A METHOD TO DETERMINE BALL IMPACT LOCATION AND ITS MOVEMENT ACROSS THE STRINGS OF A TENNIS RACKET

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INTRODUCTION: The impact location of a ball and its movement across the strings of a given tennis racket influence ball speed, direction of flight, and the resulting spin of the ball. Compared to recreational players, good tennis players achieve high ball speeds and high accuracy with relatively little physical effort. Hitting the strings at the right spot will result in high ball velocities and transfer low shock and vibration to the player. This location on the racket head is typically referred to as the sweet spot on a tennis racket. Brody (1988) identified three different sweet spots on a tennis racket. The first sweet spot is defined by the location on the racket head where the highest rebound velocity occurs. For shots of the ball on linearly moving tennis rackets this sweet spot is located close to the point of maximum string plane deformation, always below the racket head center. The second sweet spot refers to a ball impact location on the racket head, creating minimal shock to the hand-arm system. At ball contact the tennis racket creates a moment around the wrist. The magnitude of this moment depends on the location of ball impact on the string area. Since the ball causes a translatory as well as a rotatory movement of the racket, there is an impact location (center of percussion) where these two movements partially cancel each other, thus leading to a minimum shock generation at the hand. The third sweet spot (the node of the first harmonic oscillation of the racket) identifies an impact location that leads to a minimum of racket vibration. Although it would be desirable to have all three sweet points at one location, this is not possible. What is generally referred to by tennis players as the sweet spot of a racket is a location somewhere in the middle of these three spots. In this area a high speed of the ball, low initial shock, and low vibration amplitudes at the hand provide the sensation of a good shot.
The above definitions of the three sweet spots by Brody are based on the application of the laws of physics to a simple mechanical body - the tennis racket only. In a real game situation, however, tennis rackets are not simple and well-defined mechanical bodies. The player’s muscle actions continuously modify the grip forces at the racket handle. With dynamic grip forces varying mechanical coupling of the racket handle with the body occurs, thus resulting in a complex mechanical behavior of the racket-arm system. Therefore, it is desirable to analyze the contact between racket and ball in game-like situations. The accuracy and resolution of cinematographic recordings are limited, because the racket head area is small in comparison to the necessary object space for filming. Because the interaction of the tennis racket with the ball is of fundamental importance for the game, an instrumented tennis racket was developed to electronically determine the point of ball impact on the strings.

METHODS: A „Kuebler Inertial Light" tennis racket was used for this study. 32 very thin steel wires were woven around 14 longitudinal and 18 transverse string sections of the racket head. This resulted in a 14 by 18 wire matrix, covering an area of 14.5 cm by 23.5 cm in the center of the elliptical racket head frame (max. width = 24.1 cm, max. length = 32.8 cm). Each steel wire was electrically insulated and connected to its own charge amplifier by a thin, shielded cable. The thin cable bundle from the 32 sensors was guided along the racket handle to a small electronic unit, which was attached to a belt and carried by the subjects. The physical characteristics of the instrumented racket are summarized in Table 1.

Table 1: Characteristics of the instrumented racket (RHC=racket head center,

mass	length	RHC	MCOR	COP	NODE
361 g	69 cm	51.7 cm	41 cm	52 cm	54 cm

MCOR= maximum coeff. of restitution, COP= center of percussion)

Total racket weight increased slightly by the wires, but was in the range of weights for commercially available tennis rackets. By friction of the ball with the ground and during its flight in the air the tennis ball was electrically charged before it made contact with the racket head. Within a few milliseconds after the ball left the ground, the finite electrical insulation of the ball material caused an even distribution of the charge across the surface of the ball. At contact with the racket the electrostatic charge from the ball surface was detected by the steel wires and electronically processed by their charge amplifiers. Using a data acquisition system with a high sampling frequency, each wire was sampled with 5 kHz. In a pretrigger mode data were collected for a total of 12 ms, beginning 4 ms before initial charge detection on the sensors. Following data collection, further numeric processing was performed by multiplying the charge values of each of the longitudinal sensors with all transverse sensors, resulting in a 14 by 18 matrix of numbers. By geometric averaging of all matrix values the point of contact on the string area could be determined. Using the instrumented racket 18 expert, 18 intermediate, and 19 recreational male players performed 30 right-handed strokes in each of 3 conditions: straight serve (S), forehand stroke (F), and backhand stroke (B). The 36 expert and intermediate players also performed 30 strokes in three additional conditions: second serve (SS), forehand topspin (FT), and backhand slice (BS). Across all players and playing conditions 8.190 ball contacts with the racket head were measured and evaluated. Simultaneously with the determination of the ball's impact location on the strings, the transfer of shock and vibration from the racket to the arm, and ball velocities were recorded. For the measurement of shock and vibration an accelerometer was fastened to the wrist (Proc. styloideus ulnae). Ball velocity was determined by a laser array photocell arrangement above the net. For statistical analyses of the variables a repeated measures ANOVA with post-hoc comparisons was used. For six conditions fifteen individual post hoc comparisons must be performed. Therefore, a conservative significance level of $p<0.01$ was chosen.

RESULTS AND DISCUSSION: According to the judgment of experienced tennis players, the handling of the instrumented racket was very similar to a regular racket for forehand and backhand strokes, as well as the serves. Only for topspin and slice strokes did they recognize a slightly increased spin production on the ball. Subjects felt comfortable with the racket, some of them achieving ball speeds above 190 km/h for the serve. The matrix sensor arrangement and the time resolution of 0.2 ms guaranteed an accurate determination of the contact location of the ball and its movement across the string area. To allow a comparison between all six types on tennis strokes, the following results are based on all 6480 trials of the intermediate and expert players (Table 2).

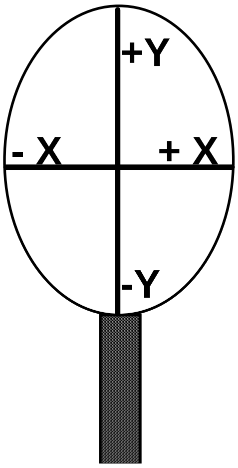

Figure 1: The y axis coincides with the longitudinal axis of the racket with its origin at the center of the racket head. Negative y-values refer to impact locations closer to the racket handle, and with increasing positive values the ball contacts move toward the top of the racket head. The negative x-axis refers to the left side of the racket, as viewed from behind during a serve. For the forehand and backhand strokes, negative x-values identify the upper half of the racket head.

	Unit	F	FT	B	BS	S	SS
Ball Speed	km/h	98.6	92.1	97.3	78.9	155.9	119.2
Delta-t	ms	5.25	5.29	5.27	5.86	5.12	5.53
Roll Distance	mm	24.5	39.3	20.6	41.8	17.9	40.1
X - On	mm	-16.1	-27.2	0.3	+18.1	-17.5	1.3
X - Off	mm	-1.1	.8	0.6	-13.3	-22.1	-29.0
Y - On	mm	4.5	16.0	4.1	-16.3	10.9	10.6
Y - Off	mm	21.5	32.1	22.0	5.3	22.1	22.7

Table 2: X-On/Off and Y-On/Off are the impact locations relative to the racket head center at initial contact and ball take-off. Delta-t is the contact time, and the roll distance refers to the movement of the ball across the racket head. (**F**orehand, **F**orehand **T**opspin, **B**ackhand, **B**ackhand **S**lice, Straight **S**erve, **S**econd **S**erve)

As expected, ball speed during a first straight serve was highest, followed in velocity by a 'safe' second serve, and forehand as well as backhand strokes. The lowest ball velocities were recorded for the backhand slice shots. Ball contact times for the straight serve were significantly shorter ($p<0.01$) compared with the times of all other strokes. Similarly, BS and SS had significantly greater contact times as

compared to B ($p<0.01$) and S ($p<0.01$). The second serve contact time had the highest value and differed significantly from all other contact times ($p<0.01$). The shortest roll distance of the ball was found for the straight serve with a major movement direction along the longitudinal axis Y. For the three kinds of strokes with increased spin production, roll distances increased by a factor of almost two compared to all other strokes. Only the three t-tests between FT, BS, SS and the comparison of B vs. S did not show statistically significant differences.
Initial ball contacts for all kinds of strokes were fairly close to the racket head center within a radius of less than 3 cm. However, within this small area significant differences were found for most comparisons between the various kinds of strokes. Of the 15 individual X-On comparisons, only the t-tests between F vs. S and B vs. SS were not significant. For the Y-On analysis only F vs. B and S vs. SS did not demonstrate statistical significance. For the straight serve the ball shows only minimal movement in the transverse direction (< 5 mm) and a small movement (<12 mm) along the longitudinal axis. For the three stroke types with increased spin production (FT,BS,SS) the ball moves approximately 3 cm across the strings in the transverse direction. For all strokes the forehand topspin ball impact is closest to the top of the racket, whereas the backhand slice impact occurs closest to the grip. The backhand slice is the only condition with an impact location below the racket head center. Due to the rotation of the racket during swing in all kinds of strokes the ball moves towards the upper end of the racket (Y-Off).

CONCLUSIONS: Although the physics of a tennis racket has been well documented by Brody (1988), in real game situations a complex interaction of the player with the tennis racket can be observed. The player's grip forces continuously cause changes in the mechanical coupling between the racket and the hand, thus resulting in a complex mechanical behavior of the racket-arm system. An instrumented racket was developed to investigate ball impacts on the racket head during six kinds of typical tennis strokes. During ball contact the electrical charge of the tennis ball was detected by a wire matrix along the racket head strings. Using a high measuring frequency a time resolution of 0.2 ms for the detection of ball location on the strings was achieved. Therefore, initial contact of the ball, its movement across the racket head and the location of ball take-off could be determined. With 55 players of different playing expertise, more than 8,000 ball contacts, using six different kinds of strokes, were recorded. The initial analysis showed that the instrumented racket provided information about contact times, roll distances and typical impact locations of the ball on the racket head for the different types of strokes. Further data evaluation will be performed to analyze differences in racket use by the three groups of recreational, intermediate, and expert players. The collected data will also be used to determine relationships between ball impact location, ball speed, and the transfer of shock and vibration from the racket to the arm. This information may prove useful for future designs of tennis rackets to enhance performance and reduce overuse injuries.

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