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A Study in Biomechanics and Biophysics: A Deeper Look Behind the Curtain of Tennis

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Abstract

At first glance, tennis may appear to rely primarily on reflexes and technique; however, the sport is governed by fundamental principles of physics. While previous studies have explored isolated physics concepts in sports, there is limited research that synthesizes multiple physical principles within the context of tennis as an educational tool for learning physics. This literature-based study addresses this gap by reviewing and integrating existing research on motion, force, energy transfer, friction, Newton's laws, and the Magnus effect as they apply to tennis. By analyzing patterns and insights across prior studies, this paper demonstrates how real-world athletic scenarios can enhance conceptual understanding of physics. Connecting abstract physics principles to tennis provides a meaningful framework that supports student engagement and improves comprehension by allowing learners to observe scientific laws in action rather than solely through theoretical examples.

Keywords: Biomechanics of sport, Biophysics of motion, Sports physics, Energy transfer, Newtonian mechanics, Human movement, Injury prevention

1. Introduction

Tennis provides a clear real-world example of how physics principles operate in sports. Previous research has examined the physics of tennis in detail, including how spin affects ball trajectory, how energy is transferred between the racket and ball, and how racket materials influence power and control. These studies have helped explain tennis mechanics, but they often focus on professional performance or complex physical models rather than classroom learning. As a result, there is limited research that presents these physics concepts in a way that is accessible and engaging for middle and high school students. The purpose of this literature review is to synthesize existing research on the physics of tennis and present it as an educational tool for learning physics concepts. By connecting motion, force, energy transfer, and spin to a familiar sport, this review aims to help students better visualize and understand abstract physics ideas. This approach supports more engaging and meaningful learning by showing how physics applies to real-life activities students recognize.

2. Methods

This study employs a qualitative literature review synthesis to examine existing research on the physics of tennis. Sources were selected using specific inclusion criteria: credibility of the author or organization, relevance to core physics concepts (such as motion, force, energy transfer, friction, and spin), and applicability to secondary-level physics education. Priority was given to peer-reviewed articles, educational databases, technical science publications, and materials published by recognized governing or professional organizations in tennis and sports science. Each source was evaluated for accuracy, clarity of scientific explanation, and consistency with established physics principles, and information was cross-checked across multiple sources to reduce bias or misinformation. Sources that focused solely on professional performance without clear educational relevance or that lacked scientific rigor were excluded, ensuring the review remained both academically sound and accessible for student learning.

3. Findings

3.1 Newton's Laws of Motion in Tennis

Newton's three laws of motion apply to all objects, including a tennis ball during play. Newton's first law states that an object at rest remains at rest and an object in motion remains in motion unless acted upon by an external force. A tennis ball lying on the court will not move unless a force, such as a racket strike, wind resistance, or gravity, acts on it (EE Times Europe, 2022). Once hit, the ball continues moving forward until forces like air resistance and friction slow it down.

Newton's second law, expressed as $F = ma$, explains how force, mass, and acceleration are related. The mass of a standard tennis ball remains constant during play at approximately 56.0–59.4 grams (International Tennis Federation, as cited in Tennis Warehouse University, 2021). Because mass stays the same, increasing the force applied by the player increases the ball's acceleration. For example, professional tennis serves can exceed 120 mph (about 54 m/s), which requires a very large force applied over a contact time of only a few milliseconds (EE Times Europe, 2022; Kellogg, 2019). Even at the high school level, harder swings during groundstrokes result in noticeably faster ball speeds, showing this relationship clearly.

Newton's third law states that for every action, there is an equal and opposite reaction. When a player strikes the ball, the racket applies a force to the ball, and the ball simultaneously applies an equal force back onto the racket (Di Maria, 2021). This reaction force can be strong enough to cause vibrations in the racket, which players feel in their hand and arm. As a result, grip strength, string tension, and racket materials are important for absorbing these forces and reducing strain while maintaining control (Tennis Warehouse University, 2011).

3.2 The Magnus Effect and Spin

In tennis, spin is created when the racket does not hit the ball straight through the center but instead brushes across its surface. Topspin occurs when the racket moves upward along the back of the ball, causing the top of the ball to rotate forward. Backspin (also called slice) is produced when the racket moves downward, making the ball rotate backward, while sidespin is created when the racket brushes across the side of the ball, causing sideways rotation (Florida Tennis, 2025; Tennis Without Talent, n.d.; AMbelievable™ Team, 2024). These different types of spin change how the ball interacts with the air as it travels (Lasky, 2022).

When a spinning tennis ball moves through the air, it experiences the Magnus effect, which explains why the ball curves or dips during flight (Lasky, 2022; EE Times Europe, 2022). As the ball spins, air moves faster on one side of the ball and slower on the other, creating a pressure difference. This pressure difference produces a force that pushes the ball in a specific direction. For example, a topspin shot causes lower pressure above the ball and higher pressure below it, forcing the ball downward more quickly than a flat shot (Florida Tennis, 2025; Tennis Warehouse University, 2021).

This effect is clearly seen during a topspin forehand, where the ball arcs high over the net and then drops sharply into the court before bouncing upward aggressively (Chiangpradit, 2024). In contrast, a backspin slice stays in the air longer, travels more slowly, and bounces lower, making it difficult for an opponent to attack the shot (Tennis Warehouse University, 2011; Stanford Advanced Materials, 2025). Sidespin is often used on serves, such as a wide slice serve, where the ball curves away from the receiver after crossing the net (Di Maria, 2021; Kellogg, 2019). These examples show how spin allows players to control ball placement, speed, and bounce, making the Magnus effect a key principle in modern tennis strategy (Florida Tennis, 2025).

3.3 Energy Transfer: Racket to Ball

Energy transfer in tennis is one of the most visible applications of physics. As a player prepares to hit a serve or groundstroke, the body stores potential energy in the muscles of the legs, core, shoulders, and arms. When the player begins the swing, this stored energy is converted into kinetic energy as the body segments rotate and the racket accelerates forward (Tennis Warehouse University, 2021). Before the swing, the racket is nearly at rest, but as swing speed increases, its kinetic energy increases as well. During impact, energy is transferred sequentially from the player's body to the racket and then into the tennis ball (Tennis Warehouse University, 2021).

Not all of this energy becomes forward motion of the ball. Some energy is released as sound at impact, while additional energy is lost as thermal energy due to friction and deformation of both the ball and the strings (Tennis Warehouse University, 2021). The amount of usable energy transferred depends on the coefficient of restitution, which measures how elastic the collision is (Stanford Advanced Materials, 2025). Tennis balls typically have a coefficient of restitution of around 0.7, meaning roughly 70% of the kinetic energy is retained after impact, while the rest is lost (Stanford Advanced Materials, 2025). A higher coefficient allows the ball to rebound faster, while a lower value results in reduced speed.

Professional players maximize energy transfer by striking the ball in the racket's sweet spot, where energy loss from vibration is minimized (Tennis Warehouse University, 2011). Off-center hits increase energy loss and reduce control, which is why timing and technique matter more than raw strength. By efficiently transferring energy through proper body mechanics and racket control, skilled players can generate powerful shots with less effort and reduced strain on their muscles (Kellogg, 2019). Tennis is therefore a game of efficiency and controlled energy flow rather than brute force.

3.4 Equipment and Material Physics

The design and materials of a tennis racket significantly influence how the ball behaves after impact. One of the most important factors is string tension. Higher string tensions, often around 55–65 pounds, provide greater control but less power because the strings deform less and absorb more energy during impact (Tennis Warehouse University, 2021). In contrast, lower string tensions, typically around 45–50 pounds, allow the strings to stretch more and return more energy to the ball, increasing rebound speed and power (Di Maria, 2021). This difference can be compared to bouncing a ball off a rigid wall versus a trampoline: the wall offers predictability and control, while the trampoline increases rebound energy but reduces precision.

Modern tennis rackets are primarily made of graphite or carbon fiber because these materials are lightweight, strong, and efficient at transferring energy (Tennis Warehouse University, 2021). A stiff racket frame bends less during impact, allowing more energy to be transferred to the ball and resulting in higher ball speeds, but it also transmits more vibration back to the player's arm (Kellogg, 2019). Softer frames flex more, absorbing a greater portion of the impact energy, which reduces shock but also slightly decreases shot power. Additionally, racket head size affects the sweet spot, with larger heads—often over 100 square inches—providing greater forgiveness on off-center hits by reducing energy loss and vibration (Tennis Warehouse University, 2011).

Because of these physical differences, professional players carefully select rackets that match their playing style and physical needs. By optimizing string tension, frame stiffness, and head size, players can balance power, control, and comfort, demonstrating how physics plays a direct role in racket selection and performance (Tennis Warehouse University, 2021).

3.5 Player Biomechanics and Serve Power

Serving is the only shot in tennis where all power is generated entirely by the player's body, making biomechanics especially important. A tennis serve relies on the kinetic chain, meaning energy is produced and transferred through the body in a precise sequence. The motion begins in the legs, where bending the knees and pushing against the ground generates force through ground reaction forces that can exceed several times the player's body weight (Kellogg, 2019). This energy is then transferred through the hips and core, which rotate rapidly to store and release energy in a spring-like motion (Chiangpradit, 2024). As the body uncoils, energy flows upward into the shoulder and arm.

During the forward swing, the double-pendulum effect occurs. The upper arm begins rotating first, followed by the forearm and racket accelerating forward at much higher angular speeds because they are connected and rotate about the shoulder joint (Tennis Warehouse University, 2011). Studies have shown that racket head speeds during professional serves can exceed 30–35 m/s (approximately 67–78 mph) just before ball contact, even though the arm itself moves much more slowly (Kellogg, 2019). Immediately before impact, the wrist undergoes pronation, snapping inward to add additional speed and control over the racket face (Chiangpradit, 2024).

This entire motion must be precisely timed. If any segment of the kinetic chain activates too early or too late, energy transfer becomes inefficient, resulting in reduced serve speed and accuracy (Tennis Warehouse University, 2011). This explains why professional serves often appear effortless: the power comes from efficient sequencing rather than muscular force alone. Using the full body also reduces injury risk by distributing forces across multiple joints instead of concentrating stress in the shoulder or elbow. A powerful serve is therefore the result of efficient mechanics and timing, not simply swinging as hard as possible (Kellogg, 2019).

3.6 Court Surface and Environmental Physics

Different tennis court surfaces affect ball motion because each surface has distinct physical properties, particularly friction and energy absorption. Grass courts have very low friction, causing the ball to skid forward and stay low after bouncing. Because the grass blades bend and slide under the ball rather than gripping it, the ball retains more horizontal speed, often bouncing at angles under 15°, which shortens reaction time and speeds up points (AMbelievable™ Team, 2024). Clay courts, in contrast, have high friction coefficients, allowing the ball to grip the surface, lose more horizontal velocity, and rebound at steeper angles. Topspin shots on clay can bounce over 50% higher than on grass, giving players more time to react and favoring longer rallies (Florida Tennis, 2025). Hard courts fall between grass and clay, offering a balance of speed and bounce that supports a wide range of playing styles (Chiangpradit, 2024).

Environmental conditions also play a significant role in ball behavior. Temperature affects air density: in warmer conditions, air density decreases, reducing drag and allowing the ball to travel faster, while colder air increases resistance and slows the ball (EE Times Europe, 2022). Humidity can increase the effective mass of the ball as moisture is absorbed into the felt, reducing rebound height and speed (AMbelievable™ Team, 2024). Altitude has a major effect as well; at elevations above approximately 1,500 meters, thinner air significantly reduces drag, causing the ball to travel farther and faster, which forces players to rely more on spin for control (Di Maria, 2021). Wind adds additional external forces that can change the ball's direction and speed during flight, making shot placement less predictable. Because of these factors, players continuously adjust their positioning, shot selection, and spin. Whether consciously or not, tennis players constantly apply physics principles to maintain control and consistency during a match (Florida Tennis, 2025).

4. Conclusion

This literature review demonstrates that tennis is governed by several core physics principles, including Newton's laws of motion, the Magnus effect, energy transfer, biomechanics, and material science. Together, these concepts explain how forces, motion, spin, and equipment design influence ball behavior and player performance. From an educational perspective, connecting physics concepts to a familiar sport provides a meaningful way to improve student engagement and conceptual understanding, especially for learners who struggle with abstract, textbook-based instruction. A limitation of this study is that it relies solely on secondary sources and does not include experimental data or classroom-based testing of learning outcomes. Despite this limitation, the review contributes by synthesizing diverse research into an accessible, education-focused framework, and future work could include experimental studies or curriculum development that measure how sport-based learning impacts physics comprehension.

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