handle clamped solidly and with foam rubber inserted between the handle and clamp, and hand held, 3. ball coefficient of restitution using a hitting machine designed to allow movement of the racket about the long axis while varying the ball velocity, racket velocity, firmness of clamping and point of ball impact on the strings, and 4. the force transmitted to the hand of two professionals and one club player during the swing and at impact.

Ball Coefficient of Restitution - Strings Only

Eleven balls from various sports were chosen so string characteristics could be obtained when the ball hardness, weight and coefficient of restitution were very different. Table 1 shows the mean coefficient of restitution of nine rackets when the head was clamped as compared to the coefficient of restitution when bounced on cement at 15 ft/s. The coefficients were nearly the same for all balls except the lightest, even though the strings were in different frames at different tensions, and made of both nylon and gut. This shows that the strings' restitution fully compensated for any lack of ball restitution.

Coefficient of Restitution - Static Racket

The coefficients of restitution of the eleven balls were next obtained by bouncing them off the strings with the racket handle clamped three and five inches from the end. The static racket was then hand held with the results shown in Table 1. When clamped only three inches from the end, there was too much movement of the whole racket to allow good ball rebound. All coefficients improved when the racket was more stable, clamped five inches up the handle, with the heaviest balls increasing the most at this low ball velocity. When the rackets were hand held, all coefficients increased again except the three heaviest balls where the larger momentums overcame the ability of the hand to stabilize the racket. These combinations of testing show the importance of momentum and ball hardness and show how the force needed to bend a tennis frame and stretch the strings is related to the deformation and restitution of the ball. This led to further tests to obtain the relationship between the momentum of the ball and the momentum of the racket.

TABLE 1

Coefficient of Restitution

Ball	Wt. (gms)	Ball vel. 15 f/s (e) cement	(e) strings N=9	Handle clamped (e) 3"	(e) 5"	Hand Held
Steel ball	286	.4	.95	.2	.73	.17
Golf ball	45	.8	.96	.35	.42	.8
Baseball	151	.55	.95	.2	.56	.39
Superball	52	.95	.97	.3	.48	.95
Lacrosse ball	162	.85	.95	.2	.62	.39
Tennis ball	57	.8	.9	.3	.39	.75
Handball	61	.85	.95	.35	.42	.8
Paddleball	41	.85	.93	.4	.56	.88
Squash ball, hard	33	.54	.93	.4	.6	.89
Squash ball, soft	25	.37	.7	.3	.46	.6
Ping Pong ball	2	.8	.58	.3	.6	.76

A tennis ball can be classified as a meduim weight, soft ball among the 11 balls tested. Only the tennis ball was used on a static racket clamped solidly at the handle, but the ball velocity was varied between 58.7 ft/s and 88 ft/s. The tests were repeated with impacts approximately two inches off center along the transverse axis. There was little difference in the coefficient of restitution for center hits between the solidly clamped handle and the foam rubber handle. The rubber encased handle allowed the racket to twist more on off center hits, which produced the greatest decrease in rebound ball velocity. (Table 2.) The nine rackets showed similar results so firmness of the handle and off center hits were much more important than the variations in the rackets and strings.

TABLE 2

Coefficient of Restitution

	Handle Clamped Solidly		Handle Clamped-Rubber	
	58.7 ft/s	88 ft/s	58.7 ft/s	88 ft/s
Tennis ball	.4	.35	.4	.37
2 in. off center, transverse axis	.38	.33	.33	.29

Coefficient of Restitution - Moving Racket-Stationary Ball

A device was constructed to swing a racket on an arm which allowed rotation of the system around the long axis when a ball was struck off center. Varying degrees of firmness when clamping the handle were again accomplished by using foam rubber around the handle. 15 rackets were tested having varied head sizes, weights, flexes, string tensions and types of string.

A tennis ball and a lacrosse ball (three times heavier but almost the same coefficient of restitution) were suspended by a string and hit at varying racket velocities with the handle solidly clamped and with foam rubber inserted. The center of the racket velocity was varied from 29 ft/s to 51 ft/s. The ratio of the ball velocity after impact to the racket head velocity before impact was 1.2 to 1.1 for the lacrosse ball and 1.5 to 1.6 for the tennis ball. (Ball velocity greater than racket velocity.) This ratio was the same for both the solid and foam rubber grips. When the ball velocity minus the racket velocity after impact was divided by the racket velocity before impact, the ratio for the lacrosse ball with foam rubber averaged .7 and dropped to .4 when solidly clamped. The tennis ball was .75 with foam rubber and .6 when solidly clamped. This shows that the ball velocity was little affected by the grip changes, but the racket velocity after impact was greater when the handle was solidly clamped. (The lower the ratio, the greater the racket velocity after impact.) These tests showed that firmness of the grip was not an important factor when the ball had no velocity and was struck in the center of the strings.

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When the tests were repeated hitting off center balls on the transverse axis, the greater the distance off center, the more the racket would twist around the long axis and the less the ball velocity after impact. The tennis ball velocity was reduced 11% if hit within 1.5 inches of the center, while the lacrosse ball velocity decreased 17%. The drop in velocity was 35% for the tennis ball and 45% for the lacrosse ball when hit three inches off center. It made very little difference what racket was used or how it was strung. The dominant variable was the distance off center of ball impact.

Coefficient of Restitution - Moving Racket-Moving Ball

Several tests were done using the racket swinging device and a ball throwing machine. The racket velocity was varied between 29 ft/s and 51 ft/s and the ball velocity was varied between 40 ft/s and 81 ft/s. The racket handle was again solidly clamped and clamped with foam rubber inserted. The range of the closing velocities was from 70 ft/s to 130 ft/s.

These velocities were chosen because most players adjust the racket swing speed to the ball speed. Everyone has a different level of closing speed that is acceptable and fits their ability to control the racket head, hit center shots and thus control the ball. During a serve, the maximum racket velocity is about 130 ft/s when the ball velocity is 0 ft/s. The return of serve has a closing velocity of about 130 ft/s for good players (ball 75 ft/s, racket 55 ft/s), and 70 ft/s for poorer players (ball 40 ft/s, racket 40 ft/s.) The closing velocity remains fairly constant for all types of shots: ground strokes, volleys, overheads, serves and returns of serve. If the ball speed is high, the racket speed is low and if the ball is slow, the racket is usually swung faster.

Sixty-three rackets were tested at the high range of closing velocities (ball 81 ft/s, racket 43 ft/s = closing 124 ft/s) with seven frames tested using both nylon and gut. The ratio of the ball velocity after impact to the ball velocity before impact varied from .71 to .95. The rackets producing the lower coefficients were either the most flexible shafts, the lowest string tensions or the lightest. The highest coefficients were the medium flex frames, strung at medium tensions or, the heaviest frames and frames with the highest center of percussion. Another test with 23 rackets and a closing velocity of 110 ft/s gave similar results.

The velocities of balls hit off center were determined on 11 rackets. A side view camera recorded the racket and ball velocities at 200 f/s while a front view camera recorded the impact point on the strings. The velocities were reduced 15% when hit one inch off center and up to 44% when hit three inches off center. The drop off was not as great at the lower closing velocities or when hit high on the longitudinal axis. There was no drop in velocity of balls hit within 1½ inches of the center but low on the longitudinal axis. The lower closing velocities had less change in ball velocities for all off center hits. (Table 3)

TABLE 3

Velocity Decreases on Off center Hits

	Transverse Axis		Longitudinal Axis	
Off Center	% Decrease, High Closing Velocity	% Decrease Low Closing Velocity	Above Center	Below Center
1 in.	15%	2%	0	0
1½ in.	28%	11%	3%	0
2 in.	35%	20%	10%	4%
2½ in.	40%	30%	12%	10%
3 in.	44%	35%	22%	15%
3½ in.	55%	40%	28%	20%

These data show that some rackets performed better at low closing velocities and others at high closing velocities. A flexible shaft with tight strings or a stiff shaft with loose strings performed about equally at low closing velocities. However, at high closing velocities the differences in rackets became more pronounced. The point of impact on the strings was always a more dominating factor than the racket type, strings, or tension for producing ball velocity at a specified racket swing velocity.

<u>Force on the Hand</u>

A pressure transducer was placed between the hand and racket grip at the base of the index finger. This is the pivot point during the impact of a forehand serve, since the racket tends to revolve about this point as the fingers exert a counter force to the ball impact. If the ball is hit off center, the hand must squeeze the grip to keep it from twisting and the combination of this squeeze and the force due to the ball impact were recorded on an oscilloscope. The force on the hand during ground strokes varied from 28 to 56 lbs., and during the serves from 30 to 70 lbs. Volleys were measured while hitting a controlled ball velocity of 59 ft/s from a ball machine and the forces on the hand varied from 18 to 48 lbs. Balls that were hit toward the tip of the racket and off center recorded the highest forces for all strokes and with all rackets. During games played, the range of forces were within those of the controlled tests. Good hand firmness at impact is essential for good play to counter any off-centeredness of impact, so the hand squeeze usually began about 0.2 seconds before impact when hitting all shots, except serves. While serving, the squeeze occurred closer to impact. The prior to impact squeeze force varied according to the difficulty of the shot, but always occurred to insure good racket stability no matter where the ball struck the strings. If a player has a difficult shot and anticipates the difficulty of hitting a center shot, the anticipatory squeeze is also greater. If the racket has a large momentum and the ball a low momentum, the force is minimal except on off-center hits. The greater the closing velocity and the larger the distance the ball is struck off-center, the larger the forces recorded.

The forces on the hand recorded during the swing were approximately one-third the impact forces at all velocities, so should not contribute to arm injuries as much as impact forces. Frame vibration takes place as a result of impact, and each subsequent vibration of the frame is small in comparison. A force transducer was placed under the tip of the index finger to measure the force of vibration of the recoil. The immediate recoil from the initial bend due to impact produced a force about one-third of the impact force on the transducer, and all subsequent vibrations were less than the force due to hand squeeze. After doing tests where the strings were driven by a shaker, the frame plucked for vibration and the damping of the racket measured, it was decided this vibration was a needless measurement. The direct measurement of the force on the hand eliminated the need for other tests. The period and magnitude of frame oscillation produces a specific "feel" that players readily adapt to after using a given racket, but the oscillations are negligible compared to impact forces.

Conclusions

An often used statement is that a racket that produces greater ball velocity is best for power and worst for control. This actually depends on the ball velocities and racket swing velocities which characterize a player's game. A low velocity producing racket could require an individual to swing faster than his ability to control the racket, so he would probably play better with a racket-string combination that produced more ball velocity. A faster swinging person would probably play better with the lower velocity producing racket. No general statement encompassing everyone can be made about control or greater ball speeds, as no one racket can be best for everyone. The results of all the experiments and data gathering show the importance of the racket lies in the player's ability to get the racket on the ball with a center hit. This means it must be the proper weight and balance to have consistently well-timed impacts. Assuming a player has timed the swing properly, the following conclusions can be made from the research completed.

1. Hitting the ball off-center is frequent at all levels of play and is the overwhelming dominant factor affecting ball control, loss of ball velocity and stress on the musculature of the forearm.

2. At low ball velocities and a stationary racket, the coefficient of restitution was the same for center hits with a change in firmness of the clamp on the handle. Off-center hits caused a reduction in ball velocity when the handle was not solidly clamped. Firmness of the grip and off-center hits were much more important factors than the type of rackets and strings used.

3. When the racket was moving and the ball was stationary, the grip firmness was not important during center hits, but for off-center hits the ball velocity decreased up to 35% when struck three inches from the center on the transverse axis. Again the dominant variable was the distance off-center of ball impact, and it made very little difference what racket and string were used.

4. When the racket was moving and the ball was moving, the grip firmness had little effect during center hits, but off-center hits reduced the ball velocity by 15% at one inch and up to 44% when hit three inches off-center on the transverse axis. The drop off was not as high when the ball was struck high on the longitudinal axis and even less when struck low on the longitudinal axis. The

lower closing velocities had less change in ball velocities than high closing velocities for all off-center hits.

5. The highest closing velocities showed differences in rackets. The medium flex, medium string tension, heavier frames with a higher center of percussion were the best for producing greater ball velocity. The light, most flexible, loose string tension was the poorest.

6. The forces on the arm and the need for the tightest grip squeeze increase as the ball velocity becomes greater and the racket velocity slower. The least stress on the arm occurs when the ball velocity is slow and the racket velocity is larger than the ball velocity. Balls hit off-center and high toward the tip of the racket recorded the highest forces on the arm and resulted in the greatest reduction of ball velocity for all rackets.

7. Forces of impact are three to four times greater than swing forces.

8. The vibration of the frame after the initial ball impact produces a force about one-third of the impact force on the recoil and is then negligible on subsequent vibrations.

9. Both low and high string tensions, whether using gut or nylon, did not produce the ball velocities of the medium string tensions.

10. The oversized heads were no better for maintaining ball velocity or reducing forces on the arm than regular sized rackets when hitting off-center. They are capable of hitting balls in a larger area where the frame would be on a regular racket. They have the center of the strings lower (closer to the hand) than regular rackets, which places the center of percussion higher than the center of the strings -- one of the desirable traits of the best rackets. The oversized head performed equally well with other rackets at low velocities, but slightly poorer at high velocities when measuring ball velocities.

11. The relationship between the momentum of the racket and the momentum of the ball is very important as certain rackets play better at specific closing velocities. Specific racket comparisons are not made because the important factor which overshadows everything else is the impact position on the strings regardless of the racket size, shape, weight or balance.

12. When selecting a racket the important factors are: a. to use a weight and balance that allows a controlled swing resulting in a high percentage of center hits; b. to have good stability during impact (peripheral weight and grip size); and c. to have a frame flex and stringing that best match the closing velocities characteristic of your game.

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