TENNIS RACKET BIOMECHANICS - AN EMPIRICAL APPROACH

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Stiffness of a racket frame, geometry of the racket head, string arrangement and string tension all contribute to the accuracy of play as well as tennis ball velocity. Mechanical racket characteristics can well be described by the laws of physics. However, empirical studies are necessary in evaluating the effect of tennis racket construction features on stress to the body as well as playing performance. Using accelerometers, grip force transducers, and a measuring matrix on the tennis racket strings allow an in depth analysis of the tennis stroke. Through several experiments it could be shown that shock and vibration transfer to the arm is influenced by ball impact location on the racket head, racket stiffness, and grip force. Playing performance of a racket, as one might predict from its mechanical characteristics, is often not reflected by its functioning in a game situation.

KEY WORDS: tennis elbow, shock, vibration, grip force, ball impact location

INTRODUCTION: During their tennis career more than one third of all tennis players will suffer at least once from tennis elbow. During the last decades many studies with inconsistent results have been published about tennis elbow. The most popular explanation of this overuse complaint has been presented by Cyriax in 1936. Repeated stress and strain, as they occur primarily during backhand strokes, cause macroscopic and microscopic tears between the common extensor tendon and the periosteum of the lateral humeral epicondyle. From a study of 2633 tennis players Priest et al. (1980) concluded that advanced age and frequency of play are the main factors for the likelihood of elbow pain. From kinematic and EMG data Blackwell and Cole (1994) showed that novice as compared to expert players had more eccentric wrist extensor muscle activity in backhand strokes. Thus novice players may be more at risk for lateral tennis elbow. The tennis racket has always been suspected to be an additional cause in the multifactorial etiology of lateral elbow pain. It is known that tennis players do not like vibrations of their racket and Segesser (1985) suggested that tennis racket oscillations in the range of 80 to 200 Hz are likely to contribute to the development of tennis elbow. Brody (1988) defined 3 different ‘sweet spots’ on the strings of a tennis racket. When a ball hits the racket at its point of maximum restitution (COR), the rebound velocity of the ball will be highest. For ball hits at the node of the racket vibrations are minimal. Ball contacts at the center of percussion (COP) cause minimal shocks to the arm. According to the laws of physics one can not construct a tennis racket where these three favorable spots meet in a single point. However, tennis racket manufacturers try to construct rackets in which these points are as close as possible together. The effect of grip force on ball rebound velocity has been the subject of many studies in the past. Whereas most studies found that ball velocity is independent of grip force magnitude, some authors reported increased ball speeds with higher grip forces (Hatze, 1976).

VIBRATION TRANSFER FROM THE TENNIS RACKET TO THE ARM: The impact induced oscillation of the racket-and-arm system at ball contact is believed to contribute to the risk of lateral elbow pain. In two studies the influence of tennis racket construction on the vibration at the arm was investigated. Two miniature accelerometers at the wrist and the elbow of 24 tennis players were used, to determine the influence of tennis racket construction on vibration loads at the arm (Hennig et al, 1992). 23 different tennis racket constructions were evaluated in a simulated backhand stroke situation. The influences of body weight, skill level and tennis racket construction onto the magnitude of vibrations at wrist and elbow were investigated. Amplitudes, integrals, and Fourier components were used to characterize arm vibration. More than fourfold reductions in acceleration amplitude and integral were found between wrist and elbow. Off-center as compared to center ball impacts resulted in approximately three times increased acceleration values. Between subjects, body weight as well as skill level were found to influence arm vibration. Compared to expert players, a group of less skilled subjects demonstrated increased vibration loads on the arm. Between different racket constructions, almost threefold differences in acceleration values were observed. Increased racket head size as well as a higher resonance frequency of the racket were found to reduce arm vibration. The vibration at the arm after ball impact showed a strong inverse relationship (r=-0.88) with the resonance frequency of tennis rackets. Due to the construction geometry, wide body rackets generally show a higher stiffness that results in increased resonance frequencies. To further examine the strong influence of resonance frequency on the vibration of the arm a follow-up study with 4 specially constructed rackets was carried out (Hennig et al., 1993). The rackets were built with an identical shape, equal mass, and with the same location of the center of gravity. They differed only in the mass distribution inside the frame and/or the carbon fiber composition. Although all rackets looked identical and had similar construction characteristics, the response of each racket at ball impact was different. The strong inverse relationship between the acceleration integral at the arm and the resonance frequency is shown in figure 1. It demonstrates the strong influence of dynamic racket stiffness onto the magnitude of vibration transfer to the arm.

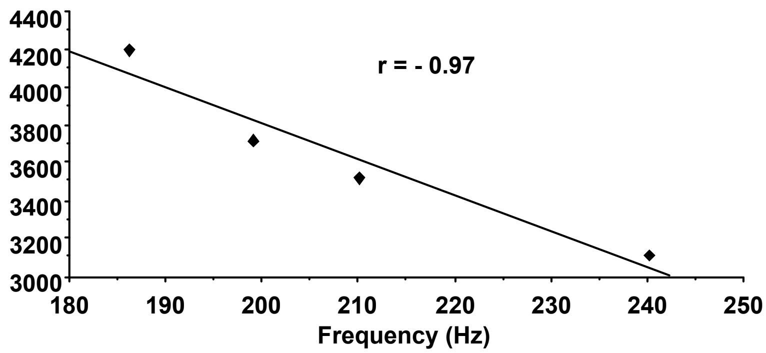

Figure 1 - Acceleration integral (of the rectified acceleration signal) at the wrist of tennis players using four different rackets with different resonance frequencies.

THE INFLUENCE OF GRIP FORCE ON BALL VELOCITY AND ARM VIBRATION: The effect of grip force at a tennis racket on ball rebound velocity and the transfer of vibration on the arm of 15 subjects was investigated (Hennig & Milani, 1995). A capacitive force transducer measured the grip forces, and an accelerometer at the wrist measured the vibrations that were transferred from the racket to the body. With a speed of 50 km/h tennis balls were shot at two marked center and off-center locations of the string area, while subjects held the racket in a back hand stroke position. For both impact locations, higher grip forces at the racket handle resulted in substantial increases of arm vibration loads. However, ball rebound speed was not influenced by the magnitude of grip force. Reduced grip forces, causing a reduction of vibration loads at the arm, may prevent tennis elbow without sacrificing ball velocity (figure 2). In a follow up study the dynamic grip forces from 19 expert players were compared to those of 13 intermediate players (Hennig & Schnabel, 1996). Although ball velocity was considerably higher and the vibrational arm load was much lower for the expert players, grip forces did not differ between the groups. For both groups the maximum grip forces occurred approximately 30 ms before ball contact. The authors concluded that players reduce grip forces towards the moment of ball impact to protect their body from vibrational loads.

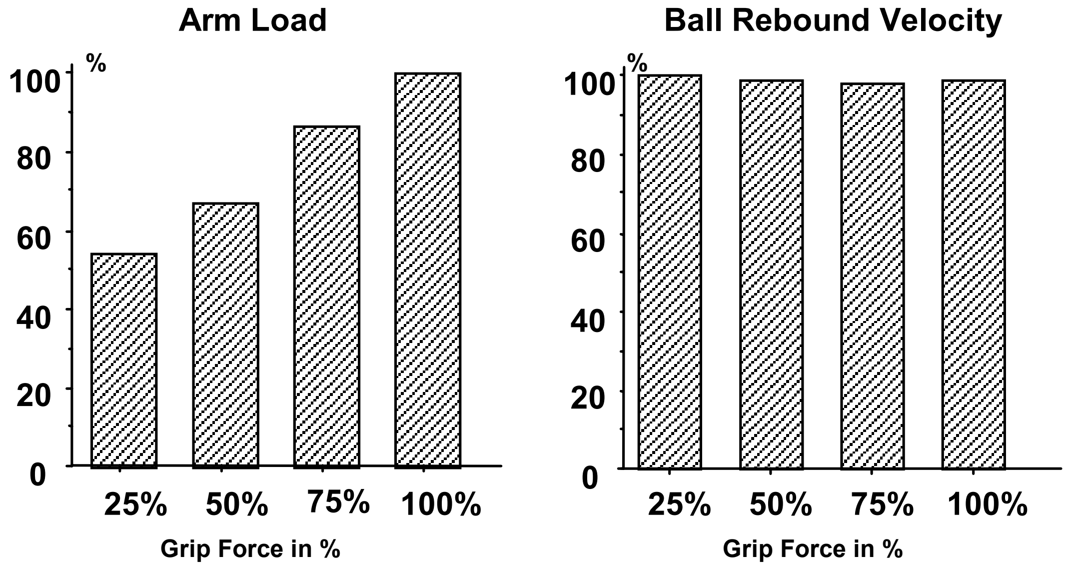

Figure 2 - Acceleration integral (arm load) and ball rebound velocity at four levels of grip forces for off-center ball shots on the racket head.

BALL IMPACT LOCATION ON A TENNIS RACKET HEAD: To study the interaction of the player with the tennis racket, a racket was developed to electronically determine the point of ball impact on the strings. Using very thin steel wires, woven around the strings, a 14 by 18 wire matrix was built. Through friction of the ball with the ground and during its flight in the air the tennis ball is electrically charged before it makes contact with the racket head. At ball contact the electrostatic charge was detected by the steel wires, which were connected to charge amplifiers (Hennig & Schnabel, 1998). Data were collected (5 kHz / Ch) for a total of 12 ms, beginning 4 ms before initial charge detection on the racket head. Geometric averaging of all charge signals was used to determine the point of ball contact on the string area. The matrix wire arrangement and the time resolution of 0.2 ms guaranteed an accurate determination of ball contact location and its movement across the string area. For the measurement of shock and vibration from the racket to the arm an accelerometer was fastened to the wrist. Ball velocity was measured by a laser array photocell arrangement. 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 (Table 1). To compare the results of our study with those, predicted by Brody (1988) on racket characteristics, we selected the results of the 30 forehand and backhand strokes from the 19 expert players. As apparent from Table 2, in forehand and backhand strokes neither the point of minimum shock nor the point of minimum vibration were found at those racket locations (Center of Percussion, Node), described by Brody. Brody also predicted the point of maximum ball speed below the racket head center. Our data showed the opposite in detecting the maximum ball velocity location slightly above the racket head center. Rotation of the racket during the swing increases the velocities for more distally located racket points. Apparently, this effect has more influence on ball speed as compared to a lower coefficient of restitution for the racket at higher locations. The results of our study did not confirm the hypothesized sweet spot racket points by Brody (1988) of minimum vibration, minimum shock or maximum ball velocity. Mechanical coupling of the hand with the racket and the contribution of racket rotation during the swing seem to have a major effect on racket characteristics.

Table 1 X-On/Off and Y-On/Off are the impact locations relative to the racket head center at initial contact and ball take-off. Negative values of X refer to contacts left from the racket axis – as seen from behind the player. Negative values of Y refer to contacts below the racket head center. Delta-t is the contact time and the roll distance refers to the movement of the ball across the racket head. (Forehand, **F**orehand **T**opspin**, B**ackhand**, B**ackhand **S**lice**, S**traight **S**erve**, S**econd **S**erve**.)**

	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	4.8	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 Comparison of COP and Node Values with Empirically Identified Points of Minimal Shock and Vibration to the Arm in a Game-Like Situation

	Brody, 1988	**Forehand / this study**	**Backhand / this study**
Point of minimum arm shock	3 mm above racket head (COP)	shock is reduced with lower impact locations	shock is reduced with lower impact locations
Point of minimum arm vibration	23 mm above racket head center (Node)	18 mm below racket head center	18 mm below racket head center

CONCLUSIONS: As described above, biomechanical experiments are necessary to determine the loads on the body and to describe the mechanical behavior of tennis rackets. It is important to record mechanical loads from tennis ball impacts directly at the human body. Thus, the overall effect of a mechanical racket to hand coupling in combination with movements of the racket in a game like situation can be determined. The results often contradict findings, gained through modeling or mechanical racket testing.

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