

THE BALL'S IN YOUR COURT

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Computer simulation of ball impact helps design better tennis rackets.

Modern predictive models show that improvements in tennis rackets — which primarily focus on reduced mass and increased structural stiffness — allow a player to serve 17.5 percent faster using modern equipment compared to what was available in 1870 [1]. To make further improvements in rackets requires more complex and less obvious changes — such as the coefficient of friction (COF) between the strings and the ball as well as the position of the racket's balance point.

A team of researchers at Sheffield Hallam University (which includes the author, Steve Haake and Simon Goodwill) have developed models with ANSYS LS-DYNA software that accurately

simulate ball-on-tennis racket impacts. These models are being used to investigate the individual and combined effects of many different design variables and to develop insights for improving the design of tennis rackets produced by Prince Sports.

SEARCH FOR A BETTER RACKET

University researchers used ANSYS LS-DYNA explicit dynamics software to simulate tennis racket-ball impacts. The software simulates short-duration events with severe loadings and large deformations, thus helping researchers to understand what happens during crashes, explosions and metal forming operations. LS-DYNA is available within the ANSYS Workbench environment, which provides extensive CAD interfaces, automatic meshing, integration with other simulation tools and design optimization.

In simulating a tennis ball against a racket, conditions were designed based on an elite player's typical topspin groundstroke. The racket

impact was assumed to be at the center of the stringbed, because elite players typically hit the ball in this position. The racket model had a mass of 0.348 kg, a balance point located 0.324 m from the butt and a natural frequency of 135 Hz, all representative of an International Tennis Federation-approved racket.

MODEL CHARACTERISTICS

Tennis rackets are made by hand, so they do not exactly match the design geometry. Researchers scanned a racket with a laser to produce a surface model that reflected the geometry of a real racket. They used a linear elastic material model for the racket's frame, which was meshed with 27,410 shell elements. The racket model included an interwoven stringbed that had a linear elastic material model. The stringbed was nonrigid, and the individual strings had the capability to move where they intercept other strings.

The ball model consisted of a felt cover and rubber core, with an airbag replicating internal pressure. Prior to generating the racket model, the ball

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model's separate parts were independently validated against experimental data. In the racket model, ball-to-stringbed contact was defined using the automatic surface-to-surface contact algorithm. The research team evaluated the COF at 0.0, 0.2, 0.4, 0.5, 0.6, 0.7, 0.8 and 1. The simulation projected the tennis ball onto an initially stationary, freely suspended racket.

Engineers compared simulation results to the International Tennis Federation's custom racket impact machine, designed to simulate non-spinning impacts between a tennis ball and a racket at a range of velocities and locations on the long axis of the stringbed. Previous studies with a high-speed video camera demonstrated that this machine provides comparable results to a freely suspended racket. The model was in good agreement with experimental data for a range of velocities and impact locations. The marginal discrepancies between the two sets of data were within

the measurement error. The root mean squared error of 1 m/s corresponds to 3 percent at 30 m/s and 2 percent at 45 m/s. All errors were less than 5 percent.

UNDERSTANDING THE PHYSICS

Once the model was validated, researchers used the results to gain a better understanding of the physics involved in the racket's performance. Simulation provides far more insight and results than can be obtained from physical testing. For example, it's very difficult to measure the impact forces of the ball on the racket experimentally, but these results can easily be obtained from simulation.

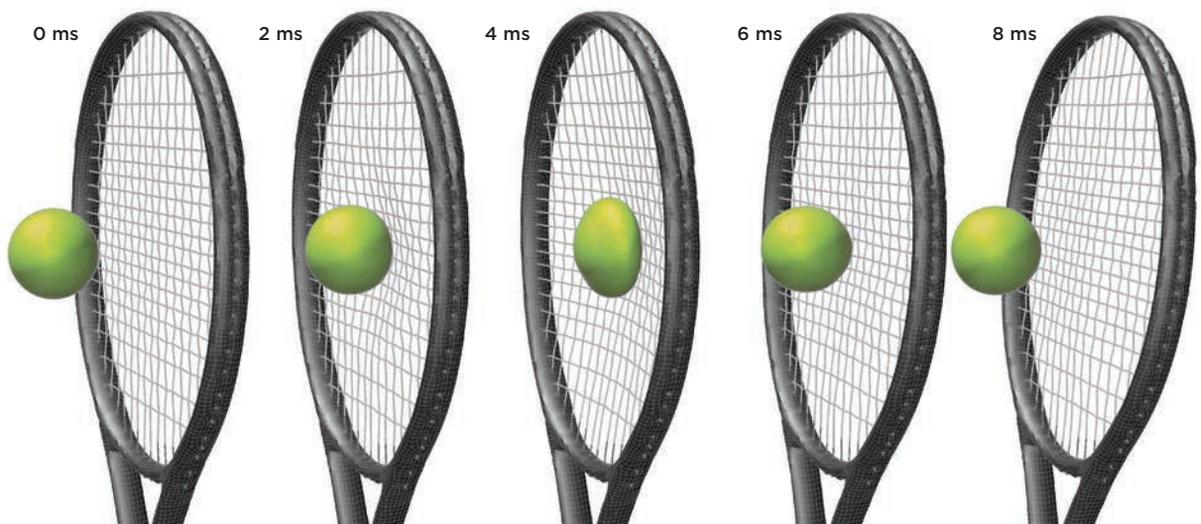
The analysis showed that a tennis ball typically goes through three separate phases during an oblique impact: sliding, overspinning and rolling.

The ball remains in the sliding phase throughout impact if the friction force acting on it is relatively low. During this first phase, the ball's topspin increases

while the velocity parallel to the surface decreases. The magnitude at which the velocity and spin change is determined by the frictional force acting on the ball. The frictional force is dependent on impact conditions and the COF. A higher coefficient of friction causes a larger change in the ball's velocity and spin. If the ball slides throughout the impact, it will always rebound more slowly and with more topspin for an impact on a high-friction surface.

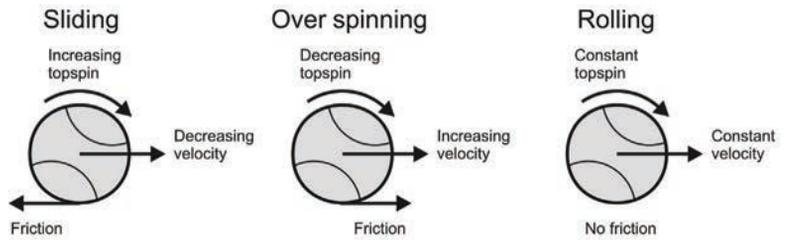
If the frictional force acting on the ball is sufficiently large, it will pass from the sliding phase to the overspinning phase. During this segment, the frictional force acting on the ball changes direction, causing increased velocity parallel to the surface and decreased topspin. So the maximum possible topspin is achieved if the ball rebounds at the end of the sliding phase. At the end of the overspinning phase, the ball begins to roll if the frictional force is large enough. Once the ball begins to roll, there is essentially no change in horizontal velocity or topspin. Since the ball can spin more rapidly when it is rolling, it is possible for it to rebound with less topspin from a surface with high friction. However, the maximum possible rebound topspin will always be higher for a surface with high friction.

This image sequence shows a ball impacting perpendicular to the face of a freely suspended tennis racket. 0 milliseconds (ms): ball traveling toward racket prior to impact; 2 ms: initial contact between ball and racket; 4 ms: maximum deformation of ball; 6 ms: end of contact; 8 ms: ball rebounding from recoiling racket



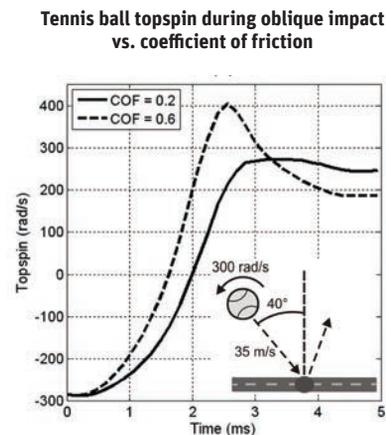
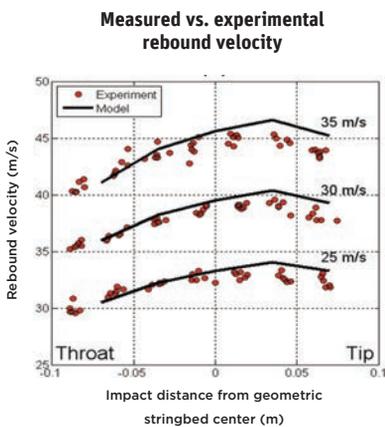
IMPROVING RACKET DESIGN

Researchers used simulation to investigate the effects of changing the COF between the strings and the balls. The results showed that with low rebound angles (relative to racket face normal), the COF did not have a major impact on the ball's rebound characteristics. Examination of simulation results showed that the ball was effectively rolling off the stringbed, so coefficient of friction made little difference. The COF has a larger impact if the ball is sliding or overspinning on the racket at the end of the impact. The ball is less likely to roll during the impact if the inbound horizontal velocity or the backspin is increased. The ball is also less likely to go from overspinning to rolling during an impact if the COF is low.



Three stages of tennis ball impact

The tennis equipment manufacturer, Prince Sports, has begun making low-friction strings based on the results of this study.



The team conducted simulations with an impact angle of 40 degrees to determine the amount of topspin that the ball would rebound with when the COF was 0.2 and 0.6. The rebound topspin was 33 percent higher when the COF was 0.2 because the horizontal force reversed direction approximately 1 ms later in the impact. This demonstrates that the ball is likely to rebound with more topspin from a low-friction stringbed than from a high-friction stringbed if the inbound velocity, angle and backspin are all large. The ball will have the maximum possible rebound topspin if it rebounds from the stringbed at the instant at which it starts to overspin. These results are significant because of the important role played by topspin in tennis. Topspin causes the ball to curve downward as it travels in the air, making it possible to hit the ball harder yet keep it inbounds.

The results of this and other studies of tennis rackets using ANSYS LS-DYNA have been employed by Prince Sports, which sponsored this research. The tennis equipment manufacturer has begun

making low-friction strings based on the results of this study. Researchers are currently performing additional studies to evaluate other aspects of racket design. For example, future work will look at the effect of racket design on a player's potential to suffer from tennis elbow and other injuries. One of the causes of tennis elbow is believed to be a torque on the elbow generated by the racket; researchers will look at how the racket can be designed to reduce this torque. ▲

Reference

Haake, S.; Allen, T.; Choppin, S.; Goodwill, S. The Evolution of the Tennis Racket and its Effect on Serve Speed. *Tennis Science and Technology* 3, 2007, Vol. 1, pp 257–271.