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Tennis Serve Biomechanics in Relation to Ball Velocity and Upper Limb Joint Injuries

Introduction

In the professional male game, the serve has been reported to be the most important stroke.[1] From a strategy and tactics perspective, the main keys to a successful serve are velocity, spin and placement. Statistics from the 2009 US Open show that for the men's draw, 5 of the top 10 ranked players also had the highest serve speed.[2] Indeed, the ability for tennis players to produce high ball velocity during the serve is a crucial element of a successful play because it puts the opponent under stress and may hinder its return. Consequently, if you ask tennis coaches *"what their main priorities when teaching tennis serve are"*, their responses could be "improving performance, especially ball velocity" but also "preventing injury". Indeed, epidemiological studies have associated the serve with overuse injuries in the upper limb joints,[3,4,5] which are a common medical problem in all competitive levels in tennis.[6,7] The purpose of this review is to assimilate all the available scientific research on tennis serve biomechanics related to ball velocity and upper limb joint injuries.

Ball Velocity and Tennis Serve Kinematics

In tennis, the serve is a sequence of motions referred to as a 'kinetic chain'[8] that begins with the lower limb action and is followed by the trunk and the upper limb. Fleisig et al.[9] have shown that tennis players produce a rapid sequence of segment rotations (Table 1). The order of maximal angular velocities is trunk tilt (280°/s), upper torso longitudinal rotation (870°/s), pelvis rotation (440°/s), elbow extension (1510°/s), wrist flexion (1950°/s), and shoulder internal rotation (2420°/s).[9] These joint and segmental rotation contributions to racket velocity in the serve are of great interest in the literature.[10,11,12,13] The major contributors to the mean linear velocity of the racquet at impact are internal rotation of the shoulder, flexion of the hand, horizontal flexion and abduction of the shoulder and trunk flexion (see Table 2).

Table 1

Peak values of joint rotations during the tennis serve

Studies	Knee extension (°/s)	Pelvis rotation (°/s)	Shoulder rotation (°/s)	Shoulder Internal rotation (°/s)	Elbow Extension (°/s)	Wrist Flexion (°/s)
Elliot et al [10]	/	/	/	2090 ± 330	1230 ± 180	1720 ± 580
Fleisig et al [9]	800 ± 400	440 ± 90	870 ± 120	2420 ± 590	1510 ± 310	1950 ± 510
Reid et al [14]	533 ± 69	/	/	/	/	/
Wagner et al [15]	/	510 ± 110	/	5580 ± 2350	1670 ± 380	/

Table 2

Segment contributions to linear racket velocity in the tennis serve

Studies	Elliot et al [10]	Sprigings et al [12]	Tanabe et al [13]
Number of players	11	1	66
Trunk flexion	9.7 ± 1.8	7.4	/
Shoulder internal rotation	54.2 ± 4.1	30	41.1 ± 14.7
Shoulder horizontal flexion and abduction	12.9 ± 5.9	24	6.4 ± 11.7
Elbow extension	-14.2 ± 6.4	/	3.2 ± 6.0
Elbow pronation	5.2 ± 4.1	15	3.6 ± 5.0
Wrist flexion	30.6 ± 9.1	26	31.7 ± 7.5
Wrist ulnar deviation	0.6 ± 1.2	/	0.8 ± 5.9

The proficiency of these rotations through the kinetic chain involves a transfer of linear and angular momentum from the legs to the trunk and then to the arm and the racket.[16] Although the concept of angular momentum transfer is frequently reported to be critical in producing explosive serves, [8,14,17,18,19,20,21,22] few studies have studied angular momentum during the tennis serve.[11,16,23] Only Bahamonde [16] has described, quantified and explained the evolution of angular momentum during the tennis serve about the three orthogonal axes (transverse or "cartwheel", anteroposterior or "shoulder-over-shoulder", longitudinal or "twist") in five collegiate tennis players. It has been reported that most of the clockwise angular momentum about the transverse axis is concentrated in the trunk and the racket-arm. The angular momentum about the longitudinal axis of rotation is small and lacked a consistent pattern. Moreover, Bahamonde [16] has noticed that the difference between the players with the highest ball speeds (51.0, 46.3 and 50.4 m/s) and the players with the lowest ball speeds (39.8 and 43.9 m/s) is the contribution of the trunk to the total anteroposterior axis angular momentum. A recent study has identified the relationships between segmental angular momentum and ball velocity in professional players. The results of this study indicate that from maximal elbow flexion to ball impact, the players with the highest values of trunk and racket-arm angular momentums about the transverse axis are those with the highest ball velocity. As a consequence, it seems that the ability of a player to produce high upper body segmental angular momentum values about the transverse axis during the serve increases ball velocity. For the cocking, and acceleration phases of the serve, there were significant correlations between the trunk angular momentum values about the anteroposterior axis and ball velocity. In other words, the more the players produce trunk angular momentum about the anteroposterior axis between maximal elbow flexion and ball impact, the higher the ball velocity will be. These strong relationships confirm the results of Bahamonde [16] suggesting that the rotation of the trunk about the anteroposterior axis (also called "shoulder over shoulder" rotation) differentiates players with the highest ball speeds from players with the lowest ball speeds.

Ball Velocity and Tennis Serve Kinetics

Elliott et al. [24] have demonstrated that male professional players commonly recorded higher torques and forces at the shoulder and elbow joints than their female counterparts. According to them, these higher kinetic measures are an important factor in producing the significantly higher serve velocity for this group of players. Davis et al. [24] have proposed efficiency measurements for the baseball pitch about the relationship between ball velocity and kinetics.[25] They divided joint loadings by ball velocity in order to better understand the pitcher's efficiency. Indeed, a highly efficient pitcher or server is one who can maximize output (ball velocity) with the least joint load.[26] Martin et al. [27] shown that advanced tennis players are less "efficient" than professional ones since they increase both their shoulder and elbow kinetics compared to professional players without reaching higher ball velocity. It is assumed that the low efficiency measured in advanced players could be related to improper mechanics of the kinetic chain. It has been indicated that any disruption to the kinetic chain caused by improper mechanics could result in increased loading of upper limb joints in the sequence of movements.[28] As a consequence, it can be supposed that advanced players tried to compensate for the kinetic chain disruption caused by improper serve mechanics by increasing segment activation and loading. [29]

Upper Limb Joint Injuries and Tennis Serve Biomechanics

Overuse injuries in sport can result from a complex interaction between various risk factors such as age, gender, muscle weakness and imbalance, poor equipment, number of repetitions during trainings and competitions, and excessive joint loadings.[30] Among all the risk factors in overhand throwing and striking activities, excessive joint loadings (forces and torques) are known to be a crucial risk factor causing repetitive microtrauma that are responsible for overuse upper limb joint injuries. [28,29,30,31] Indeed, it appears logical that players subjected to higher loadings might be more likely to sustain joint overuse injury.[32] Concerning tennis, the serve has been reported to be a traumatic skill, as it causes high loads on the shoulder and elbow joints in professional tennis players,[24,32] almost identical to those reported for baseball pitchers (Table 3).[33]

The traumatic effect of the tennis activity is also linked to the repetitive nature of the serve movement throughout the player's competitive career. Interestingly, tennis players hit between 50 and 150 serves during a match. This result is increased by the number of single matches played by the players during a competitive season (around

Table 3

Peak values of joint kinetics measured for the tennis serve and the baseball pitching

Study	Population	Shoulder internal rotation torque (N/m)	Shoulder horizontal adduction torque (N/m)	Elbow varus torque (N/m)	Elbow flexion torque (N/m)	Shoulder proximal force (N)
Elliot et al (24)	8 professional tennis players	71 ± 15	108 ± 25	78 ± 12	37 ± 23	608 ± 110
Reid et al (32)	12 elite tennis players	23 ± 8	/	/	/	229 ± 52
Fleisig et al (43)	60 professional baseball players	68 ± 15	109 ± 85	64 ± 15	58 ± 13	1070 ± 190
Fleisig et al (33)	26 elite baseball players	67 ± 11	100 ± 20	64 ± 12	61 ± 11	660 ± 110

60 matches), without considering double matches and training sessions.[14] This repetition of serves inflicted on the upper limb joints in competitive tennis players may explain why overuse injuries of the upper limb joints are a common medical problem in all competitive levels in tennis.[4,34,35,36] Indeed, these overuse injuries concern not only professional tennis players but also recreational and advanced competitive players.[6,7,35] Tennis is a world-class competitive sport attracting tens of millions of players all around the world, and the majority of them is presumed to be recreational or advanced rather than elite. Consequently, Martin et al.[27] have compared the joint kinetics and stroke production efficiency for the shoulder, elbow, and wrist during the serve between professionals and advanced tennis players. Peaks of shoulder inferior force, shoulder anterior force, shoulder horizontal abduction torque, and elbow medial force are significantly higher in advanced players.[27] Ball velocity is significantly faster for the professional players (177.8 ±17.3 km/h) compared to the advanced players (143.3 ± 14.4 km/h).[27] Consequently, professional players are more efficient than advanced players, as they maximize ball velocity with lower or similar joint kinetics. Since advanced players are subjected to higher joint kinetics, the results suggest that they appear more susceptible to high risk of shoulder and elbow injuries than professionals, especially during the cocking and deceleration phases of the serve.
According to Fortenbaugh, changes in kinematics can increase or decrease velocity or not affect it at all.[37] Clearly, any kinematic pattern that significantly increases kinetics values without increasing velocity is pathomechanical. Indeed, even minor technical and temporal errors, which are continually repeated throughout a match, a competitive season, or a career, may affect the performance, increase joint kinetics, and consequently cause tendon overuse microinstability problems.[30,38] Conversely, it has been suggested that proper temporal mechanics may enable athletes to achieve maximum performance with minimum chances of injury. Concerning the tennis serve, it has been reported that a poor leg drive decreases ball velocity [19] and increases shoulder and elbow kinetics during the tennis serve (+15 % for the peak of shoulder internal rotation torque and +18 % for the peak of elbow varus moment).[24] Moreover, Elliott et al. [24] shown that the type of backswing influences shoulder anterior force. Indeed, higher normalized anterior force at the shoulder joint was noticed for those players with an abbreviated swing compared with those players who used a full backswing (+ 34 %). In baseball, it is believed that the safest and most efficient pitching depends on the correct timing and sequence of motions as much as the quality of the motions themselves.[25] In such a sequence of motions, the timing of trunk and shoulder rotations seems to be crucial because the trunk and the shoulder are links that considerably contribute to the body angular momentum and can affect tennis performance.[23,39] Consequently, research has focused on the effects of trunk rotation timing on upper limb joint kinetics during the tennis serve. [40] The purposes of this study were to measure the effects of temporal parameters on both ball velocity and upper limb joint kinetics to identify pathomechanical factors during the tennis serve and to validate these pathomechanical factors by comparing upper limb joint injured and non-injured players. The later timing of peak trunk angular velocities and the improper timing between the shoulder horizontal adduction and the external

rotation are indeed associated to higher upper limb joint kinetics and lower ball velocity.[40] Non-injured players are able to maximize ball velocity and reduce upper limb joint kinetics by rotating their trunk at maximal velocities earlier than injured players, allowing the energy to pass from the trunk to the shoulder at precisely the right timing within the correct sequence of movements. Moreover, during the cocking and acceleration phases of the tennis serve, the arm moves from horizontal abduction to adduction and to extreme angles of external rotation. The correlation analyses show that the more the instant of shoulder external rotation precedes the instant of shoulder horizontal adduction, the more the shoulder anterior force ($r=0.40$, $p<0.001$) and horizontal abduction torque increase ($r=0.40$, $p<0.001$) and the more the ball velocity decreases ($r = -0.26$, $p<0.05$).[40] According to the results, non-injured players are more effective because they achieve shoulder horizontal adduction just before extreme positions of external rotation. As a consequence, they are able to maximize ball velocity and limit upper limb joint loadings by using proper temporal parameters during the serve. Conversely, injured players "leave" their arm in horizontal abduction for too long during the shoulder external rotation phase. Consequently, injured players reach significantly lower ball velocities, and demonstrated higher joint kinetics.[40] Excessive shoulder horizontal abduction that occurs during the late cocking phase of the throwing motion has been reported to be critical for internal impingement[41] caused by a translation of the humeral head relative to the glenoid,[42] which may lead to rotator cuff tears, shoulder tendinopathies, and labral lesions.

Conflicts of Interest: none declared.

References

1. Johnson CD, McHugh MP, Wood T, Kibler B. Performance demands of professional male tennis players. *Br J Sports Med* 2006;40:696–699.
2. Roetert P, Kovacs M. Tennis anatomy. Champaign: Human Kinetics, 2011.
3. Carroll R. Tennis elbow: incidence in local league players. *Br J Sports Med* 1981;15:250–256.
4. Hjelm N, Werner S, Renstrom P. Injury risk factors in junior tennis players: a prospective 2-year study. *Scand J Med Sci Sports* 2012;22(1):40–8.
5. Priest JD, Nagel DA. Tennis shoulder. *Am J Sports Med* 1976;4:28–42.
6. Jayanthi N, Sallay PI, Hunker P, Przybylski M. Skill-level related injuries in recreational competition tennis players. *J Med Sci Tennis* 2005;10:12–5.
7. Pluim BM, Staal JB, Windler GE, Jayanthi N. Tennis injuries: occurrence, aetiology, and prevention. *Br J Sports Med* 2006;40:415–23
8. Elliott B. Developing racquet velocity. In: Elliott B, Reid M, and Crespo M, (editors).*Biomechanics of advanced tennis*. London: ITF Ltd, 2003.
9. Fleisig G, Nicholls R, Elliott B, Escamilla R. Kinematics used by world class tennis players to produce high-velocity serves. *Sports Biomech* 2003; 2:51–64.
10. Elliott B, Marshall R, Noffal G. Contributions of upper limb segment rotations during the power serve in tennis. *J Appl Biomech* 1995;11:433–442.
11. Gordon BJ, Dapena J. Contributions of joint rotations to racquet speed in the tennis serve. *J Sports Sci* 2006;24:31–49.
12. Sprigings E, Marshall R, Elliott B, Jennings L. A three dimensional kinematic method for determining the effectiveness of arm segment rotations in producing racket-head speed. *J Biomech* 1994;27:245–254.

13. Tanabe S, Ito A. A three dimensional analysis of the contributions of upper limb joint movements to horizontal racket head velocity at ball impact during tennis serving. *Sports Biomech* 2007;6:418–433.

14. Reid M, Elliott B, Alderson J. Lower-limb coordination and shoulder joint mechanics in the tennis serve. *Br J Sports Med* 2008;40:308-315.

15. Wagner H, Pfusterschmied J, Tilp M, Landlinger J, von Duvillard SP, Müller E. Upper body kinematics in team-handball throw, tennis serve, and volleyball spike. *Scand J Med Sci Sports* 2012 Jul 19. doi: 10.1111/j.1600-0838.2012.01503.x. [Epub ahead of print]

16. Bahamonde R. Changes in angular momentum during the tennis serve. *J Sports Sci* 2000;18:579–592.

17. Chow JW, Park SA, Tillman MD. Lower trunk kinematics and muscle activity during different types of tennis serves. *Sports Med Arthrosc Rehabil Ther Technol* 2009;1:1–24.

18. Elliott B. Biomechanics and tennis. *Br J Sports Med* 2006;40:392–396.

19. Girard O, Micallef JP, Millet G. Influence of restricted knee motion during the flat first serve in tennis. *J Strength Cond Res* 2007;21:950–7.

20. Girard O, Micallef JP, Millet G. Lower-limb activity during the power serve in tennis: Effects of performance level. *Med Sci Sports Exer* 2005;37:1021–1029.

21. Groppel JL. *High tech tennis*. Champaign, IL: Leisure Press, 1992.

22. Knudson D. Qualitative biomechanical principles for application in coaching. *Sports Biomech* 2007;6:109–118.

23. Martin C, Bideau B, Nicolas G, Delamarche P, Kulpa R. How does the tennis serve influence the serve-and-volley? *J Sports Sci* 2012;30:1149–1156.

24. Elliott B, Fleisig G, Nicholls R, Escamilia R. Technique effects on upper limb loading in the tennis serve. *J Sci Med Sport* 2003;6:76–87.

25. Davis JT, Limpisvasti O, Fluhme D, et al. The effect of pitching biomechanics on the upper extremity in youth and adolescent baseball pitchers. *Am J Sports Med* 2009;37:1484–91.

26. Aguinaldo AL, Chambers H. Correlation of throwing mechanics with elbow valgus load in adult baseball pitchers. *Am J Sports Med* 2009;37:2043–2048.

27. Martin C, Bideau B, Ropars M, Delamarche P, Kulpa R. Upper limb joint kinetic analysis during tennis serve: Assessment of competitive level on efficiency and injury risks. *Scan J Med Sci Sports* 2013 Jan 7. doi: 10.1111/sms.12043. [Epub ahead of print]

28. Kibler WB. Biomechanical analysis of the shoulder during tennis activities. *Clin Sports Med* 1995;14:79–85

29. Lintner D, Noonan TJ, Kibler WB. Injury patterns and biomechanics of the athlete's shoulder. *Clin Sports Med* 2008;27:527–551.

30. Kannus P. Etiology and pathophysiology of chronic tendon disorders in sports. *Scand J Med Sci Sports* 1997;7:78–85.

31. Anderson MW, Alford BA. Overhand throwing injuries of the shoulder and elbow. *Radiol Clin North Am* 2010;48:1137–1154.

32. Reid M, Elliott B, Alderson J. Shoulder joint loading in the high performance flat and kick tennis serves. *Br J Sports Med* 2007:41:884–889

33. Fleisig GS, Andrews JR, Dillman CJ, Escamilla RF. Kinetics of baseball pitching with implications about injury mechanisms. *Am J Sports Med* 1995;23:233–239.

34. Marx RG, Sperling JW, Cordasco FA. Overuse injuries of the upper extremity in tennis players. *Clin Sports Med* 2001;20:439–451.

35. Abrams GD, Renstrom PA, Safran MR. Epidemiology of musculoskeletal injury in the tennis player. *Br J Sports Med* 2012;46:492–498.

36. Ellenbecker TS, Roetert EP, Safran M. Shoulder injuries in tennis. In: Wilk KE, Reinold MM, Andrews JR, eds. *The athlete shoulder*. Philadelphia, PA: Churchill Lingstone Elsevier, 2009:429–444.

37. Fortenbaugh D, Fleisig GS, Andrews JR. Baseball pitching biomechanics in relation to injury risk and performance. *Sports Health* 2009;1:314–320.

38. Kibler WB, Thomas SJ. Pathomechanics of the throwing shoulder. *Sports Med Arthrosc* 2012;20:22–9.

39. Martin C, Kulpa R, Delamarche P, Bideau B. Professional tennis players' serve: correlation between segmental angular momentums and ball velocity. *Sports Biomech* 2013;12:2-14

40. Martin C, Kulpa R, Ropars M, Delamarche P, Bideau B. Identification of temporal pathomechanical factors during the tennis serve. *Med Sci Sports Exerc* 2013;45(11):2113-9.

41. 41. Mihata T, McGarry MH, Kinoshita M, Lee TQ. Excessive glenohumeral horizontal abduction as occurs during the late cocking phase of the throwing motion can be critical for internal impingement. *Am J Sports Med* 2010;38:369–74.

42. Burkhart SS, Morgan CD, Kibler WB. The disabled throwing shoulder: spectrum of pathology. Part I: pathoanatomy and biomechanics. *Arthroscopy* 2003;19:404–20.

43. Fleisig GS, Barrentine SW, Zheng N, Escamilla RF, Andrews JR. Kinematic and kinetic comparison of baseball pitching among various levels of development. *J Biomech* 1999;32:1371–1375.

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