DETERMINING SUBJECT-SPECIFIC PARAMETERS FOR A COMPUTER SIMULATION MODEL OF A ONE-HANDED TENNIS BACKHAND

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A subject-specific computer simulation model of a one-handed tennis backhand was developed to investigate the mechanisms that may cause injury to the elbow. Subject-specific parameters for the ball, racket and human were determined. Firing tennis balls from a pneumatic air cannon onto a force plate enabled parameters to be determined for a spring-damper model of a tennis ball. Data from further ball cannon tests allowed the spring constants for the stringbed and the coefficient of friction between the ball and stringbed to be optimised using a computer simulation model. The fundamental modal frequencies of the racket frame were obtained by Doppler laser vibrometry and its inertia parameters were determined from the results of oscillation and balance tests. An elite tennis player performed isovelocity tests at the wrist, elbow and shoulder to establish torque / angle / angular velocity relationships. Inertia parameters of the human segments were calculated from ninety-five anthropometric measurements using a geometric model.

KEY WORDS: simulation, parameters, tennis

INTRODUCTION: Subject-specific computer simulation models have been created with a view to analysing the mechanics of a sporting movement (e.g. Yeadon & King, 2002). Creating a subject-specific model allows simulations to be compared with performances by the same subject and therefore the model can be evaluated. When the model has been shown to accurately represent the real life situation, the researcher can be confident in its capabilities and then use the model to address the pertinent research questions (Hubbard, 1993).

The citations for the aetiology of 'tennis elbow' are numerous and often speculative. However, there is general agreement that players performing one-handed backhand strokes are more susceptible to elbow injury (Roetert et al., 1995). This paper describes a computer simulation model of the one-handed backhand and the methods used to determine its subject-specific parameters. The purpose of this work is to investigate the factors that may increase the potential for upper-extremity injury to the tennis player.

METHOD:

Computer simulation model: A three-dimensional subject-specific simulation model of a human arm and torso segment linked to a ball-racket system was developed (Figure 1). A ball-stringbed system allows oblique impacts to occur at nine specified locations on a stringbed of varying stiffness. Two rigid bodies, connected by torsional spring-dampers at the antinodes of the fundamental modes of vibration (in and out of the plane of the racket), allow the vibration of the racket frame to be modelled. Spring-dampers at the thenar and hypothenar eminences of the hand enable the racket to be gripped and forces to be transferred between the player and the racket system. Joint angle time histories drive a rigid thorax, upper arm, forearm and hand segment which are connected by simple pin joints. Establishing joint torque / angle / angular velocity parameters at each joint means that one-handed backhand techniques are limited to those that are within the strength capabilities of the subject. Wobbling mass segments to represent the soft tissue motion are attached to the forearm and upper-arm rigid bodies by spring-dampers.
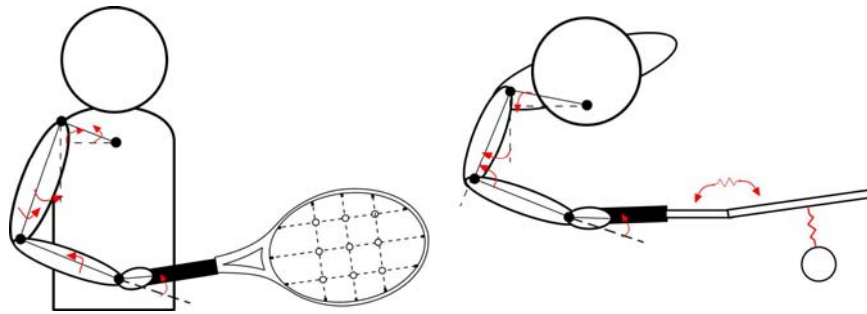
Figure 1: Subject-specific computer simulation model of the one-handed tennis backhand

Data Collection: Multiple data collections and subsequent processing of the data were needed to determine the subject-specific model parameters. To determine parameters for the normal component of a three-dimensional tennis ball model, balls were fired normal to and at the centre of a piezoelectric Kistler force plate using a custom-built pneumatic air cannon. A model based on theoretical considerations by Babitsky and Veprik (1998) that uses the force trace and initial ball velocity as input, was used to optimise the spring-damper coefficients. Rebound angle data for oblique impacts at nine specified locations on the stringbed was collected and used to optimise the coefficient of friction between the ball and stringbed using a simulation model of the ball and stationary racket. For all data collections, a range of racket angles and ball velocities were used that replicated the relative velocities between the racket and ball.

To calculate the spring constants for the stringbed, balls were fired from the pneumatic air cannon to impact normally onto the nine points of the stringbed. The initial force (tension) in the springs and the spring stiffnesses were varied within a computer optimisation programme until a best match was found between the actual coefficient of restitution and that calculated by the simulation model.

A modal analysis allowed the mode shapes and natural frequencies of the racket frames to be determined. The frames were stimulated and the Doppler shift between the frequency of the transmitted and reflected light from retro-reflective tape was measured at several locations using a Polytec laser vibrometer. The outputs from the force transducer and the laser vibrometer were input to a spectrum analyser to obtain the frequency response function.

The moments of inertia of both racket parts, about the frontal and transverse axes, were calculated using simple pendulum oscillation tests. A custom built rig, housing a laser, a receiver and an oscilloscope was used to time the period of the racket oscillation. For the polar moments of inertia, an industrial measurment device with a custom-built attachment was used to give a direct reading. A fixed knife edge and an additional knife edge on a set of electronic scales were used to balance the racket and calculate its centre of mass by taking moments about a point.

To calculate the stiffness of the torsional springs in both racket planes, a simulation model of the tennis racket was created with the appropriate inertia parameters. The model frame was stimulated by a sinusoidal force with a frequency equal to that calculated from the modal analysis. The stiffness was then varied until the maximum amplitude of vibration was found for a simulation. The racket frame was struck with an impact hammer at the location of a tri-axial accelerometer in the racket handle. The damping coefficient of each torsional spring was peturbed until the time taken for the vibration of the frame to decay to zero matched that determined experimentally.

Torque / angle / angular velocity relationships were established for the wrist, elbow and shoulder joints (Yeadon et al., 2006). The subject performed maximal effort isovelocity trials for a range of angles and angular velocities using an isovelocity dynamometer. Inertia parameters of the human segments were calculated from ninety-five anthropometric measurements on the subject using the geometric model of Yeadon (1990).

The initial gripping forces at the thenar and hypothenar eminences were taken from single cell force sensor data collected during the performances whilst initial estimates for the stiffness and damping coefficients of wobbling masses were estimated from the literature (Pain, 2001). These parameters were then allowed to vary in a matching optimisation.
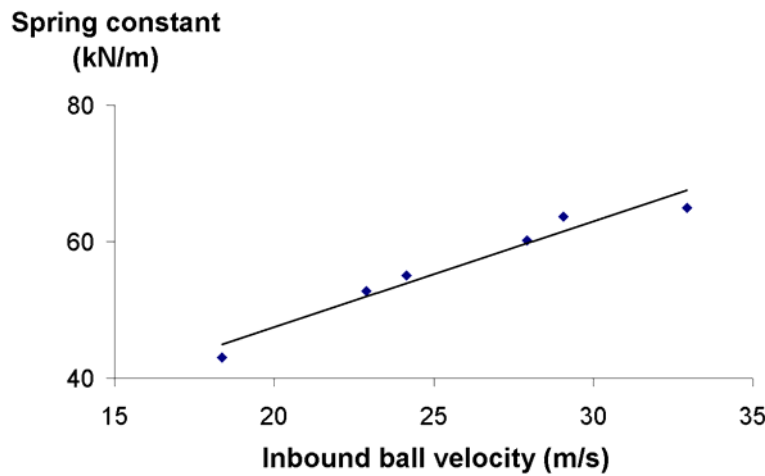

Figure 2: Spring constants of the tennis ball impacting normally onto a surface

RESULTS: Since they are too numerous to show in their entirety, a selection of results are presented in this section. Figure 2 shows the relationship between the optimised spring constant for the ball and the inbound ball velocity calculated using experimental force plate data and a theoretical model.

Figure 3 shows the raw data and the surface function which allows joint torque to be expressed as a function of joint angle and angular velocity.
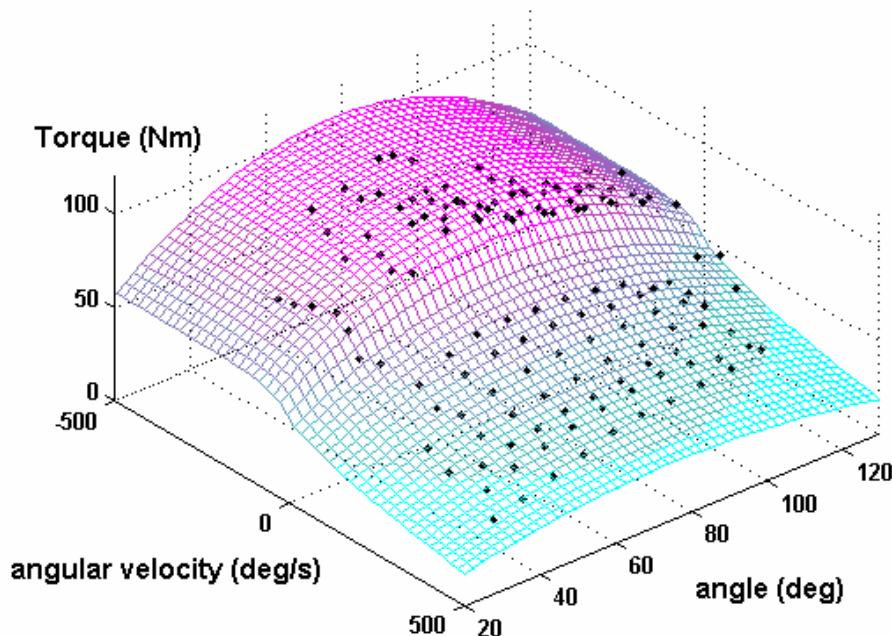

Figure 3: A joint torque / angle / angular velocity surface function fitted to raw data

Table 1 expresses the inertia parameters of the two racket frame parts, separated at the antinode of the fundamental mode of vibration.

Table 1 Inertia parameters of racket frame parts

Racket part	Mass (kg)	Centre of mass (m)	MoI about polar axis (kgm^2)	MoI about frontal axis (kgm^2)	MoI about transverse axis (kgm^2)
Part A (with handle)	0.13350	0.11365	0.00004	0.00173	0.00172
Part B (with stringbed)	0.16050	0.15032	0.00137	0.00465	0.00331

DISCUSSION: A computer simulation model has been customised to individual performances of one-handed backhand strokes by calculating subject-specific parameters. This allows the simulated performance of the model to be compared with the performances by the same subject. Where possible, parameters have been determined by experimental means. Alternatively, experimental results and / or findings from the literature have been used to form sensible starting values and bounds for matching optimisations. Although the simulation model is a simplification of what is a complex interaction between the human and equipment, initial results show that the values of the parameters determined result in realistic model outputs.

CONCLUSION: This paper identifies the methods that have been used to determine parameters for a subject-specific computer simulation model of the one-handed tennis backhand. Having evaluated the model, these parameters will be perturbed within forward dynamics simulations to examine the effect that the parameter change has on the forces and vibration transmitted to the wrist and elbow joints of the tennis player.

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