# THE SWEET SPOT OF A BAT OR RACQUET

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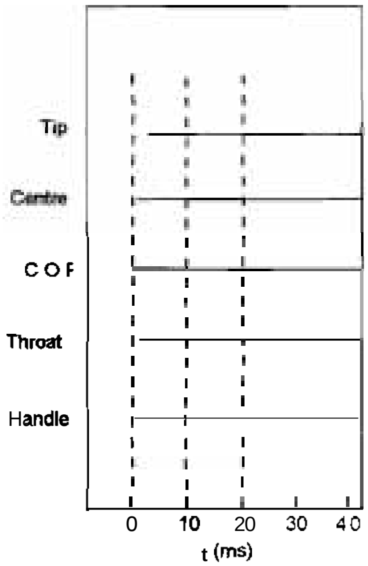
The sweet spot of a bat or racquet is sometimes identified as a vibration node, sometimes as the centre of percussion **(COP)** and sometimes as the **impact** point where the ball rebounds with maximum speed. The batter or player is more likely to identify the sweet spot as the impact point that results in minimum shock and vibration, and therefore as the point that feels best. Theoretical and experimental results described in this paper indicate that the sweet spot is a narrow zone, located between the fundamental vibration node and the **COP,** where the energy transferred to the handle is minimised.

KEY WORDS: sweet spot, bat, racquet, centre of percussion, vibration node

INTRODUCTION: The sweet spot of a baseball bat or a tennis racquet is rewgnised by most players as the point that feels best when the ball is struck. The player feels almost no shock or vibration for an impact at the sweet spot. Conversely, the impact can be moderately painful for an impact well removed from the sweet spot. Various studies (eg Brody, 1986) have indicated that the sweet spot might coincide with the fundamental vibration node of the bat or racquet, or it might coincide with the centre of percussion (COP). Many authors assume that the sweet spot also coincides with the point at which the ball rebounds with the maximum possible speed. The latter assumption is clearly incorrect. If a tennis ball is incident on a stationary racquet, it bounces best near the throat of the racquet and worst near the tip. Conversely, if the ball is stationary and the racquet is swung towards the ball, as in a serve or smash, the ball speed is maximised for an impact nearer the tip since that is where the racquet is moving fastest. The sweet spot of the racquet, or the point that feels best, is near the centre of the strings. For certain combinations of ball and racquet speed, the ball might rebound with maximum speed at the sweet spot, but this not generally true.

In previous studies (Cross, 1998, 1999) the sweet spot areas on a tennis racquet and a baseball bat were investigated by measuring the forces transmitted to the hands. In the case of a baseball bat, it was found that the sweet spot is a narrow zone located between the fundamental vibration node and the COP. The forces on the hands did not drop to zero in the sweet spot zone but were significantly smaller than at other impact locations. Outside the sweet spot zone, both the fundamental and second vibration modes contributed significantly to the impact forces transmitted to the hands. A similar result was found for a tennis racquet, although the second vibration mode is not excited significantly since the impact duration, about 5 ms, is too long to excite high frequency modes in the racquet frame. There is no impact point on a tennis racquet where the forces transmitted to the hand are zero. Regardless of the impact point, the force of the ball on the strings acts to push the racquet head backwards, resulting in rotation of the hand about an axis through the wrist. Consequently, a force acting in the same direction as the incident ball is exerted at the base of the index finger, for a forehand shot, and a force in the opposite direction is exerted by the butt end of the handle on the tip of the little finger. The net force on the hand is such that, in a reference frame where the racquet is initially at rest just prior to the collision, the hand and forearm both move in the direction of the incident ball for an impact near the throat of the racquet. For an impact near the tip of the racquet, the hand and forearm both move, as a result of the collision, in the opposite direction to the incident ball. For an impact at the COP, the forces on the upper and lower parts of the hand are equal and opposite, so there is no sudden motion of the hand or forearm as a result of the collision. These effects are illustrated in Fig. 1, showing the velocity of the forearm for different impact points on the racquet. The piezo disc acts as an accelerometer. The output signal was integrated to monitor the velocity of the forearm.



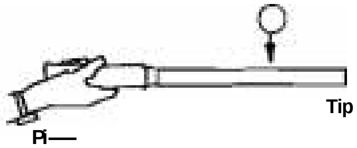




Figure 1 - Velocity of the forearm, measured using a **piezo** disc strapped to the wrist, when a ball is dropped onto a racquet at the positions indicated. The upper waveform shows the force of the ball on the racquet. The horizontal line through each waveform is the zero velocity baseline. A positive velocity corresponds to motion of the forearm vertically upwards. No racquet vibrations are excited for an impact at the centre of the strings. No sudden motion of the forearm is experienced for an **impact** at the COP.

BEAM EXPERIMENTS: An analysis of the impact between a bat or racquet and a ball can be attempted by assuming that the bat or racquet is a rigid beam and that no impulsive force is exerted by the hand on the handle. In fact, a tennis racquet is a much more complex structure than a uniform beam, but it can be modelled as such as a first approximation. The centre of mass of a racquet is usually quite close to the centre of the racquet, so it has an approximately uniform mass distribution. Furthermore, the locations of the vibration nodes and the COP are consistent with the locations expected for a uniform beam. However, real bats and racquets are flexible rather than rigid. A simple experiment was therefore devised to examine the effects of beam flexibility on the behaviour of a bat or racquet. The experimental arrangement is shown in Figure 2. A rectangular aluminium beam was chosen as an idealised bat or racket so that its length and stiffness could easily be vaned and so that simple beam theory could be used to analyse the results. A ball was mounted as a pendulum at the apex of a V-shaped string to impact at low speed on the beam, and the incident and rebound speeds of the ball were measured by allowing a card glued to the ball to intercept a laser beam. The ratio of the rebound to the incident speed is the apparent coefficient of restitution (ACOR). It is plotted as a function of the impact position in Figure 3, together with two theoretical estimates of the ACOR. The agreement is excellent, and the results are very interesting.

The ACOR remains essentially constant over most of the length of the beam, decreases to zero at the free end and rises to $e = 0.85$ at the clamped end. The ACOR in the central section is not affected by unclamping the clamped end or by shortening the beam to $L = 60$ cm. These results demonstrate that the impact is strongly influenced by the effects of wave propagation along the beam. The impact generates a pulse that propagates to each end of the beam and is then reflected back towards the impact point. If the ball rebounds before the reflected pulses arrive back at the impact point, then the ends of the beam have no effect on the bounce. In this case, a clamped end has the same (zero) effect as a free end, and a short beam behaves the same as a long beam. The relevance to a bat or racket is that the rebound speed of the ball is independent of whether the handle is gripped firmly or not at all. For a baseball bat, the impact duration is about 1 ms, and the travel time for a pulse up and down the bat is at least 2 ms. For a tennis racquet, the impulse duration is about 5 ms, and the travel time is at least 10 ms. In fact, the relevant travel times are longer than those quoted, since most of the energy of the impact is coupled to low frequency components which travel at a lower group velocity than components near the fundamental vibration frequency.

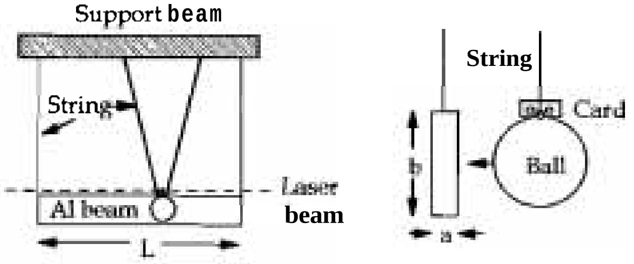



Figure 2 - Arrangement used to measure the ACOR of a superball incident at low speed on an aluminium beam. In this experiment, a = 6 mm, b = 32 mm and L = **110 cm**.

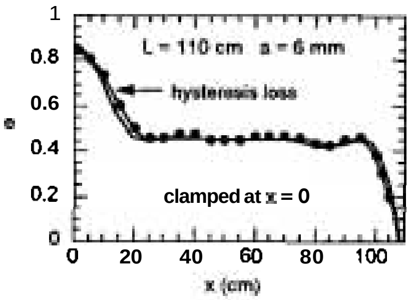



Figure 3 - ACOR **(e)** for a superball incident on an aluminium beam of length L = **110** cm and thickne a = 6 mm, as a function of the impact distance, x, along the beam. The beam is clamped at x = **0.** The black dots are experimental data points. The solid curve is theoretical, assuming that the ball **COR =0.85** on a rigid surface. The thinner **curve** is based on the measured hysteresis losses in the ball.

**BEHAVIOUR** OF A FLEXIBLE RACQUET: Flexible beam calculations for a freely suspended racquet, of mass 320 gm and length 72 cm, are shown in Figs. 4 and 5. It is assumed that a ball of mass 57 gm is incident normally on the racquet, at a distance x from the tip, and the racquet is initially at rest. Fig. 4 shows the fraction of the incident ball energy coupled to translation, rotation and vibration of the racquet, as well as the fraction dissipated in the ball (the loss curve) and the fraction remaining as kinetic energy in the rebounding ball. The Ball KE curve in Figure 4 is simply the **ACOR** curve squared and is in good agreement with observations obtained with actual racquets. As expected, the energy coupled to racquet vibrations is a minimum at the fundamental vibration node, but this does not lead to an increase in the kinetic energy of the rebounding ball since the energy coupled to translation and rotation of the racquet is a maximum near this node, as shown in Figure 5. Also shown in Figure 5 is the energy coupled to the last 10 cm of the handle. This result was obtained by dividing the racquet into 39 equal segments, then summing the energy of all segments in the last 10 cm of the handle. The significance of the sweet spot is clearly demonstrated by this calculation. An impact at the node in the handle (at x = 56 cm) leads to a small local reduction in the handle energy, due to the reduced vibrational energy. An impact at the node in the centre of the strings (at x = 15 cm) leads to a much larger reduction in the handle energy. This is because such an impact is close to the **COP**, meaning that the translational and rotational energy of the handle, as well as its vibrational energy, is minimised. The sweet spot therefore extends over a small zone of width about 5 cm in Fig. 5, lying between the fundamental vibration node and the **COP**.

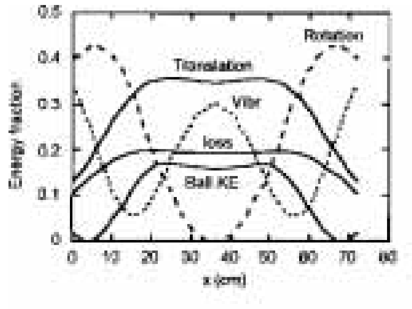



Figure **4 -** Calculated loss fractions for a tennis ball incident on a stationary, freely supported racquet of mass 320 gm, and length **72cm,** when the ball impacts a distance x from the tip.
Loss refers to the energy dissipated in the ball.

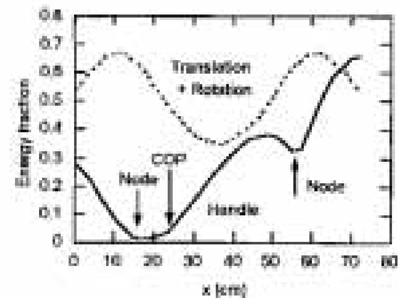



Figure **5** - The total loss fraction due to Translation and rotation, for the data in Fig. **4.** Also shown is the energy coupled to the last **10** cm length of the handle.

CONCLUSION: The sweet spot zone of a bat or racquet has been clearly identified in this paper in terms of the forces transmitted to the hand and arm, and in terms of the energy coupled to the handle. Further work is needed todetermine (a) the equivalent zone in other equipment such as a golf club, (b) the relation between impact forces and injuries to the arm, and (c) the effects of a non-uniform and/or two-dimensional mass distribution.

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