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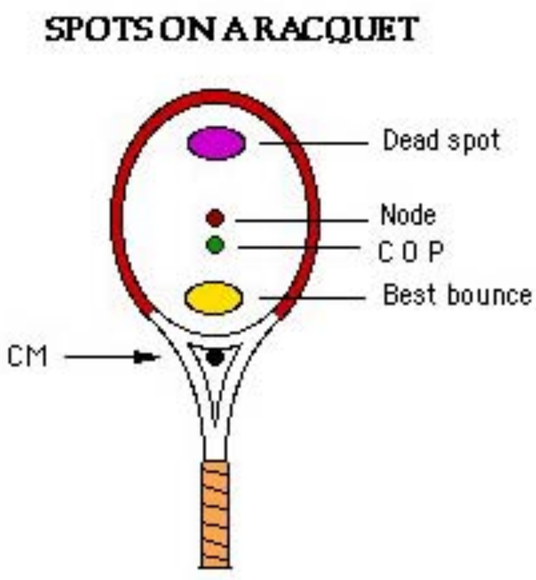
Word count:

"How does the spot on the racquet affect the height of the rebound?"

On the face of the tennis racquet, there are several points that are important to players; these are the center of percussion, the vibration node, the best serving spot, the best returning spot and the dead spot. A couple of the spots are shown on the diagram below. The center of percussion is one of the two "sweet spots" of the racquet. This is because at the point of impact between the center of percussion and the ball, the hand can feel no impact. This is due to the fact that the center of percussion is located near the center of the face of the racquet.

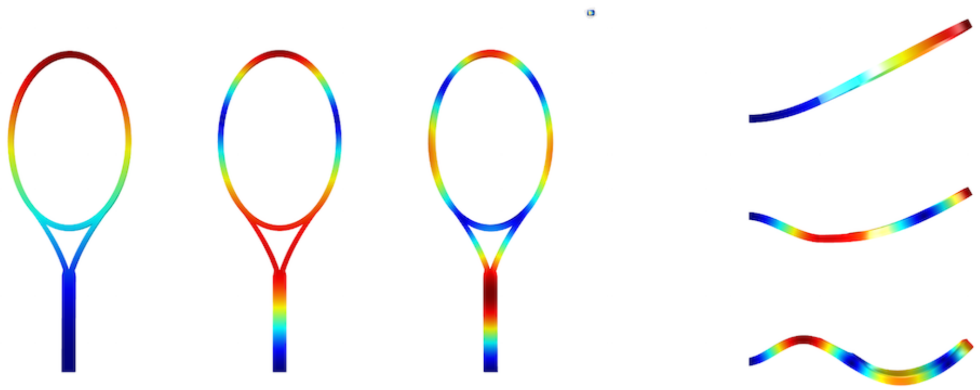
A tennis racquet, like a baseball or cricket bat, has a sweet spot. If a ball impacts at the sweet spot, the force transmitted to the hand is sufficiently small that the player is almost unaware that the impact has occurred. If the ball impacts at a point well away from the sweet spot, the player will feel some jarring and vibration of the handle. The sweet spot is a vibration node, located near the center of the strings. Another potential sweet spot is the center of percussion (COP). These and some other significant spots on a racquet are shown below.



Contrary to popular opinion, the sweet spot does not coincide with the point at which the ball rebounds with maximum speed, nor does it locate the spot where the force on the hand is zero. Forces on the hand arise from three independent motions of the handle, namely rotation, translation and vibration. The vibrational component is absent when a ball strikes the vibration node. The rotational component, arising from recoil of the racquet head, exerts a torque on the hand, causing it rotate about an axis through the wrist. As a result, a force is always exerted on the upper part of the hand, and a force in the opposite direction is always exerted on the lower part of the hand.

The COP shown in the diagram above is located close to the node point when the racquet is freely suspended, but it shifts into the throat area of the racquet when the racquet is held in the hand. Consequently, the COP shown in the diagram is NOT the sweet spot that players talk about.

In mechanical vibration theory, the *vibrations nodes* are defined as the points that never move when a wave is passing through them. Because of a wave created by the impact of a ball hitting a racket, the racket will, in turn, begin to oscillate and vibrate. By looking at the mode shapes of the racket — held by a player at the end of the grip — we could identify points where the vibration motion is zero (i.e., where the magnitude is zero at any time during vibration). Here are the first three mode shapes of a tennis racket computed with COMSOL Multiphysics:



The first three mode shapes of a tennis racket, from left to right and top to bottom. The fundamental mode is at 15 Hz, the second mode is at 140 Hz, and the third mode is at 405 Hz.

As illustrated above, many different points feature this behavior. So why am I talking as if there is only one vibration node? In reality, there is actually an infinite number of vibration nodes. Upon impact, the ball generates an infinite number of harmonic series at different frequencies. An infinite number of frequencies are excited at one time, but which vibration node is the "sweet spot"? Is it the fundamental mode shape vibration node or is it a node that results from the crossing of different harmonics?

The fundamental mode vibration node cannot be the sweet spot for an obvious reason: It is located at the grip. Try hitting the ball with the grip to pass it over the net. If you are very lucky, you may succeed, but most likely, you won't. The second vibration mode, meanwhile, has two nodes: one at the grip and one on the strings near the frame head. The latter is considered the sweet spot. Any player that hits the ball at this point will feel almost no vibration during impact.

There are, of course, vibration nodes on the strings for higher modes, as depicted in the third mode from the simulations above. However, as the natural frequency of the mode increases, the magnitude of the vibration drastically *decreases*. The graph below shows the frequency response of a sinusoidal load of 5 ms — approximately the duration of a ball's impact upon hitting a racket — on a beam-like structure. For frequencies higher than 300 Hz, the magnitude is almost zero. That is, the influence of the third mode or higher is negligible. No matter where the ball strikes, even at points where the magnitude of the mode shape has reached its maximum, the higher modes will not have any influence at all because they are not excited.

http://www.physics.usyd.edu.au/~cross/tennis.html

https://www.comsol.com/blogs/the-physics-of-tennis-racket-sweet-spots/