RESEARCH ARTICLE

Biomechanical analysis of tennis serve and performance enhancement strategies

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Tennis serve represents a fundamental technical component in competitive play, heavily influenced by both kinematic and kinetic factors. This study conducted a comparative analysis of five professional players and five amateur players, systematically measuring initial serve velocity, racket angular velocity, ground reaction force, terminal racket speed, and serve placement deviation to identify the critical biomechanical determinants of serve quality. The results showed that professional players demonstrated superior energy transfer, more efficient angular momentum conversion, and greater impact stability compared to their amateur counterparts. Based on empirical data, four key optimization strategies were proposed as enhancing lower-limb push-off mechanics to increase ground reaction force, thereby improving kinetic chain efficiency; optimizing trunk rotation to maximize angular momentum transfer, leading to greater racket acceleration; strengthening the wrist snap effect to amplify terminal racket velocity, crucial for generating a powerful serve; refining serve placement precision to improve stability, ensuring greater consistency in competitive scenarios. Furthermore, the integration of artificial intelligence (AI) and machine learning for intelligent biomechanical analysis presented an innovative approach to personalized serve optimization. By providing quantitative, data-driven insights, this study contributed to the advancement of scientifically structured training methodologies, fostering enhanced performance in tennis serve execution.

Keywords: tennis serve; biomechanical analysis; kinematics; kinetics.

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Introduction

Tennis serve is a fundamental scoring mechanism that dictates match dynamics and significantly influences the probability of victory. A high-quality serve enhances a player's tactical advantage, yet its execution involves an intricate interplay of biomechanical components ranging from lower limb propulsion and trunk rotation to upper limb racket acceleration and wrist snap mechanics. Optimizing these elements to augment serve velocity and precision remains a focal point of research [1].

Recent advancements in biomechanical analysis have deepened the understanding of the intricate movements involved in a tennis serve. Techniques such as kinematic and kinetic analyses have become instrumental in identifying the key contributors to serve quality [2-4].

Previous studies revealed that serve velocity was influenced by lower limb strength, trunk rotation, and wrist snap mechanics with a complex transfer of energy across the kinetic chain from the legs to the racket. As such, optimizing these elements through targeted training strategies can significantly enhance serve performance [5, 6]. Despite these advancements, the current research faces a significant gap in directly quantifying and comparing the biomechanical disparities between professional and amateur players. There is also limited research focusing on the integration of biomechanical data into practical training methodologies for performance enhancement [7, 8]. By analyzing the factors such as serve velocity, accuracy, and energy transfer efficiency, the scientifically backed strategies for improving serve performance can be proposed [9]. Further, the integration of biomechanical modeling, kinematic analysis, and experimental simulations using artificial intelligence (AI) and machine learning for intelligent biomechanical analysis can provide athletes and coaches with scientifically substantiated training strategies, which is a novel paradigm for performance enhancement in tennis and can ultimately apply to the broader field of sports science [10].

This study aimed to systematically quantify key biomechanical indicators during the serve motion of both professional and amateur players to investigate the biomechanical factors that contributed to the differences in serve performance, elucidate these technical disparities, and propose targeted optimization strategies. The study combined biomechanical modeling, kinematic analysis, and experimental simulations approaches to enable a detailed investigation of the key biomechanical variables involved in the tennis serve motion such as racket speed, ground reaction forces, and joint angular velocities. This research bridged the gap between biomechanical theory and practical application in sports training and laid the groundwork for future applications of artificial intelligence and machine learning in serve optimization.

Materials and methods

Research subjects

A total of 10 tennis players comprising 5 professional players and 5 amateur players, aged between 18 and 35 years old, were recruited in this study. All procedures of this research were approved by an Institutional Review Board of College of Humanities, Hebei Oriental University, Langfang, Hebei, China.

Experimental data acquisition

Each participant performed a series of serve trials under varied conditions including differences in lower limb push-off angles, racket swing speeds, and wrist snap mechanics with all motion data being recorded. Specifically, kinematic data was captured using the Vicon Vero v2.2 motion capture system (Vicon Motion Systems Ltd., Oxford, Oxfordshire, United Kingdom) to accurately track joint trajectories, particularly at the shoulder, elbow, and wrist, to enable the calculation of angular velocities and accelerations. Ground reaction force (GRF) during the lower limb push-off phase was measured using a Kistler 9287CA force platform (Kistler Instrumente AG, Winterthur, Zurich, Switzerland) to quantify lower limb force contribution. The moment of impact was recorded using the Photron FASTCAM Mini UX100 high-speed camera system (Photron Limited, Tokyo, Japan) with 1,000 frames per second to provide critical data on ball velocity and terminal racket speed. Additionally, two advanced biomechanical modeling platforms were employed to simulate and analyze the serve motion, which included OpenSim, version 4.3, developed by the National Center for Simulation in Rehabilitation Research, Stanford University (Stanford, CA, USA) to enable the construction of virtual human models and dynamic motion analysis and AnyBody Modeling System, version 7.4, (AnyBody Technology A/S, Aalborg, North Denmark Region, Denmark) to simulate kinematic responses and mechanical output under various serve techniques. These software tools allowed for the integration of empirical data with virtual simulations to assess and optimize biomechanical strategies.

Biomechanical model construction
The collected data was used to construct a comprehensive biomechanical model, facilitating the investigation of the most influential factors for serve optimization. To support theoretical interpretation, three classical biomechanical models were utilized in this study including the double-pendulum model, the angular momentum conservation model, and the impulse-momentum model. These models served to simulate dynamic interactions between the arm and racket, examine angular momentum transfer across the shoulder, elbow, and wrist joints, and evaluate the effect of force application duration on serve velocity.

Statistical analysis
SPSS software (IBM, Armonk, New York, USA) was employed for comparing serve velocity, racket speed, ground reaction force, and serve accuracy between professional and amateur groups by using independent samples t-tests. *P* value less than 0.05 was defined as statistically significant difference.

Results

Kinematic data analysis
In the biomechanics of tennis serving, swing velocity serves as a primary determinant of initial ball speed, directly influencing serve power and effectiveness. To quantitatively assess this parameter, the angular velocity of the racket swing in both professional and amateur players were measured. The results demonstrated that professional players exhibited significantly higher maximum of 980 ± 40 rad/s with an average of 950 ± 50 rad/s swing angular velocities than amateur players' 820 ± 35 rad/s and 800 ± 45 rad/s, respectively ($P < 0.05$), which suggested that professionals achieved greater joint rotational amplitudes within shorter timeframes, resulting in superior racket acceleration (Figure 1). Additionally, professional players displayed noticeably higher shoulder and elbow angular velocities, which underscored their enhanced ability to harness angular momentum transfer throughout the kinetic chain, thereby increasing terminal racket speed. The elevated wrist angular velocity among professionals further amplified the whip-like effect, leading to a more forceful impact and a higher initial ball velocity (Table 1).

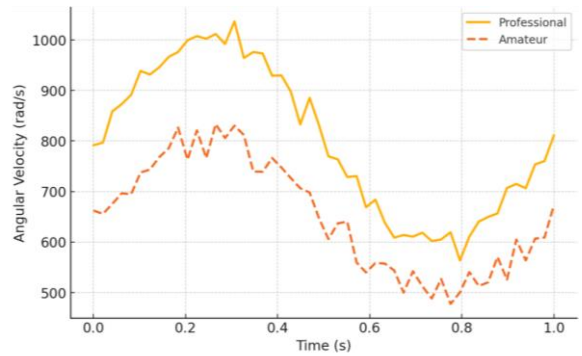

Figure 1. Comparison of swing angular velocity between professional and amateur players.

Shoulder rotation plays a pivotal role in the kinetic chain of energy transfer during the tennis serve, serving as a critical mechanism for maximizing angular momentum and optimizing racket acceleration. By examining the correlation between shoulder rotation amplitude and initial serve velocity across different player groups, the results demonstrated that professional players showed a significantly greater shoulder rotation angle of 110 ± 5° than that of amateur players' 85 ± 7°, which was associated with higher initial serve velocity of 45.2 ± 3.1 m/s *vs*. 35.8 ± 2.5 m/s ($P < 0.05$) (Table 2). Professional players exhibited a significantly greater shoulder rotation angle (110°) than that of amateur players (85°), reinforcing the notion that a larger trunk rotation enhanced energy transmission efficiency. This optimized energy transfer directly translated into higher racket velocity and increased serve speed. By accumulating a greater amount of angular momentum through trunk rotation, professional players generated more powerful and explosive serves, whereas the limited shoulder rotation of amateur players inhibited energy transfer,

Table 1. Comparison of swing speed between professional and amateur players.

Group	Max swing angular velocity (rad/s)	Average swing angular velocity (rad/s)	Shoulder angular velocity (rad/s)	Elbow angular velocity (rad/s)	Wrist angular velocity (rad/s)
Professional	980 ± 40	950 ± 50	320 ± 30	460 ± 40	170 ± 20
Amateur	820 ± 35	800 ± 45	270 ± 25	390 ± 35	140 ± 18
P value	< 0.001	< 0.001	0.003	0.005	0.008

leading to suboptimal serve performance.

Table 2. Impact of shoulder rotation angle on initial serve velocity.

Group	Shoulder rotation angle (°)	Initial serve velocity (m/s)
Professional	110 ± 5	45.2 ± 3.1
Amateur	85 ± 7	35.8 ± 2.5
P value	0.001	< 0.001

Kinetic data analysis

Ground reaction force (GRF) serves as a critical determinant of tennis serve velocity, playing a fundamental role in facilitating kinetic chain energy transfer. A greater GRF enables athletes to efficiently channel push-off forces from the lower limbs through the trunk and into the upper extremities, thereby enhancing racket acceleration and impact power. The analysis of kinetic parameters revealed that professional players exhibited significantly greater ground reaction force (GRF) generation during the serve motion than that of amateur players. Specifically, professionals produced a maximum GRF of 2,200 ± 200 N, while amateurs generated only 1,800 ± 150 N (P = 0.002). In addition, the force application time, defined as the duration over which the lower limbs exerted during the push-off phase, was also longer among professionals with the average of 180 ± 15 milliseconds than that of amateurs (140 ± 12 milliseconds) (P = 0.003). These findings suggested that professional athletes were more adept at harnessing lower limb propulsion, thereby initiating a more efficient transfer of kinetic energy through the body's kinetic chain from the ground through the trunk and into the upper extremities. The longer force application period not only allowed for greater momentum accumulation but also contributed to a more powerful and explosive serve (Figure 2). The results showed that professionals achieved a significantly higher initial serve velocity of 45.2 ± 3.1 m/s than that of 35.8 ± 2.5 m/s in amateurs (P < 0.001). In contrast, the lower GRF and shorter force application time observed in amateurs reflected less effective lower body engagement, limiting their ability to generate high serve velocities and reducing overall serve efficiency.

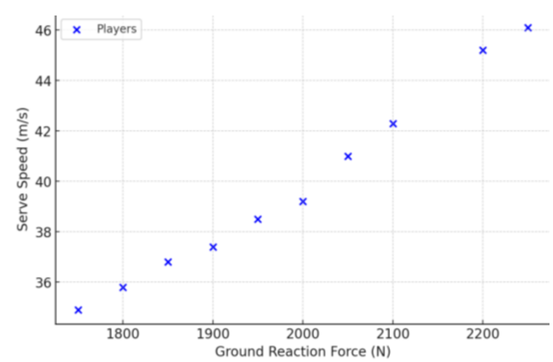

Figure 2. Relationship between ground reaction force (GRF) and serve speed.

The wrist snap effect represents a critical biomechanical mechanism in optimizing terminal racket velocity and impact force, playing a pivotal role in amplifying serve efficiency. A more pronounced wrist snap generates greater angular acceleration, thereby enhancing energy transmission from the upper limb to the racket at the moment of impact. The correlations between wrist kinematics and initial serve velocity showed that professional players attained greater wrist angular velocity, which, in turn, accelerated terminal racket speed, culminating in higher ball impact velocity (Figure 3). The superior wrist snap mechanics among professionals contributed to greater racket acceleration at impact, thereby enhancing serve velocity and power output. Conversely, the lower wrist angular velocity observed in amateur players led to suboptimal racket acceleration, restricting serve speed. These insights emphasized the necessity of targeted wrist strength training and refined swing mechanics to optimize serve quality and efficiency.

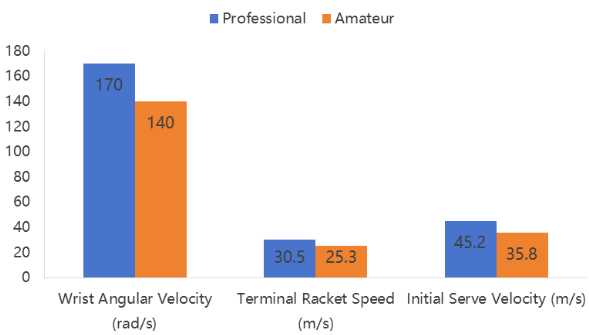

Figure 3. Comparison of key swing kinetics between professional and amateur players.

Serve placement stability analysis

Serve stability is a crucial determinant of scoring efficiency in competitive tennis with smaller placement deviations indicating greater consistency and precision. A highly stable serve enhances strategic control, minimizing unforced errors, and increasing the probability of executing tactically effective shot sequences. The results demonstrated a significant difference in serve placement stability between professional and amateur players. Professional players exhibited a mean serve placement deviation of 12.5 cm with a standard deviation of 3.2 cm, indicating a relatively high level of consistency and precision. In contrast, amateur players demonstrated a mean serve placement deviation of 18.7 cm with a standard deviation of 4.8 cm, reflecting greater variability and less precision in their serves (Figure 4). The results emphasized the professional players' superior ability to consistently place their serves within the target zone. Their enhanced ability to control racket-ball contact angles resulted in a more uniform and predictable ball trajectory, thereby optimizing serve accuracy, highlighting the biomechanical and neuromuscular factors that contributed to improved serve precision. In contrast, the greater serve placement variability among amateur players indicated technical inconsistencies, which contributed to randomized and less reliable serve execution. The findings underscored the need for systematic technical refinements, particularly in wrist flexibility, kinetic chain coordination, and lower limb force application, to elevate amateur players' serve performance toward elite standards.

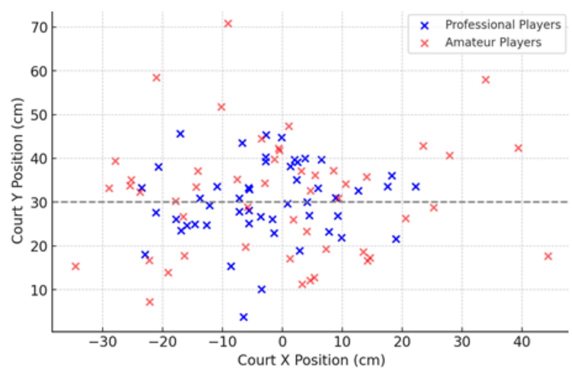

Figure 4. Distribution of serve landing points for professional and amateur players.

To further quantify and evaluate serve consistency across different player groups, this study implemented a controlled repetition-based assessment, requiring each participant to execute 20 consecutive serve trials. The distribution patterns of serve placement were meticulously recorded, and the standard deviation of serve placement deviation was computed as a measure of consistency and precision. The results underscored a notable disparity in serve stability between professional and amateur players. Professional athletes exhibited a significantly lower standard deviation in serve placement of 3.2 cm vs. 4.8 cm in amateurs, indicating a higher degree of consistency in ball trajectory and placement

Table 3. Serve placement stability assessment.

Group	Mean placement deviation (cm)	Standard deviation (cm)	Target zone accuracy (%)
Professional	12.5 ± 1.8	3.2	88.5 ± 4.2
Amateur	18.7 ± 2.1	4.8	72.3 ± 5.1
P value	0.001	0.004	0.002

precision. Moreover, the target zone accuracy for professionals reached 88.5%, substantially outperforming the 72.3% observed in amateur players (Table 3). This discrepancy further corroborated the assertion that elite players demonstrated superior technical execution and neuromuscular coordination, facilitating greater control over serve placement. Enhancing serve accuracy and consistency necessitated a multi-faceted training approach, incorporating visual-motor coordination drills, targeted serve exercises, and repetitive movement training. Specifically, fixed target serve drills, wherein players practiced serving into predefined target zones on the court, could significantly improve precision, spatial awareness, and overall serve stability. Such structured training methodologies offered quantifiable performance benefits, ensuring greater tactical effectiveness in competitive play.

Discussion

Strategies for enhancing tennis serve performance

Empirical findings indicated that professional players generated a significantly higher ground reaction force (GRF) than that of amateurs, underscoring their superior ability to harness lower limb propulsion during the serve. Additionally, force application duration differed markedly between two groups, demonstrating that elite athletes optimized knee flexion angles to prolong the push-off phase, thereby enhancing energy transfer efficiency. Given that lower limb force generation critically influences serve velocity, refining push-off mechanics emerge as a fundamental strategy for serve optimization. To amplify GRF output, strength training regimens should incorporate squat exercises and weighted plyometric jumps, fortifying explosive lower limb power. Additionally, fine-tuning knee flexion angles optimize energy transfer from the lower to the upper body. A recommended approach includes variable resistance training, in which push-off drills are performed under different loads to increase adaptability to dynamic ground reaction forces. Furthermore, integrating dynamic jump training enhances rapid force application capabilities, culminating in improved serve velocity and stability in match scenarios [11].

Enhancing trunk rotation and shoulder-hip coordination

Professional players exhibited a significantly greater shoulder rotation angle than that of amateurs, indicating a biomechanical advantage that was translated into enhanced racket acceleration. Additionally, swing angular velocity among professionals was notably surpassing the amateurs, which illustrated the critical role of trunk rotation efficiency in maximizing angular momentum transfer to directly elevate terminal racket speed and serve velocity. To cultivate trunk rotational power, athletes should integrate core stability training methods such as medicine ball throws, anti-rotation drills, and Russian twists, which bolster core strength and refine kinetic chain energy transfer. Dynamic flexibility drills targeting the shoulders and hips further optimize motion synchronization, thereby improving kinematic coordination [5]. Incorporating resistance band training simulating serve-specific trunk rotations strengthens neuromuscular control, promoting a more efficient angular momentum transfer mechanism, which is vital for increasing initial serve velocity.

Refining arm swing mechanics and optimizing wrist snap effect

Data comparisons highlighted a wrist angular velocity, illustrating elite players' superior utilization of wrist snap mechanics to enhance terminal racket speed. Furthermore, professional players achieved a higher terminal racket velocity than amateurs, reinforcing the paramount importance of wrist kinematics in determining serve efficiency. A higher wrist angular velocity accelerates racket speed, resulting in more forceful ball impact. To refine wrist snap efficiency, specialized training should incorporate forearm rotation drills, wrist flexion-extension exercises, and grip-strength conditioning, all of which improve wrist flexibility and explosive power. A key recommendation is weighted racket training, designed to enhance muscular endurance and strength, ultimately improving swing mechanics and impact efficiency [12]. Additionally, high-speed video feedback analysis allows players to assess and optimize individual wrist movement trajectories, fostering precision in racket acceleration. Furthermore, low-resistance elastic band exercises simulating wrist activation during ball impact could enhance rapid response capabilities, further refining serve execution [13].

Precision training to minimize serve placement deviation

Quantitative assessments revealed that professional players demonstrated significantly lower serve placement deviation than that of amateurs. Professionals also maintained a tighter standard deviation than amateurs, indicating superior serve consistency and spatial control. Precision in serve placement is pivotal in tactical execution as minimizing positional deviation directly enhances scoring potential. To elevate serve accuracy, structured target-based serving drills should be implemented with progressive difficulty adjustments in target placement to systematically enhance hitting precision. Visual feedback training by utilizing high-precision motion capture systems enables real-time adjustments in impact angles and force modulation, further refining serve consistency. Stability-enhancing protocols such as single-leg stance swing exercises could fortify postural control, mitigating serve execution variability [14, 15]. Integrating biomechanical analysis tools facilitate dynamic serve adjustments, leading to enhanced spatial accuracy and reduced variability, ultimately improving strategic effectiveness in competitive scenarios.

Training optimization strategies integrating AI and sensor technologies

The rapid advancement of modern technology has revolutionized athletic training methodologies with artificial intelligence (AI), wearable sensors and virtual reality (VR) emerging as transformative tools in tennis performance enhancement. These cutting-edge technologies not only facilitate real-time biomechanical assessment but also enable precision-driven feedback, fostering a data-driven, individualized training paradigm. AI-powered sports analytics systems have the capability to continuously monitor an athlete’s serve mechanics, offering instantaneous performance insights. By leveraging machine learning algorithms, these systems can analyze motion trajectories, ball speed, and serve placement accuracy, assisting players in refining swing tempo and maximizing serve efficiency. Furthermore, AI-driven video analysis allows for slow-motion replay and high-resolution motion capture, pinpointing subtle technical inefficiencies and generating strategic recommendations for biomechanical optimization. Wearable biomechanical sensors, including accelerometers, gyroscopes, and electromyographic (EMG) sensors, can provide real-time tracking of joint angular velocity, force output, and energy transmission dynamics. Such data offers quantifiable insights into an athlete’s technical execution, facilitating the development of personalized training regimens. Certain smart rackets are now capable of recording racket speed, spin angles, and impact force, enabling players to fine-tune stroke mechanics for optimal power and precision. Additionally, virtual reality /augmented reality (VR/AR) interactive training systems are progressively reshaping tennis training environments. VR-based simulation platforms can replicate competitive match conditions, allowing athletes to hone their serving skills within a dynamic, controlled virtual setting, thereby enhancing situational adaptability. Meanwhile, AR technology, deployed through smart glasses or projection-based systems, delivers real-time biomechanical feedback, enabling players to immediately adjust stroke mechanics and improve both stability and accuracy of serve [16]. The integration of AI, sensor-driven analytics, and immersive training technologies is poised to propel tennis training into an era of intelligent performance enhancement, significantly elevating training efficiency while providing athletes with unprecedented access to precise, data-driven insights.

Conclusion

This study employed biomechanical analysis to optimize tennis serve mechanics, systematically validating its effectiveness. Empirical findings revealed that professional players exhibited superior energy transfer, higher racket angular velocity, more pronounced wrist snap effects, and greater serve accuracy compared to their amateur counterparts, resulting in overall enhanced serve performance. The kinetic chain efficiency in professional athletes was markedly higher as evidenced by their stronger ground reaction force application, more extensive trunk rotation, and refined wrist snap mechanics, which collectively contributed to greater serve precision and stability. Based on experimental data, this research proposed four key optimization strategies to enhance serve biomechanics and efficiency, which were enhancing lower limb push-off force to improve energy transmission through the kinetic chain, optimizing trunk rotation mechanics to increase swing efficiency and angular momentum transfer, strengthening the wrist snap effect to amplify terminal racket velocity and impact force, and refining serve placement control to elevate stability and consistency in competitive play. Furthermore, integrating AI-driven motion analysis and machine learning algorithms offered the potential for personalized, intelligent training regimens, enabling continuous refinement of individualized serve mechanics. This study provided a quantitative foundation for data-driven tennis training methodologies, paving the way for the integration of smart sensors and real-time biomechanical monitoring systems to further advance intelligent tennis training frameworks.

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