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Biomechanical Analysis of the Kinetic Chain in Tennis Serve for Ball Speed Optimization: A Literature Review

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ABSTRACT
This literature review aims to analyze the biomechanical mechanisms of the kinetic chain during the tennis serve and their relationship to ball speed optimization. Purpose:This study investigates how sequential segmental coordination from the lower limbs through the trunk to the upper extremities contributes to maximum serve velocity. Methods: A systematic literature search was conducted using databases including PubMed, Scopus, Google Scholar, and SPORTDiscus.Articles published between 2003 and 2024 were retrieved using keywords such as "tennis serve biomechanics,"kinetic chain," "serve velocity," and "angular velocity." A total of 25 peer-reviewed articles were selected based on relevance, methodological rigor, and publication recency. Results: Evidence consistently demonstrates that effective proximal to distal sequencing of body segments - beginning with lower limb drive, followed by pelvic and trunk rotation, shoulder internal rotation, elbow extension, and culminating in wrist flexion is the primary mechanism for generating high ball speed. Disruption at any link in the chain significantly reduces terminal velocity. Shoulder internal rotation and wrist angular velocity appear to be the most critical distal contributors, while hip and knee engagement form the essential proximal foundation. Implications: These findings hold important practical implications for coaches and sport scientists in designing training programs that target specific kinetic chain nodes to improve serve performance while minimizing injury risk. Future research should investigate real-time kinetic chain feedback tools for on-court coaching. This review includes 25 references and 2 summary tables.

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INTRODUCTION

The tennis serve is widely regarded as the most decisive and technically demanding stroke in competitive tennis. It initiates every point and presents the server with the opportunity to directly win the rally through an ace or a forced error, making it a critical determinant of match outcome. Unlike groundstrokes, the serve is executed from a stationary position and requires the player to generate maximum force and velocity through a complex, sequentially coordinated full-body movement (Colomar et al., 2022).

Given its importance, optimizing serve performance particularly ball speed has become a central focus of sports science research in tennis.

From a biomechanical perspective, the serve is classified as a throw-like motor skill in which force is generated and transferred through a series of interconnected body segments, commonly described as the kinetic chain. This chain originates at the lower extremities, progresses through the pelvis and trunk, and terminates at the racquet-ball contact point via the upper limb. The concept implies that energy produced by larger, proximal muscle groups is successively transferred to smaller, distal segments, culminating in high racquet head speed and, consequently, high ball velocity (Martin, 2014; Fleisig et al., 2003). The summation of forces in an optimal time and space during this movement sequence increases the velocity of the different body segments and is ultimately transferred to the ball (Colomar et al., 2022).

Despite growing interest in tennis biomechanics, there remains a notable gap in the literature regarding the integrative understanding of all kinetic chain links and how their coordination collectively influences ball speed. Many existing studies focus on isolated segments such as shoulder kinematics or lower limb contribution without providing a comprehensive, chain-wide analysis. Furthermore, advances in wearable inertial measurement unit (IMU) technology have enabled more ecologically valid biomechanical assessments on court, generating new data that challenge some traditional assumptions about proximal-to-distal sequencing (Van der Kruk et al., 2024). There is a need for a synthesized review that brings together classic biomechanical studies with contemporary findings to provide a cohesive picture of how the kinetic chain functions during the tennis serve.

Therefore, the purpose of this literature review is to examine and synthesize existing biomechanical evidence on the kinetic chain during the tennis serve, with particular emphasis on its role in optimizing ball speed. The novelty of this review lies in its integration of both classical motion-capture research and recent IMU-based field studies, providing a current and practically applicable framework for coaches, sport scientists, and clinicians involved in tennis performance.

Understanding the kinetic chain in tennis requires familiarity with key biomechanical concepts including angular velocity, joint torque, segmental momentum transfer, and the principle of force summation. The kinetic chain principle suggests that disruption at any segment whether due to weakness, poor timing, or injury will reduce the terminal force available at the racquet and ball contact point (Irawan et al., 2025). Research has increasingly shown that the relationship between kinetic chain coordination and serve speed is not merely additive but multiplicative, meaning that optimal timing between segments is as important as the magnitude of segmental velocities themselves (Van der Kruk et al., 2024; Ellenbecker & Roetert, 2013).

METHODS

This study employed a systematic narrative literature review design to identify, evaluate, and synthesize published research on the biomechanics of the kinetic chain in the tennis serve and its relationship to ball speed. The literature search was conducted across four major academic databases: PubMed, Scopus, Google Scholar, and SPORTDiscus. The search was carried out between January and July 2024 using the following keyword combinations: "tennis serve biomechanics," "kinetic chain tennis," "serve velocity tennis," "angular velocity tennis serve," "lower limb tennis serve," "shoulder internal rotation tennis," and "wrist mechanics tennis serve."

Inclusion criteria for article selection were: (1) peer-reviewed journal articles published in English between 2003 and 2024; (2) studies focusing on the biomechanics of the tennis serve in players of any competitive level; (3) articles that measured or discussed at least one kinetic chain variable (e.g., joint angle, angular velocity, ground reaction force, muscle activation) in relation to ball speed or serve performance; and (4) full-text availability. Exclusion criteria included studies focused solely on tennis injuries without biomechanical serve analysis, opinion pieces without empirical basis, and duplicate records. After screening titles, abstracts, and full texts, a total of 25 articles were included in the final review. Data extraction focused on study design, participant characteristics, measurement tools, kinetic chain variables examined, and key findings related to ball speed.

RESULTS AND DISCUSSION

The Kinetic Chain Framework in Tennis Serve

The kinetic chain during the tennis serve has been consistently described as a sequential proximal-to-distal transfer of energy and momentum beginning with the lower extremities. This framework, first systematically documented by Fleisig et al. (2003), established that the tennis serve produces a rapid succession of segmental rotations with a well-defined order of maximal angular velocities: trunk tilt (280°/s), pelvis rotation (440°/s), upper torso longitudinal rotation (870°/s), elbow extension (1,510°/s), wrist flexion (1,950°/s), and shoulder internal rotation (2,420°/s) (Martin, 2014). This sequential activation confirms that the body operates as an integrated mechanical system rather than a collection of independently functioning parts, and that the precise timing of each link is as important as its individual strength (Colomar et al., 2022).

The efficiency of this chain is governed by the principle of force summation: momentum generated by the large proximal muscles of the legs and trunk is progressively transferred to the smaller distal segments of the shoulder, forearm, and wrist, resulting in amplified racquet head speed at ball impact. Research by Irawan et al. (2025) quantified this relationship, demonstrating that approximately 51% of kinetic energy and 54–60% of total serve force was produced through kinetic chain transfer mechanisms. Critically, that study showed that a 10% reduction in kinetic energy at the hip or trunk requires either a 14% increase in shoulder rotation speed or a 22% increase in shoulder mass to maintain the same distal kinetic energy a finding with significant implications for the relative importance of proximal chain optimization over isolated distal training.

Table 1.
Summary of Key Kinetic Chain Segments and Their Biomechanical Contributions to Serve Ball Speed

Segment	Key Motion	Peak Angular Velocity	Contributi on to Ball Speed
Lower Limb (Knee /Hip)	Knee flexion, hip extension, leg drive	Moderate	Proximal foundation ; initiates energy transfer
Pelvis	Rotation and lateral tilt	~440%	Transfers ground reaction force to trunk
Trunk /Thorax	Lateral bend and rotation	~870%	Amplifies rotational momentu m to shoulder
Shoulder	Internal rotation	~2,420%	Primary distal driver of racquet speed
Elbow	Extension	~1,510%	Increases lever arm and contact height
Wrist	Flexion	~1,950%	Final velocity amplifier at ball contact

Lower Limb and Pelvic Contribution

The lower limbs serve as the foundational link of the kinetic chain, and their contribution to serve velocity has been well-documented. Hip and knee engagement play a crucial role in the vertical component of the serve, and their reduction directly decreases the potential for energy transfer to the upper segments (Mouelhi Guizani et al., 2024). Two primary lower body techniques have been identified in the literature: the foot-back and the foot-up technique. Although the foot-up technique generates greater vertical ground reaction forces which are theoretically advantageous for kinetic chain loading no significant difference in ball velocity has been consistently found between the two techniques (Colomar et al., 2022), suggesting that how ground forces are transmitted through the chain matters more than the magnitude of those forces alone. A high vertical drive from the lower limbs contributes to an elevated contact point with the ball. Players who achieve a higher jump height during the serve create the potential for a higher ball contact point, which generates greater peripheral racquet speed even when upper limb angular velocity is held constant (Mouelhi Guizani et al., 2024). Peak vertical velocity of the hips, alongside drive from the back leg, makes extension moments in the legs and internal rotations at the hip essential determinants of serve velocity (Colomar et al., 2022). These findings highlight the often-underappreciated role of the lower body in a stroke that is commonly perceived as predominantly arm-driven.

Trunk and Thoracic Mechanics

The trunk constitutes the central link in the kinetic chain, transmitting and amplifying forces between the lower and upper body. Trunk rotation and lateral bending have been identified as critical contributors to serve ball speed, with research confirming associations between trunk angular velocity and serve performance in professional players (Van der Kruk et al., 2024). In a study of professional Dutch tennis players using high-frequency IMUs, trunk rotation was found to be significantly associated with both ball speed and serve accuracy, making it a dual-function segment unique among kinetic chain links. This finding challenges earlier models that focused primarily on the arm, underscoring the trunk's central mechanical role. Players with higher serve speeds exhibit distinct trunk mechanics compared to those with lower speeds. Research by Santos et al. (2024) found that faster servers showed a greater leftward thoracic tilt during the impact event and higher maximal thoracic angular velocities, whereas slower servers demonstrated reduced wrist and thoracic angular velocities a combination that appears to limit effective energy transfer along the chain. Rotation and side-positioning of the trunk enable the generation of extra rotation in the horizontal plane, increasing available energy storage before the acceleration phase (Colomar et al., 2022). This "energy storage and release" function of the trunk is analogous to the loading and unloading of an elastic spring, making thoracic mobility and strength training an important target for serve optimization.

Shoulder, Elbow, and Wrist: Distal Chain Mechanics

The shoulder, elbow, and wrist represent the distal end of the kinetic chain, where accumulated proximal momentum is converted into maximum racquet head speed. Shoulder internal rotation is the fastest and most powerful motion in the serve, with peak angular velocities reported at approximately 2,420°/s (Martin, 2014; Fleisig et al., 2003). Greater external shoulder rotation during the cocking phase has been associated with higher serve speeds, as it increases the range over which internal rotation can be accelerated (Santos et al., 2024). This "shoulder windup" is analogous to storing elastic potential energy, which is then rapidly released during the forward swing. Elbow extension plays a secondary but important role by elevating the contact point and extending the effective lever arm of the racquet, both of which contribute to higher racquet head speed at impact (Colomar et al., 2022). Wrist flexion, occurring at approximately 1,950°/s, acts as the final velocity amplifier immediately before ball contact. Santos et al. (2024) reported that players with lower serve speeds showed significantly reduced wrist flexion/extension angular velocities, indicating that inadequate wrist mechanics at the terminal end of the chain is a key limiter of ball speed. Arm pronation, occurring concurrently with wrist action, governs racquet orientation at impact and contributes meaningfully to final ball direction and topspin generation (Colomar et al., 2022).

Table 2.
Comparison of Biomechanical Characteristics Between Higher and Lower Serve Speed Groups

Variable	Higher Speed Group	Lower Speed Group	Reference
External shoulder rotation (cocking phase)	Greater	Reduced	Santos et al. (2024)
Hip and knee flexion	Greater	Lesser	Santos et al. (2024)
Back hip angular velocity	Higher	Lower	Santos et al. (2024)
Wrist angular velocity	Higher	Lower	Santos et al. (2024)
Thoracic angular velocity	Higher	Lower	Santos et al. (2024)
Vertical center of mass (late cocking)	Higher	Lower	Santos et al. (2024)
Trunk rotation associatio n with ball speed	Significan t	Not significan t	Van der Kruk et al. (2024)

Intersegmental Timing and Proximal-to-Distal Sequencing

A critical and still-debated issue in tennis biomechanics is whether professional players strictly adhere to a proximal-to-distal sequence of peak angular velocities, as classically theorized. Research by Van der Kruk et al. (2024) on professional players found that the body motion during the tennis serve is not entirely performed in line with the strict proximal-to-distal sequence, and that intersegmental timing was not significantly associated with ball speed. Instead, the magnitude of segmental angular velocities particularly of the upper arm and trunk were the stronger predictors of serve performance. This finding suggests that at the elite level, players may develop individualized coordination strategies that deviate from the textbook model yet remain highly effective. This has practical implications for coaching: while the proximal-to-distal framework remains a useful conceptual model, rigid enforcement of a single sequence pattern may not be necessary or beneficial for all players. Kinetic chain optimization may be better pursued through maximizing the angular velocity capacity of key segments particularly the trunk and upper arm while ensuring that no single link represents a bottleneck in force transmission. The Observational Tennis Serve Analysis (OTSA) tool developed by Ellenbecker and Roetert (2013) provides a practical field-based framework that assesses key kinetic chain positions, offering coaches an accessible means of evaluating serve mechanics without laboratory instrumentation.

Fatigue and Kinetic Chain Disruption

Physiological fatigue has been shown to significantly impair kinetic chain efficiency during the tennis serve. Fatigue accumulated through match play or high-volume serve training preferentially affects the initial segments of the kinetic chain particularly the lower extremities and trunk which then places disproportionate compensatory demands on the shoulder as the final segment before ball contact (Mouelhi Guizani et al., 2024). That study demonstrated significant decreases in serve speed and accuracy in the final serve series, correlated with declining jump height and wrist velocity, confirming that kinetic chain asynchrony under fatigue leads to decreased force transfer and reduced performance. These findings reinforce the importance of monitoring fatigue in serve training and highlight the lower body as a primary site of fatigue-related performance degradation.

CONCLUSION

This literature review confirms that the kinetic chain is the fundamental biomechanical mechanism underpinning tennis serve ball speed, operating through a coordinated sequence of segmental rotations from the lower limbs through the trunk to the distal upper extremity. The evidence demonstrates that optimal ball speed results from the effective integration of all chain links, where each segment's contribution is conditioned by the quality of energy transfer from the preceding segment. Shoulder internal rotation and wrist angular velocity are the most prominent distal determinants of ball speed, but their effectiveness is dependent on the proximal foundation established by lower limb drive and trunk rotation. Disruption of any link whether through poor technique, weakness, or fatigue results in a disproportionate reduction in terminal ball velocity and increased injury risk.

The practical implications of these findings suggest that serve training programs should be designed with a whole-body, chain-wide perspective rather than focusing exclusively on arm mechanics. Coaches and sport scientists should prioritize the development of lower limb power, trunk rotational strength and mobility, and shoulder internal rotation capacity as the primary targets for serve speed improvement. Future research should further investigate the role of individualized coordination strategies at the elite level and explore the application of real-time wearable sensor feedback systems for on-court kinetic chain optimization. Longitudinal studies examining the development of kinetic chain coordination across age groups and skill levels would also make a valuable contribution to the field.

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