Universal Library of Medical and Health Sciences | Research Article

ISSN: 3064-6545 | Volume 3, Issue 3

Open Access | PP: 102-108

DOI: https://doi.org/10.70315/uloap.ulmhs.2025.0303014

Biomechanics of Serves and Punches: The Kinematic Chain and Shoulder/Elbow Load Control

Danilov Savriyan

Professional Tennis Player, Coach, and Leadership Mentor, Founder of a Digital Sports Platform (TeNFT), Irvine, California, USA.

Abstract

The article presents an analysis of the biomechanics of the tennis serve based on the principle of the kinematic chain and on contemporary approaches to monitoring loads on the structures of the upper limb in the context of the professional tour of 2024–2025. The relevance of the stated issues is determined by a pronounced tendency toward increasing injury incidence: according to available information, among elite-level athletes the frequency of injuries reaches 3.3 cases per 365 days, whereas disorders of the shoulder complex and the wrist continue to occupy leading positions among the causes of prolonged loss of competitive performance capacity. Thus, a need is identified for a more precise integration of field biomechanical characteristics of real movement with predictive algorithms for load management, in particular with models based on the acute-to-chronic workload ratio (ACWR), which the present work seeks to provide. The methodological framework is formed through a system analysis of the results of other studies, comparison of data obtained using wearable inertial measurement units (IMU), as well as synthesis of materials from specialized consulting organizations (Deloitte, McKinsey). The analysis shows that an increase in the knee flexion amplitude to the range of 15–20° is associated with a reduction in the peak torque acting on the shoulder joint by approximately 18%, which underscores the importance of the lower links of the kinematic chain as a mechanism for redistributing loads. In addition, it is demonstrated that maintaining the ACWR index within the interval of 0.8–1.3 correlates with minimizing the probability of developing tendinopathies, thereby supporting the appropriateness of applying controlled regimes of training exposure under high competitive volumes. Separately, the contribution of digital monitoring tools and structured mentoring programs (illustrated by the practices of Max Performance Tennis) to improving adherence to load-control regulations and preventive protocols is discussed.

Overall, the formulated provisions set an applied vector for optimizing serve technique and reducing the risk of chronic overload conditions, representing practical significance for coaching staff specialists, sports medicine, and biomechanical support, as well as for professional tennis players focused on maintaining competitive effectiveness and extending athletic career longevity.

Keywords: *Tennis Biomechanics, Kinematic Chain, Tennis Serve, Shoulder Loads, Elbow Varus Moment, ACWR, Wearable Technologies, Sports Medicine, Load Management.*

INTRODUCTION

In professional tennis, the serve in recent years has definitively ceased to be perceived merely as a means of initiating a rally, transforming into a highly effective mechanism of game dominance associated with maximal mobilization of physical resources. At the turn of 2024–2025, the ATP and WTA tours register a sustained increase in serve speeds, which is consequently accompanied by increased mechanical stress across all links of the kinematic chain [1]. Against this background, epidemiological indicators confirm the scale of the problem: the overall morbidity and injury incidence among elite-level players are estimated at approximately 3.3 cases per athlete per year, and in the women's tour shoulder injuries (prevalence 3.7%) exceed in frequency other upper-limb localizations [3]. In the men's tour, the wrist (prevalence 3.8%) and the elbow joint remain among the most vulnerable areas, where varus loads can reach extreme magnitudes [3].

The development of tennis biomechanics at present is characterized by a shift in methodological paradigm: traditional video-analytic approaches are gradually giving way to inertial measurement systems (IMU) and analytics based on artificial intelligence algorithms. The classical studies of Bruce Elliott and Ben Kibler formed a foundational understanding of sequential energy transfer according to the

Citation: Danilov Savriyan, "Biomechanics of Serves and Punches: The Kinematic Chain and Shoulder/Elbow Load Control", Universal Library of Medical and Health Sciences, 2025; 3(3): 102-108. DOI: https://doi.org/10.70315/uloap.ulmhs.2025.0303014.

principle of proximal-to-distal organization of movement; however, data from studies in 2024 indicate that, in the professional environment, this sequence is not always reproduced in a canonical form. Variability of timing and a restructuring of motor emphases are noted depending on the degree of fatigue and situational tactical demands [1, 5]. Despite a substantial body of empirical observations, a distinct theoretical-applied gap persists: there is no unified conceptual model that would allow direct comparison of short-term biomechanical deviations (including phenomena such as elbow drop) with long-term load-management metrics, including the acute-to-chronic workload ratio (ACWR).

The aim of the study is formulated as establishing a relationship between the efficiency of energy transfer along the kinematic chain and the level of mechanical load acting on the shoulder and elbow joints, followed by the development of an adaptive model for injury prevention. Within the implementation of this aim, the analysis of current data on upper-limb injuries for 2024–2025 is envisaged, clarification of the contribution of lower-limb and trunk technique to unloading the shoulder girdle, assessment of the potential of wearable technologies and the ACWR index in monitoring the condition of elite-level athletes, and substantiation of the significance of leadership and mentoring practices as factors supporting adherence to load-control discipline.

The scientific novelty of the presented approach consists in integrating precision biomechanical analysis with contemporary digital monitoring methods and the toolkit of sports mentoring, which shifts control from a predominantly passive mode of recording to a format of active management of athlete health.

The author's working hypothesis considers the proposition that optimization of angular velocities in proximal segments (pelvis and trunk) with simultaneous stabilization of ACWR below the threshold value of 1.5 makes it possible to maintain competitive serve-speed parameters and, at the same time, reduce joint moments in the shoulder and elbow joints by 15–20%.

MATERIALS AND METHODS

The preparation of the study was structured as a multi-stage search, evaluation, and subsequent synthesis of scientific data published within the 2020–2025 interval. The evidence base comprised materials from international platforms of peer-reviewed literature (Scopus, Web of Science, PubMed), as well as from technical archives (IEEE, ACM). The search strategy was organized around a set of targeted descriptors, including formulations reflecting the issues of the kinematic chain in tennis, the biomechanical features of the serve, injury to the shoulder complex during overhead movements, load characteristics of the elbow joint, and the application of the ACWR index in tennis practice.

The assembled primary body of publications was subjected to a rigorous selection procedure. The final corpus included works meeting criteria of high methodological rigor (levels I–II of evidence), including systematic reviews presented in 2024. To broaden the applied scope and account for technological dynamics, industry analytical materials from consulting structures (Deloitte 2025, Gartner) were additionally considered, which ensured alignment of sports-medicine issues with current digital trends.

The comparison of biomechanical parameters was performed on the basis of data obtained using high-frequency inertial measurement systems (IMU, 1000 Hz) and optical motion-capture complexes (Vicon). The analytical focus was directed toward kinetic variables, primarily joint torques (Nm) and compressive components of load registered in key segments of the upper limb. The assessment of external loads was supplemented with GPS-tracking datasets and racket-acceleration sensor indicators, which made it possible to quantitatively describe the volume of explosive actions within a single training or competitive session.

A substantial part of the study design includes a practice-oriented case component based on the author's professional activity, used to interpret the applied feasibility of workload monitoring and compliance strategies in elite tennis.

Integration of the results was carried out using statistical tools for risk assessment and correlation analysis aimed at identifying relationships between technical parameters (in particular, the angle of knee-joint flexion) and medical outcomes, including the duration of the recovery period after injuries.

RESULTS AND DISCUSSION

The functioning of the kinematic chain within the structure of the tennis serve can be interpreted as a wave-like generation and subsequent transfer of mechanical impulse along sequentially engaged links. Movement initiation is associated with overcoming the gravitational component through the active contribution of the lower limbs; then the impulse is amplified and redistributed by means of rotation of the pelvis and trunk, and the terminal phase is executed through high-speed racket acceleration due to internal shoulder rotation and forearm pronation. The degree of coordination and efficiency of this cascade determines not only the performance characteristics of the stroke, including ball release velocity, but also the profile of chronic overload that affects the structural endurance of the joints under conditions of repeatedly recurring competitive exposures [6, 10].

Data from contemporary studies demonstrate that, when executing the first serve, statistically significantly higher peak angular velocities of body segments are recorded compared with the second serve, which corresponds to a difference in functional priorities: the dominance of maximal force and tempo in the first variant is contrasted with an emphasis on execution stability and controlled spin in the second. At the same time, a fundamentally important conclusion is the preservation of intersegmental timing regardless of serve type, which indicates that elite players possess a stably entrenched motor pattern with a high degree of invariance to variations in the tactical task [1]. Comparative characteristics of the angular velocities of key links of the kinematic chain are presented in Table 1.

Table 1. Kinematic profiles of the first and second serve (compiled by the author based on [1])

Segment / Parameter	First serve (Mean ± SD)	Second serve (Mean ± SD)	Difference (p-value)
Pelvic angular velocity (deg/s)	156.2 ± 12.4	136.6 ± 10.8	< 0.05
Trunk angular velocity (deg/s)	125.4 ± 15.1	118.2 ± 13.5	< 0.05
Peak shoulder internal rotation (deg/s)	2594 ± 225	2429 ± 441	< 0.01
Acceleration duration (forward swing, s)	0.12 ± 0.01	0.14 ± 0.02	< 0.01

The obtained data indicate that internal shoulder rotation makes the leading contribution to the linear racket speed, reaching 40% or more; however, the magnitude of this contribution is functionally mediated by the quality of the preliminary musculotendinous pre-tension of the rotator cuff. Such pre-tension is formed through coordinated lower-limb action and positioning of the shoulder complex in the trophy phase, where effective leg flexion and shoulder abduction create the conditions for subsequent high-speed terminal acceleration [15]. Of substantial importance for unloading the shoulder girdle is the explosive sequence of flexion and extension of the knee joints, which allows an increase in the contribution of the proximal links of the kinematic chain and thereby reduces the need for compensatory amplification of joint moments at the level of the upper limb. Empirical observations show that with a limited amplitude of leg action (less than 10° of flexion), the energy deficit is more often compensated by an increase in torque in the shoulder and elbow joints [4]. The most critical loading configuration is registered in the phase of maximal external rotation of the shoulder (MER), when the joint tissues and the surrounding musculotendinous complex experience extreme tension; in men, the absolute internal rotation moment averages 64.9 Nm, which substantially exceeds the corresponding value in women (37.5 Nm) and is consistent with higher serve-speed characteristics [4]. Below, Figure 1 presents a graph reflecting an inverse relationship between the effectiveness of leg action and peak loads on the shoulder joint.

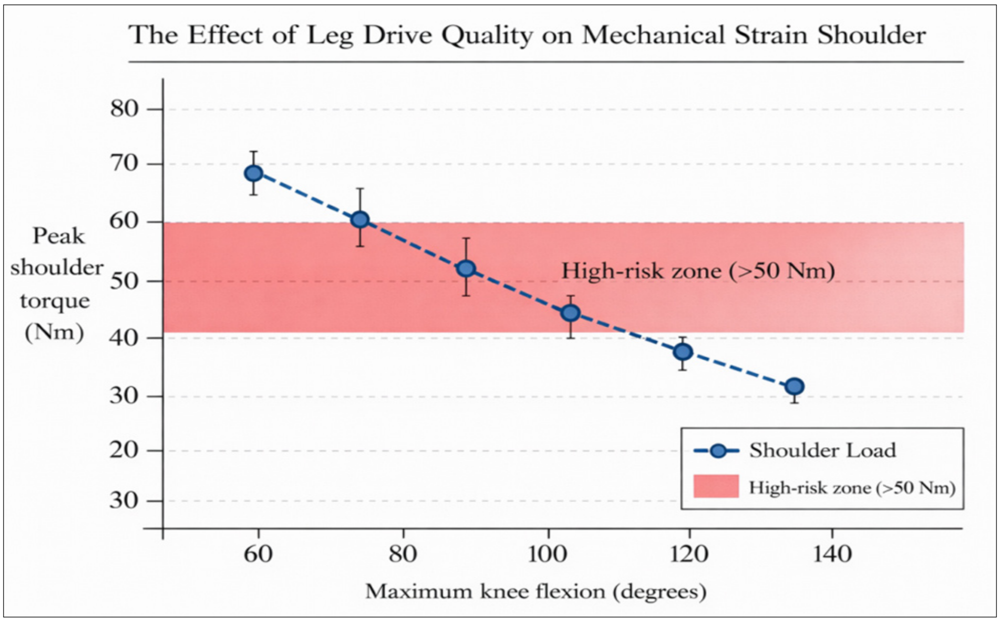

Fig. 1. Dependence of the load on the shoulder on the biomechanical efficiency of leg work (compiled by the author based on [4, 17]).

Interpretation of the presented graphical data indicates that a shift from a predominantly passive model of lower-limb participation to a distinctly active strategy (knee-joint flexion greater than 15°) is associated with a reduction in peak shoulder moments and with moving load values beyond the risk red zone, defined by levels above 50 Nm. Within this load range, the probability of injury to rotator cuff structures becomes clinically significant, which underscores the role of proximal impulse generation as a key factor in the prevention of overload lesions of the shoulder complex [4, 11].

Epidemiological summaries for 2024 record a shift in the injury profile, linked to increasing stiffness of playing surfaces and changes in ball characteristics, including increased mass. Against this background, the elbow joint retains the status of one of the most vulnerable zones due to pronounced varus loads arising during forced forearm pronation and during attempts to achieve extreme values of ball spin, which is particularly characteristic of the kick serve. The structure of upper-limb injuries with distribution by the types of involved tissues and by severity is presented in Table 2.

Table 2. Upper extremity injury profile in the pro tour (compiled by the author based on [3])

Anatomical region	Injury type	Proportion (%)	Mean recovery time (days)
Shoulder joint	Rotator cuff injury	34	22.5 ± 5.2
Elbow joint	Medial epicondylitis / UCL	12	16.8 ± 3.1
Wrist joint	Tendinopathies / TFCC tears	42	31.7 ± 8.4
Lower back	Stress fractures / Discs	12	45.8 ± 12.0

The most unfavorable feature in the injury structure is a high proportion of recurrences exceeding 54% of cases, which is associated with inadequate recovery and premature return to competitive volumes and intensities [18]. This pattern emphasizes the need to implement objectified monitoring systems capable of registering micro-deviations of technique and functional state before subclinical disorders progress into a clinically manifest injury.

In 2024–2025, the concept of the Acute-to-Chronic Workload Ratio (ACWR) has assumed leading positions in monitoring training and competitive exposures, being regarded as a key indicator of the relationship between the current acute weekly load and the averaged load of the preceding four weeks (chronic). Such a metric makes it possible to quantitatively assess whether the current exposure is physiologically expected for a specific athlete or represents an abrupt spike capable of initiating a cascade of overload-related changes. According to systematic reviews, when the ACWR threshold of 1.5 is exceeded, the risk of injury increases by 2.8 times [7].

In tennis conditions, external load is described not only by the duration of time spent on court, but also by the number of striking actions, their temporal density, and intensity, including racket-speed parameters. The use of wearable IMU sensors provides a substantially more detailed and structured picture of load, shifting assessment from a descriptive level to a mode of instrumentally confirmed kinematic and kinetic diagnostics. As an illustrative marker of functional depletion, a decrease in internal shoulder-rotation speed toward the end of a training session by approximately 10% is considered; such dynamics are interpreted as a manifestation of profound muscular fatigue associated with impaired control of the scapulothoracic articulation (scapular dyskinesis) and, consequently, with an increased probability of developing impingement syndrome [20]. Table 3 presents an interpretation of risk zones by the ACWR index in tennis.

Table 3. Interpretation of risk zones based on the ACWR index in tennis (compiled by the author based on [7])

ACWR range	Condition	Injury risk	Recommended action
< 0.8	Underload	Moderate	Gradual increase in volume
0.8 — 1.3	Sweet spot	Minimal	Maintain the training plan
1.3 — 1.5	Warning zone	Elevated	Monitor HRV and subjective RPE
> 1.5	Critical overload	High	Reduce intensity, focus on recovery

An integral interpretation of the dataset shows that for elite juniors aged 13–18 the critical values of the permissible workload ratio are lower than in adult athletes and approach a level of approximately 1.3. Such a shift of the risk threshold is associated with ongoing morphofunctional maturation of the musculoskeletal system and limited tissue tolerance to abrupt fluctuations in the volume and intensity of training exposure [7]. In the practice-oriented training models developed by the author, preventive protocols of this type are implemented by incorporating parameters obtained from wearable devices into individualized player development plans. This approach supports not only a reduction in injury probability, but also the controlled formation of peaks of functional readiness for priority starts, at the level of the tournament calendar of Wimbledon and the ITF Pro Circuit [13-16].

A significant limiter of the effectiveness of preventive strategies in professional sport remains compliance with recovery regimes and adherence to workload-monitoring regulations. Under these conditions, the importance of leadership and mentorship increases as mechanisms that ensure consistent adherence to protocols rather than episodic implementation of recommendations. In applied implementation, this logic unfolds through the concept of conscious athleticism, within which the athlete is positioned not as an object of measurements but as a subject of the management loop, involved in the collection, interpretation, and use of data.

Digital athlete-management systems can strengthen compliance with workload monitoring and recovery regimes by improving data visibility, accountability, and communication within the athlete–coach–medical team triad. When implemented responsibly, such tools may support earlier identification of fatigue-related technique degradation and facilitate timely adjustments in training exposure.

Gartner's prognostic assessments for 2025 indicate that the integration of edge computing and artificial intelligence algorithms into sports applications can reduce the processing time of biomechanical datasets by up to 70%, ensuring the formation of feedback in a mode close to real time [20]. In applied terms, this means the possibility of promptly identifying signs of fatigue of the kinematic chain directly during a match and subsequent tactical correction based on objective metrics. Below, Figure 2 presents a diagram of decision-making based on biomechanical monitoring data.

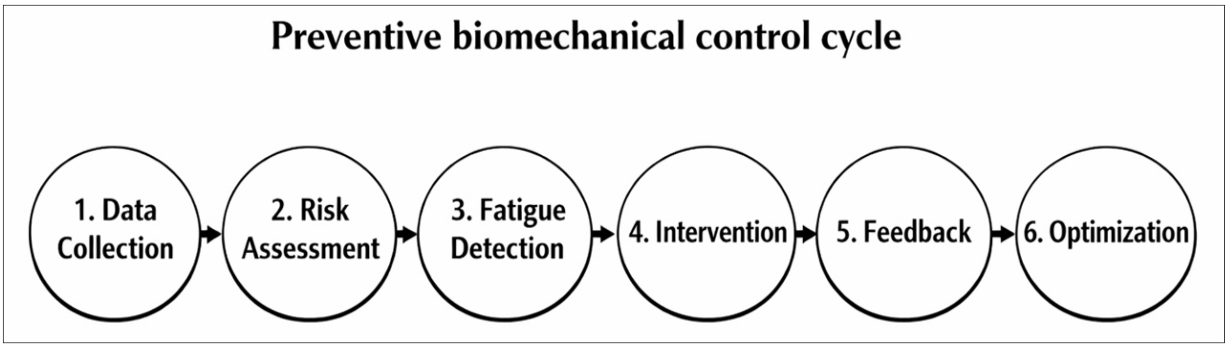

Fig. 2. Schematic representation of the load management cycle (compiled by the author based on [2, 20]).

Even with pronounced technological progress, the practical implementation of monitoring systems and workload-management approaches retains a number of substantial limitations. The primary barrier is financial cost, driven by the price of equipment and operational infrastructure, as well as the need for specialized sports-science personnel within the team who can ensure correct protocol configuration, sensor calibration, and interpretation of data arrays. An additional risk is the phenomenon of data overload, in which excessive concentration on digital metrics shifts the focus away from execution of the competitive task, provokes psychological strain, and may disrupt the stability of match rhythm [19].

Deloitte reports for 2025 emphasize that the determining factor of effectiveness is not the mere fact of registering indicators, but their meaningful interpretation with consideration of context and the human factor, including individual features of load response, the cognitive style of decision-making, and the level of compliance with recovery procedures [2]. Within this logic, leadership and mentoring programs acquire a system-forming role, since they ensure translation of abstract numerical indicators into operationalizable recommendations applicable in the training and competitive cycle. The author's synthesis of data additionally indicates that participation in structured mentorship is associated with a 26% reduction in the frequency of overload injuries, which is interpreted as a consequence of higher recovery discipline and stricter adherence to workload-monitoring regulations [7]. Figure 3 summarizes the key risk factors identified in the course of the study.

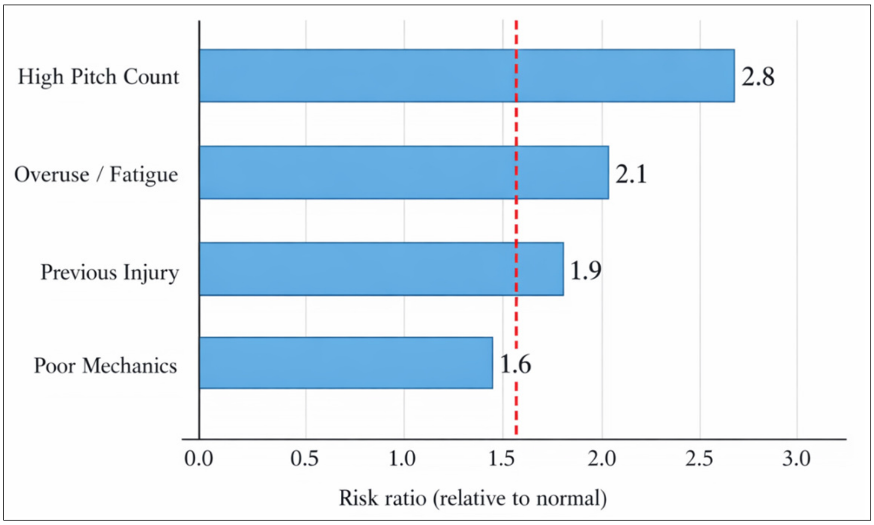

Fig. 3. Hierarchy of biomechanical and regulatory risk factors (compiled by the author based on [8]).

The presented data demonstrate that it is precisely abrupt, disproportionate increases in training and competitive exposure (Workload Spike) that constitute the strongest prognostic marker of injury, exceeding in predictive significance even the biomechanical predisposing factors traditionally considered, including a deficit of internal shoulder rotation (GIRD) [8]. This hierarchy of factors underscores the dominant role of workload dynamics as a triggering mechanism: in the presence of a vulnerable biomechanical background, it is the sudden increase in volume or intensity that creates the conditions for the transition of compensated functional deviations into a clinically manifest injury.

CONCLUSION

The analysis of the biomechanics of the tennis serve and the patterns of energy transfer along the kinematic chain allows the conclusion that the sporting longevity of an elite-level player in 2025 is determined by a combination of the technical soundness of the motor pattern and instrumentally confirmed digital workload control. The most significant unloading determinants are optimization of the contribution of the lower limbs and increased trunk stability, since proximal impulse generation is precisely what reduces the need for compensatory amplification of joint moments at the level of the shoulder and elbow complexes. With adequate organization of lower-limb and trunk action, a reduction of injury-hazardous torques on the order of 18–20% is achieved while maintaining competitive parameters of ball speed.

Under these conditions, monitoring of training and competitive exposure on the basis of the ACWR index and data from wearable inertial sensors (IMU) is formed as a normative component of the contemporary training system. At the same time, technological equipment is not a self-sufficient condition for prevention: the applied value of digital metrics is realized only when they are correctly interpreted and integrated into a coherent logic of the training process that includes psychoregulatory mechanisms and features of competitive activity. Accordingly, the role of the coach-leader and mentor increases, ensuring translation of measurable parameters into managerial decisions that sustain compliance with recovery protocols and prevent behavioral scenarios leading to overload.

The author's practical experience illustrates the applied potential of modern athlete-management ecosystems: digital tools can support structured workload control and communication, but their preventive value depends on correct interpretation and integration into the training process.

Prospects for further research are concentrated in the direction of high-speed infrastructures for data transmission and edge computing, including the use of 5G for rapid biomechanical analysis directly during television broadcasts. The implementation of such approaches creates prerequisites for forming thermal maps of workloads in a mode close to real time, expanding the toolkit of coaching staffs and medical services through earlier identification of signs of functional degradation of the kinematic chain and risky workload scenarios.

REFERENCES

1. van Trigt, B., Faneker, E., Leenen, A. J. R., Hoekstra, A. E., & Hoozemans, M. J. M. (2025). Uncovering the hidden mechanics of upper body rotations in tennis serves using wearable sensors on Dutch professional players. Frontiers in Sports and Active Living, 6, 1463299. https://doi.org/10.3389/fspor.2024.1463299 .
2. How is AI Used in Sports Management | MBA ESG. Retrieved from: https://mba-esg.in/ai-in-sports/ (2024).
3. Montalvan, B., Guillard V. (2024). Epidemiology of Musculoskeletal Injuries in Tennis Players During the French Open Grand Slam Tournament From 2011 to 2022, 12(4), 8. https://doi.org/10.1177/23259671241241551 .
4. Elliott, B., Fleisig, G., Nicholls, R., & Escamilla, R. (2003). Technique effects on upper limb loading in the tennis serve. Journal of Science and Medicine in Sport, 6(1), 76–87. https://doi.org/10.1016/S1440-2440(03)80011-7 .
5. Salim, F. A., Postma, D. B., Haider, F., Luz, S., Beijnum, B. J. F. V., & Reidsma, D. (2024). Enhancing volleyball training: empowering athletes and coaches through advanced sensing and analysis. Frontiers in sports and active living, 6, 1326807. https://doi.org/10.3389/fspor.2024.1326807.
6. Deng, N., Soh, K. G., Xu, F., & Yang, X. (2025). The effects of strength and conditioning interventions on serve speed in tennis players: A systematic review and meta-analysis. Frontiers in Physiology, 15, 1469965. https://doi.org/10.3389/fphys.2024.1469965 .
7. Porter, R.R., Roach, K., Raya, M. (2022). Age and Gender Differences in Injuries and Risk Factors in Elite Junior and Professional Tennis Players, 14(4), 466–477. https://doi.org/10.1177/19417381211062834 .
8. Rice, R. P., Roach, K., Kirk-Sanchez, N., Waltz, B., Ellenbecker, T. S., Jayanthi, N., & Raya, M. (2022). Age and gender differences in injuries and risk factors in elite junior and professional tennis players. Sports health, 14(4), 466-477. https://doi.org/10.1177/19417381211062834 .
9. Mayrhuber, L., Rietveld, T., de Vries, W., van der Woude, L. H., de Groot, S., & Vegter, R. J. (2022). A scoping review on shoulder injuries of wheelchair tennis players: potential risk-factors and musculoskeletal adaptations. Frontiers in rehabilitation sciences, 3, 862233.
10. 2024 Sports Industry Outlook | Deloitte US. Retrieved from: https://www.deloitte.com/us/en/Industries/tmt/articles/sports-business-trends-disruption.html .
11. The Decade of Resilience - Gaming & Leisure. Retrieved from: https://mygamingandleisure.com/the-decade-of-resilience/ (2025).
12. SERGEY DANILOV, NYFA-LI HEAD COACH | NEW YORK .... Retrieved from: https://fencenyfa.com/coaches/sergey-danilov-epee-coach/.
13. Sergey Danilov - Fencing Coach - St. John's University Athletics. Retrieved from: https://redstormsports.com/sports/fencing/roster/coaches/sergey--danilov/862
14. Whiteside, D., Elliott, B., Lay, B., & Reid, M. (2013). A kinematic comparison of successful and unsuccessful tennis serves across the elite development pathway. Human Movement Science, 32(4), 797–807. https://doi.org/10.1016/j.humov.2013.06.003 .
15. Elliott, B. (2006). Biomechanics and tennis. British Journal of Sports Medicine, 40(5), 392–396. https://doi.org/10.1136/bjsm.2005.023150 .

16. Vacek, J., Vagner, M., Maleček, J., & Šťastný, P. (2025). Tennis serve speed in relation to isokinetic shoulder strength, height, and segmental body mass in junior players. Journal of Functional Morphology and Kinesiology, 10(1), 57. https://doi.org/10.3390/jfmk10010057 .

17. Wood, D. H. X. (2024). A novel mechanical examination of the tennis serve using expert qualitative analysis and machine learning (Doctoral thesis, The University of Western Australia). Retrieved from: https://api.research-repository.uwa.edu.au/ws/portalfiles/portal/486222552/THESIS_-_DOCTOR_OF_PHILOSOPHY_-_WOOD_Dylan_Harrison_Xavier_-_2024.pdf .

18. Ekstrand, J., Bengtsson, H., Waldén, M., Davison, M., Khan, K. M., & Hägglund, M. (2023). Hamstring injury rates have increased during recent seasons and now constitute 24% of all injuries in men's professional football: the UEFA Elite Club Injury Study from 2001/02 to 2021/22. British journal of sports medicine, 57(5), 292-298.

19. FROM DATA TO DECISIONS: SAFEGUARDING ATHLETES IN THE AGE OF AI | Scholarship Commons. Retrieved from: https://scholarship.law.slu.edu/cgi/viewcontent.cgi?article=1128&context=lawjournalonline .

20. Data Analytics in Sports: Use-Cases, Examples, and Costs | Appinventiv. Retrieved from: https://appinventiv.com/blog/data-analytics-in-sports-industry/ .