MODELING OF ELASTIC RACKET PROPERTIES IN THE DYNAMIC COMPUTER SIMULATION OF TENNIS

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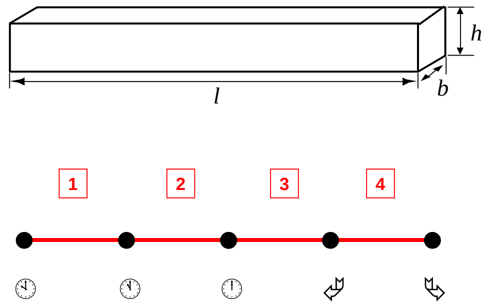
INTRODUCTION: Experimental difficulties in tennis research caused by the complexity of the stroke and the short contact phase demand the development of complex computer simulations. In this context Groppel (1986) noted that the application of rational models can lead to a better understanding of the tennis stroke. In current tennis research two different methods are in use: (1) the direct dynamics approach and (2) the finite element method.
(1) By using rigid-bodies hinged by several joints, direct dynamics simulates the dynamic interaction between arm, hand, racket and ball, considering all inertial properties. In this way, for example, Detlefs (1996) analyzed the influence of racket mass distribution on the kinetics of the striking arm, and Glitsch (1997) described the application of direct dynamics in biomechanical testing of tennis rackets.
(2) On the other hand, the finite element method (FEM) is employed to analyze the elastic behaviur of rackets under static conditions. Thus Brannigan and Adali (1981), Widing and Moeinzadeh (1990) described the use of FEM to calculate the racket deformation and vibration frequencies of a fixed racket. Because of the unrealistic boundary condition (clamped handle), these simulations led to results which do not correspond to the real stroke situation.
The aim of this study was to evaluate a complex dynamic simulation model of the tennis stroke, including inertial and elastic racket properties. Therefore a combination of both approaches was tested, using the results of a finite element analysis as input for a flexible racket model in direct dynamics. The advantages of such a combined simulation would be the possibility of analyzing racket deformation during impact and the resultant vibrations after contact in a dynamic simulation.

METHODS: According to the findings of Brody (1987) and Brannigan and Adali (1981), the racket model was an elastic beam (78 nodes) with a constant quadratic cross-sectional area, as well as homogenous mass distribution and elastic modulus (Fig. 1). Table 1 shows the input parameters for simulation of two real rackets included in this investigation. The elastic modulus *E* was determined experimentally by flexural test (Fig. 2) and calculated by the equation:

$$E = \frac{L^3 \cdot F}{3 \cdot I_a \cdot s} \qquad (1)$$

where *L* is the free length of the racket and model and I_a the area moment of inertia of the model. *F* is the appropriated force, and *s* the measured displacement of the racket in the flexure test.



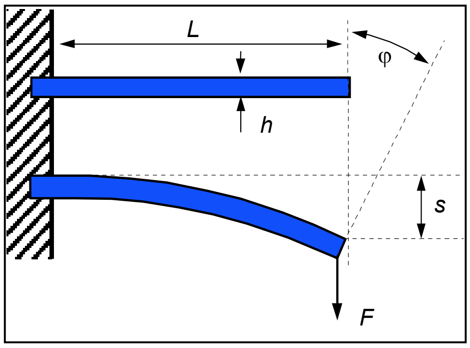


Fig. 1: Example for a beam in FEM. The nodes (-) connected by the elastic elements (1- 4) build the elastic beam

Fig 2: Experimental setup for the determination of the elastic modulus of the racket model

Then in the finite element analysis program ANSYS (Rev. 5.0, Swanson Analysis Incorporation) modal analyses were performed with the flexible racket models under different boundary conditions (one side fixed, both sides free). The results of these simulations (natural values and natural frequencies) were used to build flexible racket models in direct dynamics.

Table 1: Input parameters for two elastic racket models.

Racket			**A**	**B**
Parameter	**Symbol**	**Unit**	**Value**	**Value**
Thickness	*h, b*	m	0,03	0,03
Length	*L*	m	0,685	0,685
Cross-sectional area	*A*	m²	$0{,}9e^{-4}$	$0{,}9e^{-4}$
Area moment of inertia	I_a	m^4	$6{,}75e^{-8}$	$6{,}75e^{-8}$
Mass	*M*	kg	0,362	0,315
Density	□	Kg/m³	587,19	510,95
Elastic modulus	*E*	N/m²	$1{,}94e^{9}$	$2{,}30e^{9}$

The planar computer model used for direct dynamics was based on a multiple pendulum consisting of upper arm, lower arm, hand and racket as described by Glitsch (1997) and Detlefs (1996). The arm elements were linked by hinge joints.
In contrast to them, the elastic properties of the racket frame are now included in the racket model. The elastic properties of strings and ball are furthermore combined in an adapted spring-damper system according to Leigh and Lu (1992).
In order to check the requirements for a flexible dynamic simulation model, various stroke simulations with different hand-racket-connections (fixed, joint and stappable connection) were performed. The model setup and dynamics calculations was done with the software package DADS (Dynamic Analysis and Design System from CADSI). It provides a complete record of all kinematic and dynamic variables for each joint and body, even the flexible bodies.
The interesting parameters in this investigation are the acceleration and the vibration frequencies of the racket. They were compared with the data of real

tennis strokes recorded with a miniature accelerometer (DISYNET, Type IC 30319).

RESULTS AND DISCUSSION: First it must be stated that a complex dynamic tennis simulation, including all important mechanical properties (inertial and elastic) of the racket, is possible (Fig. 3). The combination of a finite element model of the racket, performing a modal analysis and direct dynamics enables a dynamic simulation of racket deformation and vibrations during a stroke.

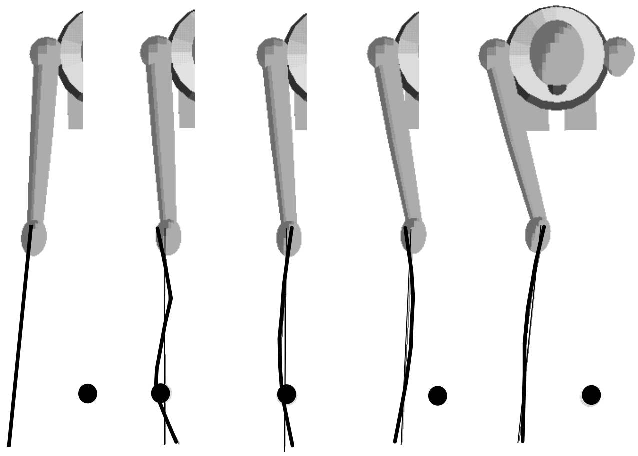


Fig 3: Animation of a simulated tennis stroke with an elastic racket model

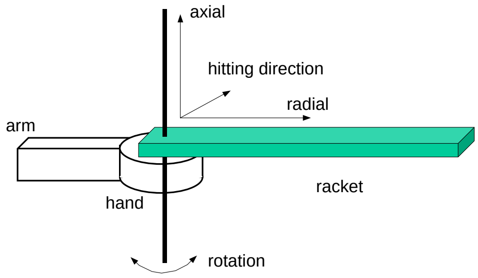


Fig.4: Bushing element in use as a loose, stappable hand-racket-connection.

Second, the analysis of the vibrational parameters indicates that the tennis racket behaves as a freely vibrating body. Thereby the results of earlier experimental studies like Brody (1987) could be reaffirmed by the application of computer simulation methods. In this investigation only the combination of a freely vibrating racket model with a loose, moveable hand-racket-connection can simulate the accelerations of a real tennis stroke (Fig 5). Therefore a bushing element (Fig 4) that allows and restrains the movement of the axis by applying forces in several directions was used. In this case the possible movement in all directions – including the rotation – was reduced by a force of 10 N. Only in the radial direction was a force of 100 N added to keep the racket in the hand. Although following examinations of modeling the racket-

hand-linkage are necessary, the comparison of racket accelerations (Fig. 5) shows that the bushing element is a practicable instrument. It simulates a stappable connection that allows racket vibration during the stroke similar to that under real conditions.
Furthermore, with the described model different results of previous studies could be validated by computer simulation. (1) It is not necessary to fix the racket with large grip forces. (2) Racket test with a clamped handle lead to incorrect results, because the vibrations of a clamped racket do not agree with them in the handheld situation.

CONCLUSIONS:

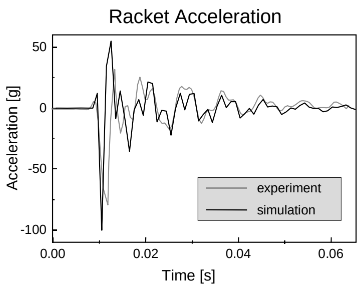


Fig 5: Comparison of acceleration profiles at the racket handle (experiment, simulation).

The findings of this evaluation study confirm the possibilities of dynamic tennis simulation. Further investigations of the influences of elastic racket properties (e.g., stiffness, node locations) on stroke characteristics are conceivable. Several optimizations of the used elastic racket model (e.g., non-constant elastic modulus or cross sectional area) are possible. Different elastic properties of handle and racket head could thus be considered in subsequent research.

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