Tennis Physics: Anatomy of a Serve

No. 5 ranked Andy Roddick has the world’s fastest tennis serve—his 155-mph scorcher in 2004 set the record—but he doesn’t like to talk about it. When he first met Patrick McEnroe, his Davis Cup coach, he said: “Whatever you do, don’t say anything to me about my serve. If I think about it, I’m in trouble.” Here PM analyzes what the 24-year-old player won’t: What happens in the two-thirds of a second between toss and ace.

By Tom Colligan
Photograph by Getty Images
Illustrations by Intoaroute
Video Courtesy of John Yandell
Published in the September 2007 issue.


RACKET-HEAD SPEED
100%
UPPER ARM
10%
LEGS AND TRUNK
20%
FOREARM
40%
HAND
30%

The Windup

As the toss goes up, players press their feet against the court, using ground reaction forces to build up elastic potential energy—rotations of the legs, hips, trunk and shoulders that produce maximum angular momentum. Exploding upward toward the ball, pro players employ extraordinary timing to efficiently transfer forces from the legs, through the body segments, to the striking hand in what biomechanists call “the kinetic chain principle.” Bruce Elliott, a professor at the University of Western Australia, has extrapolated the contributions of the body segments to racket-head speed (shown here) using 3D videography and computer analysis. “These contributions vary from person to person,” Elliott says, “but the data shows the clear importance of the trunk, shoulder internal rotation and wrist flexion in the swing to impact.”

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The Toss and The Strike

The Toss

A high, confident toss made 1 to 2 ft. inside the baseline allows the server to uncoil both upward and forward into the court, making contact at 1.5 times body height. For Roddick, at 6 ft. 2 in., that is roughly 9.5 ft. off the ground. A pro player looks for variations in height or location of his opponent’s tosses to predict where the serve is headed—and adjusts accordingly. Top servers, however, give away nothing. “Andy can hit it hard to different corners with the same toss,” McEnroe says. “Players just can’t pick it up.”

The Strike

On a 120-mph serve, the ball is in contact with the racquet strings for about 5 milliseconds, moving up to 5 in. laterally across the string plane, gathering spin. The tip of the racquet moves at nearly 120 mph, though at the point of impact, a few inches closer to the ground, the racquet is moving roughly 22 percent slower. The ball’s additional speed comes from both the elastic energy in the rubber, which returns 53 to 58 percent of the force exerted upon it, and the racquet strings (strung at an average of 60 pounds of tension), which stretch about 1 in. during the impact.

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The Windup **Acceptance Window and Spin**

Acceptance Window

As the ball rockets off the strings, it must travel within a very narrow range of angles to both clear the net and bounce inside the service box. Coaches call this tiny wedge of potential trajectories the “acceptance window.” It shrinks as the serve goes faster—requiring incredible timing and precision to deliver a 120-mph serve inbounds. There are, however, things that the server can do (short of hitting the ball slower) to increase the size of the acceptance window. University of Pennsylvania physics professor Howard Brody has identified two key tactics: Strike the ball as high off the ground as possible or give the ball more topspin, which creates an area of low pressure beneath the ball (a phenomenon known as the Magnus effect) to make it nose-dive into the service court.

Spin

A tennis ball’s spin barely decreases during flight, and actually increases when the ball hits the court. “Looking at slow-motion video, you can see that the friction of the court grabs the bottom of the ball, while the top continues to rotate, adding more spin, and converting sidespin into almost pure topspin,” says videographer and tennis instructor John Yandell. The average 2400-rpm spin rate Yandell has observed in Roddick’s 130-mph serves doubles after the ball hits the court’s surface—to a whopping 4800 rpm. This creates the “heavy ball” effect—a shot with so much movement and spin that opponents feel as though they’re returning a shot put.

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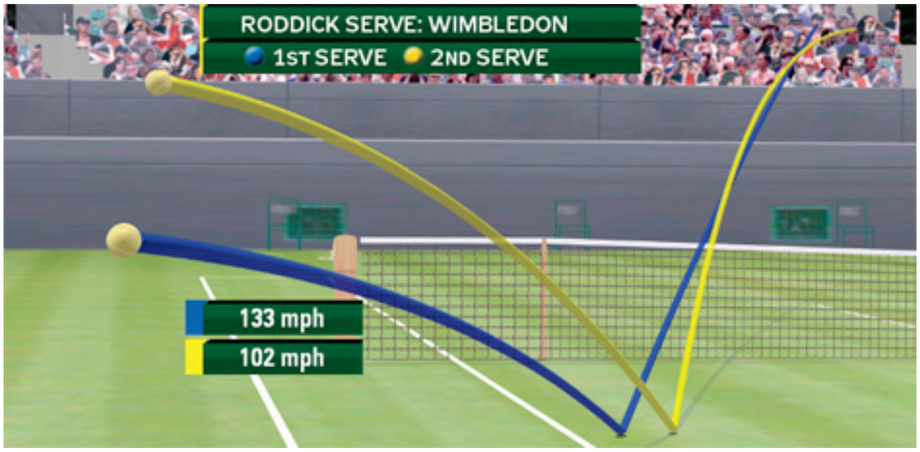
The Toss and The Strike **First and Second Serves**



First and Second Serves

Pros are successful on 50 to 60 percent of their first serves, which are faster and have flatter trajectories than their second, slower serves. At this year’s Wimbledon tournament, Roddick nailed a 133-mph first serve (blue) that hit the court hard and bounced low with slice—sidespin that curves and draws the returner wide of the sideline.

On a second serve (yellow), Roddick employed a 102-mph “kick serve” with heavy topspin, created by brushing the strings upward against the back of the ball. This made the serve dive into the box, and generated a high bounce that was difficult to return. First serves are flashy but second serves are a better predictor of success: The top three players in the world are men who’ve won the most points on their second serve.

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Acceptance Window and Spin

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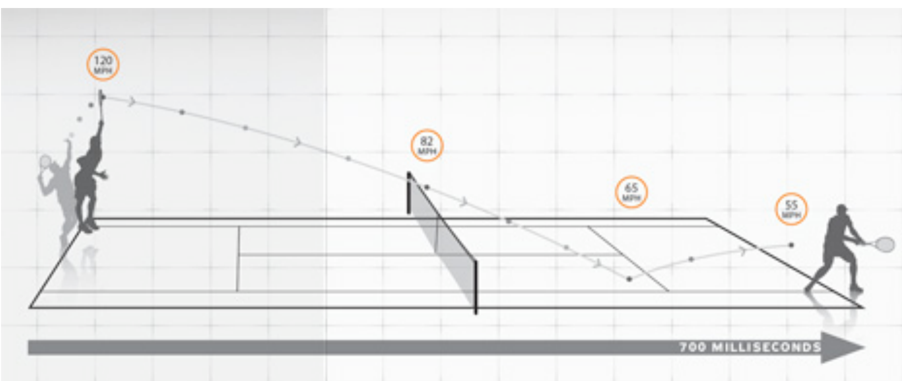
Velocity



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Velocity

The serve speeds you see on courtside digital displays are measured just as the ball leaves the racquet. Fortunately for returners, by the time the ball reaches them, air resistance and the friction of the court surface have diminished its speed by roughly 50 percent. Tennis instructor and analyst John Yandell has found that, on average, a 120-mph serve slows to 82 mph before the bounce, then to 65 mph after the bounce, and finally to 55 mph at the opponent’s racket.

How did today's serves get so fast?

The single advancement most responsible for today’s blindingly fast serves, says Rod Cross, a physicist at Australia’s University of Sydney, is the oversize racquet head. The game was transformed as the hitting surface of racquets grew to the current legal limit of 15.5 x 11.5 in.—established in 1981. “Players hit the ball as hard as they can, and give it enough topspin to make it land in the court,” Cross says. “You couldn’t do that with a small wooden racket—the ball would have clipped the frame.”

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First and Second Serves