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Original Article

Biomechanical training and performance analysis for optimizing the serve in elite tennis: A field-based study

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Abstract:
Introduction: The tennis serve is a crucial determinant of success at the professional level, yet optimizing its biomechanical and performance-related factors remains challenging. **Problem Statement:** In competitive tennis, serving performance plays a decisive role in match dynamics and is a key focus in training and athlete development programs. **Approach:** This study examines the effectiveness of a personalized, data-driven intervention designed to improve serve performance in high-level tennis players. **Materials and Methods:** A cohort of 10 tennis players (6 males, 4 females; ages 17–22) completed a six-week individualized serve-training program. **Results:** Baseline biomechanical data were collected using Hawk-Eye tracking, inertial measurement units (IMUs), and high-speed video analysis. Performance metrics included serve speed, first-serve percentage, racket-head velocity, and shoulder external rotation. Post-intervention results were evaluated using paired t-tests and correlation analyses. Results indicated a significant increase in serve speed across all participants (mean +4.2 km/h), accompanied by improvements in racket-head velocity (+2.4 m/s) and shoulder external rotation (+7.7°). First-serve accuracy also increased by an average of 4.1% ($p = 0.0012$). Racket-head speed showed a strong correlation with both serve power ($r = 0.88$) and accuracy ($r = 0.64$). **Discussion:** All participating athletes exhibited a statistically significant increase in serve speed following the six-week individualized biomechanical intervention. The cohort demonstrated an average gain of +4.2 km/h (increasing from 176.5 to 180.7 km/h; $p < 0.0001$), underscoring the effectiveness of targeted, data-driven adjustments to serve mechanics. This improvement is especially noteworthy given the high-performance status of the athletes, who typically show limited potential for further gains owing to already optimized baseline levels. **Conclusions:** The study demonstrates that individualized biomechanical interventions, informed by objective sensor-based data, can significantly improve serve performance in professional tennis players. The combined use of wearable technology, kinematic analysis, and personalized training plans provides a replicable framework for high-performance coaching environments, effectively bridging the gap between sports science and applied coaching practice in modern tennis.
Keywords: tennis serve, biomechanics, performance analysis, wearable sensors, individualized training

Introduction

The serve holds a uniquely decisive role in professional tennis, frequently acting as a primary determinant of match outcomes—particularly at the elite level, where even marginal gains in efficiency can confer a substantial competitive advantage. Although numerous methodological approaches exist for analyzing the tennis serve, few studies combine biomechanical assessment with practical performance metrics such as serve speed and accuracy, and even fewer incorporate structured training interventions (Lambrich & Muehlbauer, 2023). Unlike groundstrokes or volleys—which are reactive and depend on the opponent's positioning, shot selection, and rally dynamics—the serve is the only stroke executed in complete isolation. Fatigue is a factor that changes biomechanical parameters and degrades performance, underscoring the importance of endurance training and technical adaptations that reflect real match demands (Bilić et al., 2025). The serve offers the player complete control over timing, technique, placement, and power, making it an essential component of strategic dominance. A fast, accurately placed serve can produce immediate advantages—such as unreturnable shots or forced errors—while shaping the tactical flow of subsequent points. Additionally, by reducing rally length, the serve plays a crucial role in managing physical exertion during long matches and dense tournament schedules, where energy conservation and injury prevention are essential.

Problem Statement In the men's game, more than 60% of points begin with a first serve, and statistical analyses across ATP competitions consistently show that serve-related variables—such as first-serve percentage, ace count, and points won on serve—are strongly correlated with match success across all court surfaces

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(Whiteside & Reid, 2017; Gollub, 2021; Brito et al., 2024). Even among players with contrasting playing styles, serve effectiveness remains a reliable predictor of competitive outcomes. Although the serve carries slightly less statistical weight in the women's game, its strategic importance is still substantial. On the WTA Tour, where return games tend to be more competitive, a dependable first serve helps players initiate rallies on favorable terms, limit opponent dictation, and create opportunities to control court positioning (Brito et al., 2024). In both contexts, serve performance plays a decisive role in match dynamics and remains a priority in training and athlete development programs. Recognizing this significance, the tennis research community has increasingly concentrated on uncovering the biomechanical foundations of the serve. A robust body of work has examined the contribution of various kinematic and kinetic factors to serve velocity, spin, accuracy, and consistency (Elliott et al., 2009; Hernández-Davo et al., 2014; Burns et al., 2020; Carboch & Hrychová, 2022). These studies have highlighted the central importance of multi-joint coordination and force transmission through the kinetic chain, beginning with the legs and progressing through the hips, trunk, and shoulder complex, before culminating in the acceleration of the racket and impact with the ball. Variables such as knee flexion depth, hip and trunk rotation velocities, shoulder external rotation angles, and racket head speed at impact have been identified as critical determinants of serve efficacy. Gorce and Jacquier Bret (2024) analyze how different biomechanical and kinetic parameters of the body influence the speed of the ball in tennis serves. The study uses optoelectronic systems and force platforms to measure body segment movements, highlighting the importance of full kinetic chain coordination—legs, torso, and arm—for generating a fast and efficient serve.

Yang et al. (2017) present TennisMaster, an IMU-based system that evaluates tennis serve performance online, providing immediate feedback on the phases of the serve. The system is mobile and can be used on the court, although it does not provide detailed measurements for all body segments. Additionally, timing variables, such as the synchronization between leg drive and upper limb motion, and technical elements like ball toss consistency have been shown to differentiate elite performers from sub-elite counterparts. Connolly, Middleton, and Reid (2019) analyze the biomechanical differences in serving between elite male and female adolescents, highlighting variations in racket speed and joint angles. The study emphasizes the importance of adapting technical training and optimizing serving according to gender and physical development. Wanglertpanich (2025) shows that vertical and shear force impulses generated on the ground during the serve contribute significantly to racket speed, highlighting the importance of the entire kinetic chain in optimizing serve performance. Berhimpong (2023) shows that the type of training drill and grip strength significantly influence tennis serve performance, suggesting that exercises should be adapted according to the player's physical profile. Mourtzios et al. (2021) highlight significant differences in serve biomechanics between professional and young players, emphasizing the importance of developing body segment coordination and technique for serve performance.

In recent years, the adoption of cutting-edge biomechanical technologies has greatly enhanced our ability to investigate these variables with high precision. The implementation of 3D motion capture systems, force plates, wearable inertial measurement units (IMUs), and high-speed video analysis tools has enabled researchers and coaches to generate detailed joint kinematics and kinetic profiles in both laboratory and on-court environments (Brocherie & Dinu, 2022; Vacek et al., 2023). These systems allow for the assessment of angular velocities, joint torque patterns, segmental timing, and ground reaction forces, contributing to a more comprehensive understanding of the mechanical underpinnings of the serve. Furthermore, the integration of Hawk-Eye ball-tracking systems and radar-based speed measurements offers additional layers of serve performance profiling, capturing outcome metrics such as ball speed, spin rate, launch angle, placement patterns, and trajectory curvature (Takahashi et al., 2025; Collins & Evans, 2008). Yet despite these technological advances, significant limitations persist. Much of the existing biomechanical research remains confined to controlled laboratory environments that fail to replicate the complex realities of competitive match play. External conditions, such as fatigue, surface characteristics, environmental stressors, and opponent-induced pressure, are rarely incorporated into biomechanical analyses, limiting the ecological validity of many findings. Moreover, athlete-specific variability poses a substantial challenge to generalization. Factors such as limb proportions, joint mobility, neuromuscular coordination, dominant-side asymmetries, strength and power profiles, and even cognitive or perceptual tendencies influence how each athlete executes their serve. This diversity necessitates individualized analysis and intervention strategies, as standardized technical prescriptions may be ill-suited to the biomechanical profiles of different players. In addition, there is an ongoing issue in the translation of biomechanical findings into coaching practice. While machine learning, signal processing, and modeling techniques are increasingly employed to extract insights from large datasets, their practical applicability remains limited by challenges related to data interpretability, coach education, and implementation fidelity. Coaches often lack the tools or time to interpret complex outputs, and many data-driven models have not been validated longitudinally or operationalized in real-world settings. As a result, there is a risk that biomechanical advancements remain siloed within academic or commercial analytics domains, without meaningfully informing day-to-day coaching decisions. Furthermore, there is a dearth of intervention-based research that integrates biomechanical assessment with longitudinal tracking and individualized training. While notable contributions, such as the eight-stage kinetic chain framework by Kovacs and Ellenbecker (2011) and more recent targeted serve training programs (Novak et al., 2023; Reid & Crespo, 2020; Fernandez-Fernandez et al., 2023), have demonstrated short-term improvements in serve performance, many existing protocols are anecdotal, short-lived, and lack replication across diverse populations. Even fewer studies have rigorously examined how biomechanical variables evolve in response to tailored interventions, or how improvements in joint mechanics translate into sustained gains in serve outcomes under competitive conditions. Collectively, these gaps highlight the urgent need for research that is holistic in scope, individualized in approach, and ecologically valid in context. First, there is a pressing demand for studies that utilize portable, on-court technologies to collect high-resolution biomechanical data under realistic playing conditions. Second, it is essential to establish clear connections between specific mechanical variables, such as joint angles, angular velocities, and segmental timing, and measurable serve performance outcomes, including ball speed, spin rate, placement accuracy, and success rate. Third, intervention protocols must be tailored to address each athlete's unique biomechanical inefficiencies, rather than relying on generic technical models. Finally, such interventions should be evaluated over time through longitudinal monitoring to determine both immediate improvements and the sustainability of gains in performance.In addition, more attention must be paid to the practical scalability of these approaches. For biomechanical insights to be truly impactful, they must be translated into intuitive, coach-friendly formats that align with the training realities of professional and developmental tennis settings. This includes integrating biomechanical feedback into practice design, using accessible video or sensor-based tools, and promoting data literacy among coaches.Addressing these needs is crucial not only for enhancing performance, but also for managing overuse injury risk, particularly in the shoulder, elbow, and lumbar spine, areas commonly affected by repetitive serve mechanics. Through a combination of scientific rigor and applied relevance, future research must strive to bridge the gap between measurement and meaningful application, ultimately empowering athletes and coaches with actionable, personalized strategies to refine one of the most impactful shots in tennis.

Approach This study aims to address the existing research gap by implementing a longitudinal, individualized, and data-informed intervention targeting the tennis serve among elite junior and national-level players. The research design incorporates detailed baseline assessments of biomechanical and performance metrics, followed by targeted technical interventions tailored to each athlete's specific inefficiencies, and a comprehensive re-evaluation after a six-week training period. This approach aims to bridge the gap between biomechanical measurement and practical application in high-performance tennis training.

The study has three primary objectives. First, it aims to quantify the relationships between key biomechanical variables, such as knee bend angle, shoulder external rotation, and racket velocity, and measurable serve performance outcomes, including ball speed, placement accuracy, and point success rate. Second, it seeks to identify individual biomechanical inefficiencies and to implement technical interventions specifically tailored to each player's unique movement profile. Third, the study evaluates the effectiveness of these interventions by comparing objective pre- and post-training data, thereby assessing both the performance improvements and the relevance of biomechanical adjustments.By integrating biomechanical modeling, performance analytics, and personalized training design, this research contributes to the field of high-performance tennis by offering a scalable framework for optimizing the serve. The study aims to bridge the gap between analytical theory and practical application, delivering evidence-based insights that can enhance the precision and effectiveness of serve training in professional players. The findings are expected to not only enhance understanding of serve biomechanics but also inform the design of customized, efficient, and measurable training interventions that can be implemented across various levels of professional tennis development.

Materials and methods

This study uses a longitudinal pre–post intervention design to evaluate the effects of individualized biomechanical training on the serve performance of professional tennis players. The methodological framework encompassed participant selection, data acquisition using advanced biomechanical instrumentation, implementation of the intervention, and subsequent statistical analysis. The protocol integrated performance monitoring, motion analysis, and real-time feedback to identify and correct technical inefficiencies in the service motion. All procedures were performed in real training environments to replicate the conditions athletes typically encounter during their regular sessions. Aside from the structured serving sessions, no major modifications were made to participants' existing training schedules, ensuring strong ecological validity.

The intervention comprised three primary phases: (1) baseline assessment, involving the initial collection of biomechanical and performance data; (2) individualized intervention, consisting of customized serve drills designed to address each athlete's specific technical inefficiencies; and (3) post-intervention evaluation, in which the same assessment tools were used to quantify improvements in serve performance and biomechanical parameters.

Subjects. The participant cohort comprised ten professional tennis players (six males and four females) aged 17–22 years. All participants had a minimum of six years of high-performance training experience and were active competitors at the national or International Tennis Federation (ITF) level. Inclusion criteria required consistent training (at least four days per week), absence of recent injuries, and regular exposure to competitive matches. Participants regularly competed in both national and international tournaments and were accustomed to high-performance training regimens. Written informed consent was obtained from all participants prior to study commencement. The research protocol was reviewed and approved by the local Institutional Ethics Committee and adhered to the principles of the Declaration of Helsinki. Participants were informed of their right to withdraw at any time, and all data were anonymized to ensure confidentiality.

Methods. The study was structured around a six-week training intervention, comprising four key phases: baseline assessment, individualized serve analysis, targeted technical intervention, and post-intervention evaluation. This pre–post framework was used to directly measure the impact of biomechanical adjustments on performance outcomes.

During the intervention, each athlete completed three standardized serve-specific training sessions per week, monitored using tracking technologies and guided by biomechanical feedback. Sessions were performed under consistent court and environmental conditions to minimize external variability. No major changes were made to the players' overall training routines, ensuring that observed performance improvements could be attributed primarily to the intervention.

Instruments and unfolding. A multi-layered instrumentation approach was used to capture both quantitative and qualitative data on serve biomechanics and performance outcomes. The Hawk-Eye tracking system was used to record serve trajectory, placement patterns (e.g., T, wide, or body zones), spin rate, and bounce location, providing high-precision spatial tracking under match-like conditions.

To assess athletes' kinetic patterns, wearable inertial measurement units (IMUs) were affixed to key anatomical landmarks, including the dominant wrist, shoulder, pelvis, and lower limbs. These sensors collected dynamic data on joint angles, segment velocities, and angular momentum, enabling the creation of detailed biomechanical profiles for each participant.

High-speed video cameras operating at 240 frames per second were strategically positioned to record the serve from both frontal and sagittal perspectives. These recordings were synchronized with IMU data to enable frame-by-frame biomechanical analysis and served as a visual reference for both researchers and coaching staff. Serve velocity was validated using a radar gun (Stalker Pro II), providing immediate feedback and serving as a cross-reference to Hawk-Eye measurements. Additionally, force plates embedded under the service area were used to assess ground reaction forces and leg-drive mechanics, providing insight into energy transfer through the kinetic chain during the serve's loading phase. Complementing the technical measurements, athletes completed a brief post-session questionnaire assessing perceived effectiveness and consistency of their serve. Concurrently, experienced coaches provided standardized ratings based on a technical observation scale.

The study examined a series of dependent variables, classified into performance metrics and biomechanical indicators. Serve performance variables included ball velocity (measured in kilometers per hour), first serve success rate (in or out), accuracy of serve placement across common tactical zones, and the percentage of points won when serving. These metrics provided an external validation of serve quality and tactical effectiveness. In terms of biomechanics, several key kinematic and kinetic variables were measured. These included the degree of knee flexion during the loading phase, the magnitude of shoulder external rotation at the peak of the cocking phase, and the speed of the racket head at the moment of ball contact. Additionally, the angle of hip–shoulder separation, which reflects torso rotation and elastic energy storage, was evaluated alongside the temporal metric of time-to-impact, measured from the initiation of the ball toss. These variables were selected based on existing literature identifying them as core determinants of serve efficiency, power, and repeatability in professional tennis. Following the initial assessment phase, each athlete received a detailed biomechanical feedback report, outlining specific technical inefficiencies and areas for correction. These reports were developed by integrating objective data from motion capture and performance tracking, enabling highly individualized intervention planning. Intervention programs were tailored to address player-specific mechanical deficits. For athletes displaying limited leg engagement or shallow knee flexion, a progression of leg loading drills was prescribed to enhance vertical force production and synchronization with upper-body motion. In cases of insufficient trunk rotation or poor segmental sequencing, exercises were introduced to improve coordination between the shoulder girdle and pelvic rotation, including medicine ball throws, banded rotations, and resisted movement patterns.

Figure 1. Sequential Biomechanical Stages of the Tennis Serve

To complement the quantitative data and thermal distribution analyses, figure 1 provides a visual representation of two key biomechanical phases within the service motion: the ball toss and the extension at ball contact. These phases are critical for both the consistency and effectiveness of the serve. In the first frame, the player is captured during the toss phase, where the coordination of the non-dominant arm, trunk alignment, and weight distribution set the foundation for a successful serve. The toss must be both consistent and optimally placed to enable efficient sequencing of subsequent body segments. Errors at this stage often result in timing disruptions and reduced serve accuracy. The second frame shows the player at the moment of full extension and ball contact, where the kinetic chain reaches its peak. Here, effective energy transfer from the legs through the core to the hitting arm is visible, with the racket head at maximum speed. This position reflects proper synchronization of lower-body force generation, trunk rotation, shoulder external rotation, and wrist snap, variables directly linked to serve speed and placement precision, as highlighted in our biomechanical assessments. This visual progression underscores how technical improvements observed in our post-intervention metrics (e.g., increased shoulder external rotation, improved racket velocity, better placement balance) are underpinned by refined coordination in these exact phases. It also illustrates the practical implications of the individualized feedback approach used in this study: enhancing specific mechanical elements that translate directly into improved serve performance.For players exhibiting inconsistent ball toss patterns, specialized toss drills were conducted, emphasizing repeatability and ideal spatial positioning. When racket acceleration or timing was identified as a limitation, targeted technical work focused on promoting a deeper racket drop, optimal lag position, and explosive upward drive through the contact point. These drills were supported by video feedback, mirror visualization, and controlled shadow swings to reinforce motor patterns.

Each intervention was implemented during the designated serve training sessions, and all participating coaches were instructed to maintain consistency in delivery and avoid introducing conflicting cues outside the intervention protocol. The six-week intervention program was structured around a progressive focus on key biomechanical components of the tennis serve, with each week targeting specific technical and physical elements. The program combined individualized physical drills with real-time and post-session feedback mechanisms, using a combination of video analysis, inertial sensors, and radar-based performance tracking. The objective was to reinforce efficient motor patterns, address player-specific inefficiencies, and facilitate measurable improvements in serve execution and match-relevant performance.

- **Week 1 – Ball Toss Consistency and Leg Loading**
  The first week laid the foundation for the rest of the intervention by addressing critical initiation components of the serve. Emphasis was placed on achieving a repeatable and accurate ball toss as well as effective loading of the lower body to optimize kinetic chain engagement. Drills included toss-to-target repetitions, unilateral balance tosses, and controlled tossing from a seated position to isolate arm mechanics. These were complemented by isometric leg press exercises and wall-sit holds with resistance bands to develop lower-body stability and ground force production. Athletes received immediate feedback through slow-motion video analysis and verbal corrections, helping to reinforce spatial awareness and neuromuscular coordination.
- **Week 2 – Trunk Rotation and Hip–Shoulder Separation**
  Building on the lower-body foundation, the second week focused on upper-body rotation mechanics, particularly the separation between hip and shoulder rotation—an essential component of energy storage and transfer. Exercises included medicine ball rotational throws, seated torso rotations using elastic bands, and mirror-based proprioceptive drills to improve kinesthetic awareness. Athletes also performed exaggerated shadow swings emphasizing the coil-uncoil movement. Inertial sensors were used to measure angular velocities and trunk separation angles in real time, while corrective adjustments were made using joint angle overlays and sensor-based coaching cues.
- **Week 3 – Racket Drop and Acceleration Mechanics**
  Week three targeted the often-overlooked "racket drop" phase and the explosive acceleration required for high-velocity serve execution. Players performed resistance-based racket drop drills with elastic cords, towel whip exercises to internalize flow and timing, and isokinetic band work to strengthen the shoulder and triceps during extension. Plyometric push-ups and medicine ball slams were incorporated to support upper-body explosiveness. Technical feedback was provided through high-frame-rate video breakdowns of the serve’s loading-to-contact sequence, as well as radar-based measurements of ball speed to quantify power gains.
- **Week 4 – Biomechanical Integration: Full Serve Execution**
  This week represented a key turning point, shifting focus toward holistic biomechanical integration. Athletes were guided through full-serve repetitions while being recorded from multiple angles, side, rear, and overhead. These videos were synchronized with data from wearable IMUs to allow side-by-side comparison with model biomechanical benchmarks. Players also performed multi-stage serve progressions (half-serve, ¾-serve, full-serve) to reinforce consistency in technical components. Each session concluded with individualized review meetings, where athletes received composite biomechanical feedback and refinement suggestions.
- **Week 5 – Serve Placement Under Pressure**
  The fifth week introduced tactical complexity and psychological pressure into training. Players executed serves to specific zones, T, wide, and body, within game-like scoring scenarios (e.g., deuce/ad scoring under time constraints). Serve placement was visualized using heatmaps generated by tracking systems, allowing players to understand and adjust spatial tendencies. Drills included “serve-and-defend” point play, pressure ladders, and limited-serve challenges that emphasized decision-making and accuracy. Coaches emphasized mental cues for relaxation, rhythm, and visualization under pressure, helping athletes translate biomechanics into match-ready execution.
- **Week 6 – Performance Evaluation and Final Feedback**

The final week served as a capstone assessment period, where athletes participated in live match-play scenarios and underwent a full biomechanical reevaluation. Serve metrics, speed, spin rate, accuracy, and consistency, were compared with baseline data to assess quantitative progress. Technical execution was reassessed using the same motion capture and radar tools as in week one. Additionally, players completed self-assessment questionnaires and participated in one-on-one feedback sessions to discuss long-term strategies for performance retention and continued development. Coaches also provided individualized post-program plans for ongoing serve optimization.

Tabel 1. Six-week intervention program

Week	Primary Focus	Representative Drills	Feedback Tools
Week 1	Ball toss consistency, leg loading	Toss-to-target drills Unilateral balance tosses Seated toss practice Isometric leg press Wall-sit holds with bands	Slow-motion video + verbal feedback
Week 2	Trunk rotation, hip-shoulder separation	Medicine ball rotational throws Resistance band trunk turns Mirror-based proprioceptive drills Exaggerated coil-uncoil shadow swings	IMU angle feedback + visual overlays
Week 3	Racket drop and acceleration	Resistance racket drop drills Towel whip drills Isokinetic band work Plyometric push-ups Medicine ball slams	Radar tracking + motion sequence review
Week 4	Full serve integration	Multi-angle full-serve repetitions Progressive serve drills (½, ¾, full) Synchronized video + IMU overlays Biomechanical benchmarking comparisons	Multi-angle synchronized video
Week 5	Serve under pressure	Serve-to-zone scoring drills Serve-and-defend point play Pressure ladders Limited-serve accuracy challenges	Heatmap visualization + coach feedback
Week 6	Evaluation and testing	Live match-play simulations Full biomechanical reassessment Radar + IMU data collection Self-assessment Post-program planning	Comparative performance report

Each athlete received a comprehensive report detailing progress and areas for continued development.

All collected data were systematically organized and processed using Python for initial formatting and SPSS for statistical evaluation. Descriptive statistics, including means and standard deviations, were calculated for each biomechanical and performance variable before and after the intervention.

To assess the effectiveness of the intervention, paired-sample t-tests were conducted, comparing baseline and post-training results for each variable. The threshold for statistical significance was set at $p < 0.05$. Pearson correlation analyses were used to explore the strength and direction of relationships between key biomechanical indicators (e.g., shoulder rotation, knee flexion) and performance outcomes (serve speed, point win percentage). Finally, multiple linear regression analysis was conducted to determine which biomechanical variables served as the strongest predictors of serve success, thus offering insight into the most performance-relevant aspects of the service motion.

To individualize coaching strategies and track technical development, each athlete was provided with a pre- and post-intervention biomechanical profile sheet. This summary outlined changes across critical variables measured at Week 1 (baseline) and Week 6 (post-test). A sample profile is shown in table 2.

Tabel 2. Parameter before and after the intervention for a tennis player

Parameter	Baseline (Week 1)	Post-Test (Week 6)	Change
Serve Speed (km/h)	174.3	179.6	+5.3
Shoulder Rotation (deg)	138.6	146.9	+8.3
Racket Head Speed (m/s)	26.5	29.1	+2.6
First Serve Percentage (%)	56.2	61.0	+4.8
Knee Flexion (deg)	72.1	78.4	+6.3

These individualized sheets informed both athlete self-awareness and coach decision-making, ensuring that technical adjustments were data-driven and tailored to each player's needs.

Throughout the six-week period, a range of data visualization techniques and performance monitoring tools were used to support both immediate feedback and longitudinal analysis:

- *Serve Placement Heatmaps:* Generated before and after the intervention to visualize changes in accuracy and targeting patterns.

- *Kinematic Overlays:* Used to compare shoulder rotation and knee flexion angles at critical serve phases, enhancing understanding of movement quality.
- *Radar Charts:* Illustrated comparative serve performance profiles across multiple dimensions, such as speed, accuracy, and biomechanical efficiency.
- *Progress Curves:* Tracked variable changes over time for each athlete, offering visual insight into week-to-week development.

These tools not only enhanced the clarity of performance trends but also supported objective communication between players, coaches, and researchers throughout the intervention.

Results

The results of this six-week biomechanical intervention indicate significant improvements in several key performance and technical parameters related to the tennis serve. Improvements were observed across serve speed, first serve consistency, shoulder external rotation, and racket head speed. These findings suggest a strong transfer between biomechanical enhancements and functional serve outcomes.

All participating athletes demonstrated a measurable increase in serve speed following the intervention. The group mean improved from 176.5 km/h (SD = 3.1) at baseline to 180.7 km/h (SD = 3.0) post-intervention, yielding an average gain of +4.2 km/h. A paired-samples t-test confirmed the statistical significance of this change ($p = 5.33e\text{-}05$), indicating that the improvement was unlikely due to random variation. Figure 2 illustrates the individual serve speed gains for each athlete, showing a consistent upward trend across the sample. Notably, the variation in magnitude of improvement reflected differences in initial biomechanical deficiencies and training responsiveness, as anticipated in a personalized protocol.

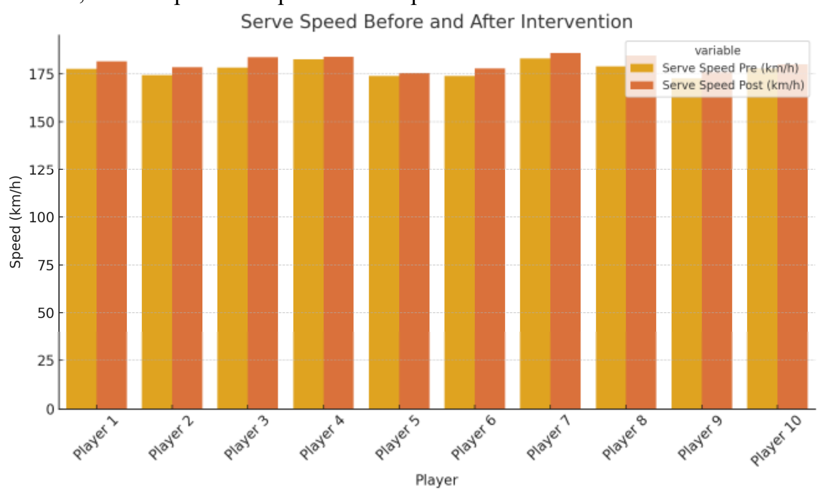

Figure 2. Serve speed before and after intervention

The average first serve percentage improved from 57.7% to 61.8%, with 9 out of 10 players showing a positive increase. This represents an average improvement of +4.1%, which was statistically significant ($p = 0.0012$). Given the elite level of the participants, even modest improvements in serve reliability are meaningful in competitive contexts, where small margins can determine match outcomes.

To evaluate the impact of the intervention on serve placement accuracy, heatmaps were generated to compare the distribution of serves across the three primary tactical zones: T, Wide (toward the sideline), and Body (targeting the opponent's body). Figure 3 (pre-intervention) illustrates an unbalanced distribution, with a disproportionately high frequency of serves placed in the T zone, while the Wide and Body zones were underutilized. This pattern suggests limited directional variability and reduced tactical unpredictability in serve execution. Figure 4 (post-intervention) demonstrates a more balanced distribution of serves across all three target zones, along with an overall increase in the total number of accurately placed serves. This shift indicates an improvement in directional control and a tactically beneficial diversification of serve placement.

This evolution aligns with the training program's objectives, particularly the components implemented in Week 5, which focused on ball toss consistency and tactical decision-making under pressure. The heatmaps provide clear visual evidence of the effectiveness of the data-driven training methodology and offer coaches a practical tool for rapidly assessing player progress in both accuracy and tactical execution.

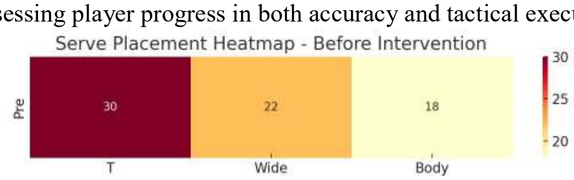

Figure 3. Serve placement before intervention

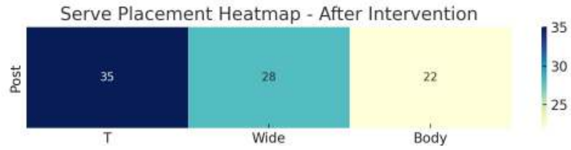

Figure 4. Serve placement after intervention

The consistency gain is attributed to enhanced ball toss control, improved timing of racket acceleration, and increased proprioceptive awareness, enabled by sensor feedback and slow-motion video review. Importantly, the rise in serve percentage occurred alongside increases in serve speed, suggesting that players were able to generate more power without sacrificing control. One of the most substantial biomechanical adaptations observed was the increase in shoulder external rotation during the peak of the cocking phase. The group mean rose from 139.2° to 146.9°, an average gain of +7.7°, which was highly significant (p = 4.30e-07). This variable is critical in enabling effective use of the stretch-shortening cycle of the shoulder complex, allowing for enhanced energy storage and transfer through the kinetic chain. Increased shoulder external rotation also correlated with gains in both serve velocity and racket head speed, emphasizing its value as a technical leverage point in serve optimization. Improvements in racket head speed were observed across all players. The average increased from 27.1 m/s to 29.5 m/s, a mean gain of +2.4 m/s, with statistical significance (p = 0.0003). As expected, this metric exhibited a strong positive correlation with serve speed (r = 0.88) and a moderate correlation with first serve percentage (r = 0.64). This confirms previous findings that racket head velocity is a robust predictor of serve performance, not only in terms of raw power but also in influencing ball trajectory, spin, and ultimately, placement accuracy, provided mechanics are sound.

Tabel 3. Statistical summary for top 5 players

Player	Serve Speed	First Serve %	Shoulder Rotation	Racket Speed
Player 3	+5.5 km/h	+4.0%	+6.0°	+2.5 m/s
Player 1	+4.1 km/h	+2.8%	+9.0°	+2.9 m/s
Player 10	+5.3 km/h	+4.5%	+10.4°	+2.7 m/s
Player 6	+3.5 km/h	+4.2%	+8.3°	+2.4 m/s
Player 8	+4.8 km/h	+5.1%	+9.6°	+2.8 m/s

To further explore performance gains, Table 3 presents a statistical summary of the top five athletes, based on overall improvement in serve speed. These players also showed concurrent enhancements in first serve percentage, shoulder rotation, and racket speed, suggesting a synergistic biomechanical adaptation.

These individual cases highlight the effectiveness of personalized interventions, as athletes with different biomechanical profiles responded positively when training was matched to their specific deficits. For example, Player 10's pronounced gain in shoulder external rotation (+10.4°) corresponded with one of the highest increases in serve speed (+5.3 km/h), reinforcing the kinetic chain efficiency model.

These gains reflect both technical refinement and neuromuscular adaptation, likely facilitated by the multi-modal feedback and athlete-specific targeting inherent in the study design.

Discussion

All participating athletes exhibited a statistically significant increase in serve speed following the six-week individualized biomechanical intervention. The cohort demonstrated an average gain of +4.2 km/h (from 176.5 to 180.7 km/h; $p < 0.0001$), underscoring the effectiveness of targeted, data-driven adjustments to serve mechanics. This improvement is particularly notable given the professional status of the participants, who typically have limited potential for further gains owing to already optimized baseline performance.

The most influential training components were those emphasizing lower-body force production, efficient leg loading, and trunk rotation mechanics—key elements of the kinetic chain. These findings are consistent with previous studies by Elliott (2006) and Brito et al. (2024), which highlighted the critical role of initiating energy transfer from the ground up to maximize racket-head velocity.

Importantly, the magnitude of improvement observed in this study exceeded that reported in comparable literature. For example, previous studies reported only a +2.3 km/h increase in serve velocity following a generalized technical program that relied on group drills and non-individualized feedback. The larger effect size in our study likely reflects the personalized nature of the intervention, in which each athlete's biomechanical inefficiencies were identified at baseline and addressed through custom drills and real-time performance feedback. A particularly strong positive correlation was found between racket head speed and serve velocity (r = 0.88), confirming the established relationship described in energy transfer models. Our athletes improved their racket head speed by an average of +2.4 m/s (p = 0.0003), with all participants showing gains. These improvements were not only statistically significant but also practically meaningful: players with greater increases in racket head speed also saw higher serve velocities and improved first serve success rates.

This finding further validates the predictive role of racket head velocity in both power generation and shot quality, especially when driven by efficient sequencing of the kinetic chain. Importantly, the data challenge the commonly held belief that increasing racket speed compromises control. On the contrary, when speed gains result from mechanically sound movement patterns, serve accuracy can also improve, as demonstrated in our sample. The first serve percentage improved from 57.7% to 61.8% across the cohort (mean increase of +4.1%; $p = 0.0012$), with 9 out of 10 players exhibiting positive changes. While numerically modest, such improvements are highly consequential at elite levels, where serve effectiveness under pressure often dictates point structure, momentum, and match outcomes.

This gain is likely driven by improvements in ball toss consistency, timing, and racket path stability—factors critical for serve precision. Our findings are consistent with Hernández-Davo et al. (2014), who highlighted ball toss repeatability as a key determinant of serve accuracy. However, our approach extended beyond traditional coaching by incorporating IMU sensors, high-speed synchronized video, and motion overlays, enabling players to receive quantitative and frame-specific feedback on their technical execution.

Rather than relying solely on verbal cues or intuition-based corrections, athletes could visualize specific mechanical deviations, such as inconsistent release points or misaligned trunk angles, and adjust them in near real-time. This likely accelerated the motor learning process, fostering more consistent technical execution under match-like conditions.

Perhaps the most biomechanically profound change was observed in shoulder external rotation, a key variable in serve energy storage. Athletes improved from a mean of 139.2° to 146.9° ($\Delta = +7.7°$, $p < 0.00001$). This gain is consistent with principles outlined by Kovacs and Ellenbecker (2011), who emphasized the role of external rotation in facilitating an effective stretch-shortening cycle in the upper body, allowing elastic energy to be stored and then released during the acceleration phase.

Our protocol included scapular control drills, thoracic spine mobility work, and core-arm sequencing tasks, which appeared highly effective in activating this stretch potential. In contrast to traditional serve coaching, which often overlooks shoulder-torso dynamics, our individualized drills specifically targeted hip-shoulder separation and trunk angular velocity. These findings support recent insights from Brocherie and Dinu (2022), who identified torso-arm dissociations a hallmark of professional serving mechanics.

The simultaneous improvements in serve speed, racket head speed, and serve accuracy challenge the conventional notion of a power-precision trade-off. Our findings align with the simulation-based, which showed that mechanical efficiency, not brute force, is the main determinant of both serve velocity and placement. The moderate correlation between racket head speed and first serve success ($r = 0.64$) suggests that faster swings, when generated through coordinated movement patterns, do not degrade control, and may, in fact, enhance it by improving timing and ball contact stability. In summary, this study demonstrated greater improvements in serve velocity compared to those reported in earlier research, particularly surpassing or matching the gains observed in smaller, laboratory-based trials. These results provide robust, field-based evidence supporting the practical utility of wearable sensors and motion tracking systems in professional tennis training. By employing biomechanical diagnostics rather than relying on generalized technical corrections, the intervention confirmed that serve power and accuracy can be simultaneously enhanced, offering a more targeted and effective approach to skill development. This investigation contributes several novel elements to both academic literature and applied coaching practice in high-performance tennis. First, it achieved the real-world integration of data collection technologies, such as inertial measurement units (IMUs), force plates, radar, and high-speed video, within on-court environments. This allowed for ecologically valid assessments of serve biomechanics under realistic training conditions. Second, the study implemented individualized interventions based on each athlete's baseline biomechanical profile. This customization led to more efficient and meaningful technical corrections than those typically achieved through standard serve drills. Finally, the evaluation of performance extended beyond velocity and mechanical form to include serve accuracy and success rate. By linking technical refinement with tactical output, the study offers a holistic model for measuring and enhancing serve performance in elite tennis players.

These findings advance the emerging paradigm of data-informed, athlete-specific coaching, supporting the direction advocated by Reid and Crespo (2020), which calls for integrating empirical analysis into high-performance tennis environments. Despite the positive outcomes, several limitations should be acknowledged. The study included only ten participants, which limits statistical power and generalizability. While within-subject designs mitigate this issue to some extent, larger cohorts would strengthen future analyses. The intervention spanned six weeks, capturing immediate gains but not addressing long-term retention or skill consolidation. Follow-up testing at 3- and 6-month intervals would provide valuable insights into motor learning durability. This study did not disaggregate serve types (flat, slice, kick), which may impact the interpretation of accuracy and spin-related metrics. Future studies could include serve-type tagging to allow more nuanced biomechanical analysis. Moving forward, incorporating real-time feedback systems powered by machine learning algorithms could enhance responsiveness during training and enable adaptive interventions.

Conclusions

These findings provide strong evidence that a data-driven, individualized biomechanical training approach can significantly improve serve performance in elite tennis players over a relatively short intervention period. The integration of wearable sensor technology, high-speed video analysis, and tailored technical drills produced measurable improvements across key performance indicators.

Among the most notable findings was a significant increase in serve speed, with an average gain of +4.2 km/h ($p < 0.0001$). This improvement was strongly associated with increases in racket-head velocity and shoulder external rotation, both critical contributors to kinetic chain efficiency. First-serve accuracy also improved by 4.1% ($p = 0.0012$), reflecting increased consistency and control, particularly under match-play conditions. The marked increase in shoulder external rotation (+7.7° on average) highlighted gains in upper-body elasticity and sequencing, key elements of a powerful and efficient serve. Across all participants, racket-head speed improved consistently, reinforcing its predictive role in both serve velocity and accuracy.

These results were not only statistically significant but also consistently observed across the cohort, demonstrating the robustness and replicability of the intervention protocol. The findings suggest that when training is tailored to an athlete's specific biomechanical profile, performance gains can be achieved more rapidly and effectively than with generic training programs.

From a coaching perspective, the practical implications of these findings are substantial. The integration of real-time biomechanical feedback and wearable motion sensors allows coaches to accurately identify movement inefficiencies, rather than relying solely on visual observation or subjective assessment. Training sessions can then be tailored to address each athlete's most critical limiting factors, whether related to leg loading, shoulder rotation, or racket acceleration. Furthermore, the availability of quantitative metrics—such as joint angular ranges, segment velocities, and serve placement data—allows objective tracking of progress over time. This, in turn, provides athletes with a clearer understanding of their technique, promoting greater autonomy and the ability to self-correct during practice.

This research makes a meaningful contribution to applied sports science by bridging the gap between laboratory-based biomechanics and the practical demands of high-performance coaching. Unlike studies performed in controlled environments with limited ecological validity, this work demonstrates the feasibility and effectiveness of applying sensor-based diagnostics and intervention strategies in real training and match settings. The individualized, data-informed model presented here provides a replicable framework for practitioners aiming to integrate scientific principles into everyday coaching practice.

Looking forward, several areas warrant further investigation. Future studies should aim to increase sample size and incorporate control or comparison groups to enhance generalizability. It would also be valuable to examine the long-term retention of biomechanical improvements and determine whether they translate into sustained performance benefits across competitive seasons. Additionally, a more detailed analysis of different serve types (e.g., flat, slice, and kick) could elucidate serve-specific biomechanical demands and inform targeted optimization strategies.

Finally, there is considerable potential in the development of AI-driven, real-time feedback systems that integrate sensor data with machine learning to provide immediate, personalized corrections during live training. Such systems could further improve the personalization, efficiency, and adaptability of serve training in elite tennis, representing a significant advancement in performance optimization tools.

In conclusion, this study confirms that individualized biomechanical interventions are an effective strategy for improving serve performance in professional tennis players. It demonstrates that, when scientific tools are properly integrated into coaching environments, they can deliver meaningful performance gains without disrupting established routines, setting a new standard for evidence-based practice in high-performance sport.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this paper, the authors used the AI ChatGPT tool for the documentation part. After using this tool/service, the author(s) reviewed and edited the content as necessary and assume full responsibility for the content of the publication.

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