THE USE OF BIOMECHANICAL ANALYSIS TO HELP REDUCE SERVE RELATED INJURIES

– Written by Caroline Martin, Pierre Touzard, and Loïc Fourel, France

INTRODUCTION

Over the last thirty years the serve has become the most important stroke for tennis performance. Directionality, accuracy and speed are key elements of a successful serve, putting the opponent under time pressure and hampering their return. However, the serve is also the most difficult, complex and physically demanding stroke in tennis, with high muscular activity and joint loads in the trunk, the lower back, the shoulder and the elbow that can cause injuries[1].

Epidemiological data generally shows a preponderance of acute injuries to the lower limbs while chronic injuries mainly affect the upper limbs[2]. Specifically, the serve has been associated with muscular strains to the abdominal muscles and with overuse injuries to the lower back, the shoulder and the elbow[3,4]. In US national collegiate male tennis players[4], the serve is the most traumatic shot. It is involved in twice as many injuries as the forehand and backhand. Injuries in tennis can result from a complex interaction between various risk factors such as skill level, age, previous injury, muscle weakness and imbalance, racket properties, number of repetitions during trainings and competitions or biomechanical factors[5].

BIOMECHANICS OF THE TENNIS SERVE

The tennis serve biomechanics are described as the coordination of body segments in a specific and difficult sequence to master, called the kinetic chain[1]. It initiates from the lower limbs, storing energy from the ground and later transferring it to the hips, the trunk and the serving arm to produce optimal racquet trajectory and velocity upon impact with the ball. In biomechanics, the serve is divided into five phases in order to better understand this kinematic chain and its influence on injury risk; the preparation phase between the start of the serve and the ball toss, the cocking phase between the ball toss and the maximum external shoulder rotation, the acceleration phase between the maximum external shoulder rotation and the ball-impact, the deceleration phase between ball impact and the maximum internal shoulder rotation, and the follow-through phase between the maximum internal shoulder rotation and the end of the serve. Figure 1 illustrates the 5 phases of serving.

In the preparation phase, the player's activity can be summed up as controlled muscular work, during which most joints perform movements with amplitudes that can be described as "normal or physiological", since they are not extreme. As a result, the risk of injury is very low.

The other phases of the tennis serve have a more ballistic nature due to the higher joint velocities involved. As a result, they are potentially traumatic.

During the cocking phase, players move the racquet away from the body to generate speed and power by combining abduction with external rotation of the shoulder and lumbar spine hyperextension[3]. At the

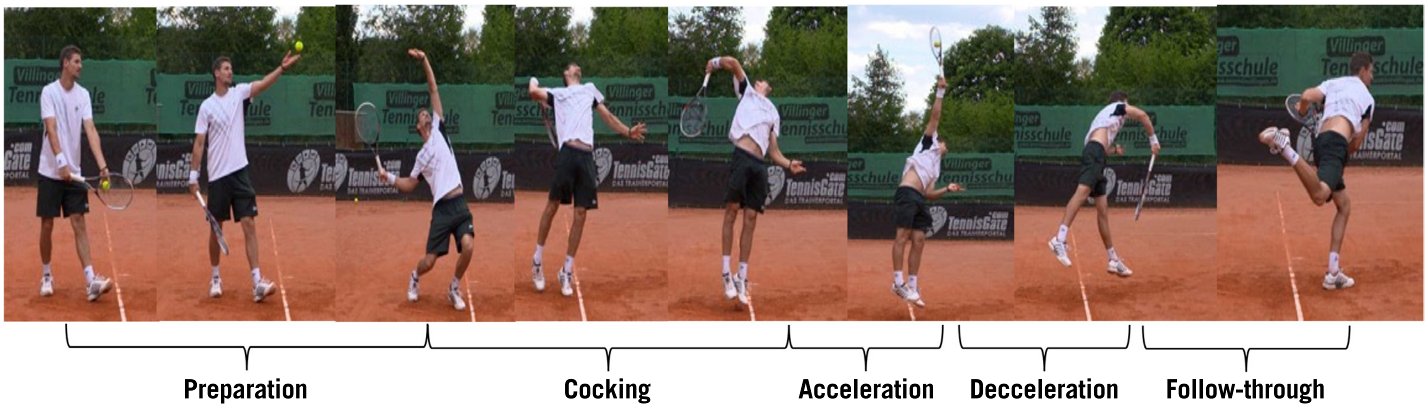


Figure 1: The different phases of the serve.

end of the cocking phase, the abdominal muscles are maximally stretched, storing elastic energy. The lumbar region sustains substantial loads, including lateral flexion forces approximately 8 times those experienced during running[6]. Moreover, the anterior capsule and ligaments of the glenohumeral joint, as well as those of the elbow joint, are stretched close to their physiological limits: the shoulder joint is externally rotated around 172°, abducted around 90 - 100° and horizontally adducted around 7°[7]. Theoretically, this arm position optimizes congruence of articular and bony surfaces and therefore confers maximum stability to the shoulder joint in static position. However, the dynamic nature of the tennis serve compromises the joint stability at the end of the cocking phase and considerably increases the risk of injury. Then, the acceleration phase marks the release of mechanical energy towards the racket, accelerating the rotations of the trunk and the upper limb segments and joints. As a result, professional tennis players experience particularly high joint loads (forces and torques) in the shoulder and elbow during the cocking and acceleration phases of the tennis serve[8]. Finally, the deceleration phase also presents a high risk of injury, as mechanical energy needs to be absorbed and segments and joints need to slow down on a very short timescale.

PATHOMECHANICAL FACTORS RELATED TO THE TENNIS SERVE

The use of inefficient serve techniques is an additional risk factor for injury. Any technical element that significantly increases the constraints (forces and moments) at the joints without increasing ball speed is considered "pathomechanical"[9]. For example, a deficit in leg action (flexion and extension) can significantly reduce ball speed[10], induce abdominal overwork[11] and increase maximum joint loads at the shoulder and elbow (+15% for internal rotation torque at the shoulder and +18% for varus torque at the elbow)[12]. Additionally, when tennis players horizontally abduct their arm for too long during the shoulder external rotation phase[9], shoulder loads increase and ball velocity decreases. This pathomechanical motion can cause rotator cuff impingement, as it can lead to translation of the humeral head in relation to the glenoidal cavity. Finally, increased wrist extension and reduced shoulder abduction during the late cocking phase can induce what is commonly known as the waiter's serve position (i.e racket face parallel to the ground during the backswing), which results in increased shoulder and elbow maximal joint loads[13].

BIOMECHANICAL ANALYSIS AND INJURY PREVENTION

While musculoskeletal screening may be a useful baseline test to help identify potential problems, there is also a need for more functional testing such as 3D kinematic analysis[14]. For example the 2022 Bern consensus statement on shoulder injury, prevention and rehabilitation[15] encourages identification of inadequate movement strategies wherever they occur along the length of the kinetic chain to improve sport-specific biomechanics/technique, but also to better prevent injury or improve the quality of rehabilitation. Biomechanical analysis can be used to estimate joint loads and identify pathomechanical factors. Consequently, it is used by scientists to better understand the etiology of serve-related tennis injuries. Increasingly, tennis players and their teams are turning to biomechanical analysis for individual screening, to help optimize performance as well as reduce injury risk.

As a result, top-level tennis players, national tennis federations and tennis academies are increasingly turning to biomechanical evaluation tests (such as those carried out by the M2S laboratory in Rennes 2 University) to optimize their serve motion through individualized analysis. Based on our last 10 years of research on tennis biomechanics we have gained a better understanding of the determinants of performance and injury risk factors, and most of the injuries we meet are shoulder and elbow tendinopathies, muscular strains in the abdominal area, and lower back injuries.

BIOMECHANICAL ANALYSIS OF SERVE USING A CASE STUDY

A 16-year-old female, right-handed competitive tennis player, usually practicing tennis five times per week, suffered from a stress response in the right L5 pars, confirmed by an MRI exam. Two years earlier, she already had a history of a stress fracture in the right L5 pars region. After diagnosis, her medical team prescribed six weeks of rest which resolved the pain. She then resumed low-intensity physical activity (walking, cycling, pilates) and followed a graduated muscle strengthening program with a fitness coach to improve her core strength. Twelve weeks after the injury, she made a staged return to tennis, without hitting a single serve. She was then allowed to serve again at progressively increasing

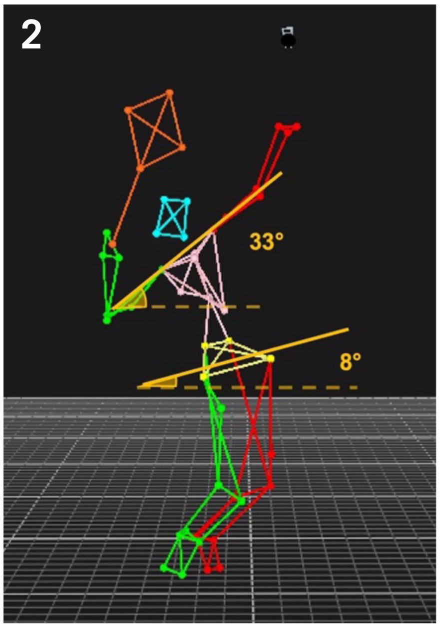


Figure 2: Angles of upper trunk and pelvis lateral flexion during the cocking phase at the instant of trophy position.

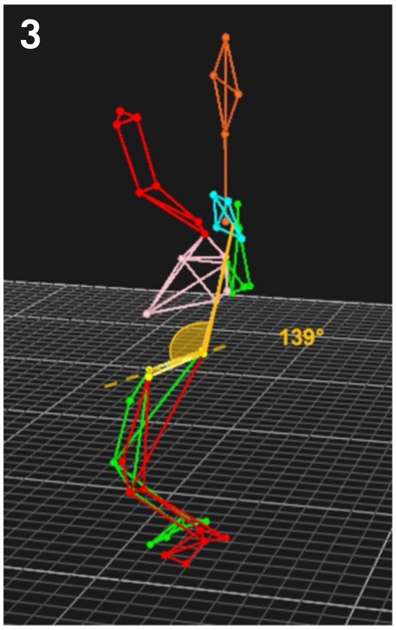


Figure 3: Trunk extension angle during the cocking phase.

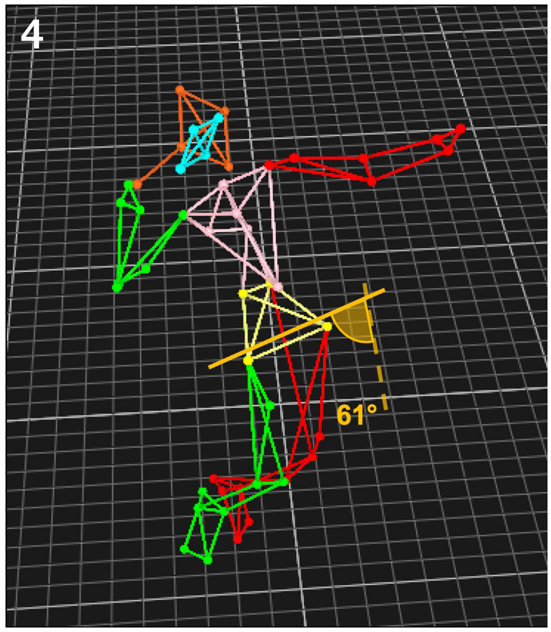


Figure 4: Angle between the pelvis and the baseline in the transverse plane during the cocking phase.

intensity. Unfortunately, the pain in her right lower back returned with serving. Her team thought that her lower back problems might be linked to incorrect tennis serve biomechanics. As a consequence, they scheduled a biomechanical analysis test of her serve.

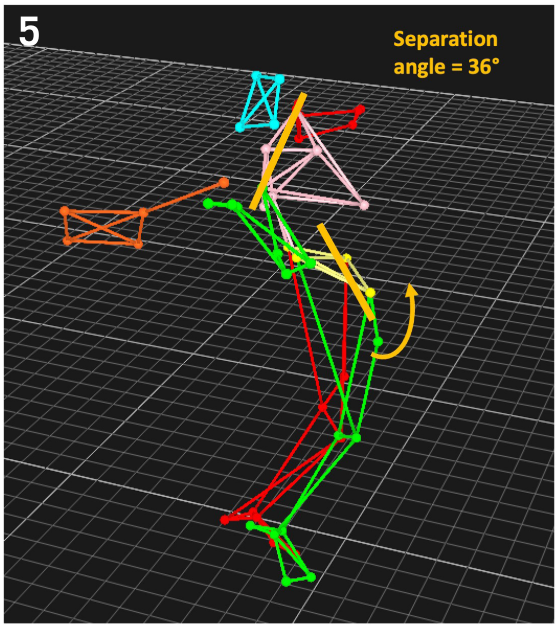
TESTING PROCEDURE

The test took place on an indoor tennis court. The player was equipped with 38 retroreflective markers placed on anatomical landmarks determined in agreement with previously published data[9]. Five additional landmarks were positioned on her racket. She wore a bra and a tight shorts to limit movement of the markers. She used her own racket during motion capture to ensure she felt as comfortable as possible during her serves. Before the test, she had as much time as needed to familiarize herself with the testing environment and the landmarks set. After a warm-up of 20 min (stretching and low intensity serves), she performed five successful “flat” serves from the right service court to a 1m x 1.50-m target area bordering the T of the “deuce” service box. She was asked to serve with her usual foot-up stance technique, bringing the back foot close to the front foot before pushing against the ground. A 30-s rest period was allowed between serve trials. A motion capture system with 23 cameras sampling at 300 Hz (Oqus, Qualisys AB., Göteborg, Sweden) was used to record the trajectories of the three-dimensional anatomical landmarks. Postimpact ball speed was measured for each trial by use of a radar (Stalker Professional Sports Radar) fixed on a 2.5-m height tripod placed 2 m behind the player in the direction of the serve.

BIOMECHANICAL VARIABLES MEASURED

According to scientific literature two main mechanisms are considered as risk factors for pars stress fracture injuries in tennis[16]: compression forces related to excessive trunk rotations or traction forces exerted by lumbar muscles to compensate for an inefficient leg action. When the lumbar spine extends, tilts and rotates longitudinally during the serve, the inferior articular process of the cranial vertebra may impact the pars interarticularis of the caudal vertebra, a compressive mechanism known as “nutcracker”. These repetitive compressive impacts can produce a stress or fatigue fracture of the pars interarticularis. The second mechanism is that the pars interarticularis fails in tension through a traction mechanism caused by the contraction of the muscles[16]. To differentiate from these two potential mechanisms given the serve technique of this player and her injury, we measured various kinematic parameters that have been previously linked to lower back injuries during the serve:

- the angles of upper trunk and pelvis lateral flexion during the cocking phase at the instant of trophy position (Figure 2). For right-handed players, excessive lateral trunk tilt to the right during the trophy position of the tennis serve can cause compressive load in the right lumbar region[6].
- the maximal angle of trunk extension during the cocking phase (Figure 3). Trunk hyperextension during the tennis serve is associated with a high rate of lower back radiological abnormalities in tennis players[17].
- the angle between the pelvis and the baseline in the transverse plane during the cocking phase (Figure 4). Campbell et al. (2014) showed that players with lower back pain demonstrated more pelvis rotation towards the net in the horizontal plane than players without lower back pain during the tennis serve[6]. Moreover, players with lumbar spine abnormalities tended to initiate their pelvis rotation towards the net earlier than players without spine abnormalities during the serve[18].
- the maximal separation angle between the shoulders and the hips in the transverse plane during the cocking phase (Figure 5). This angle between



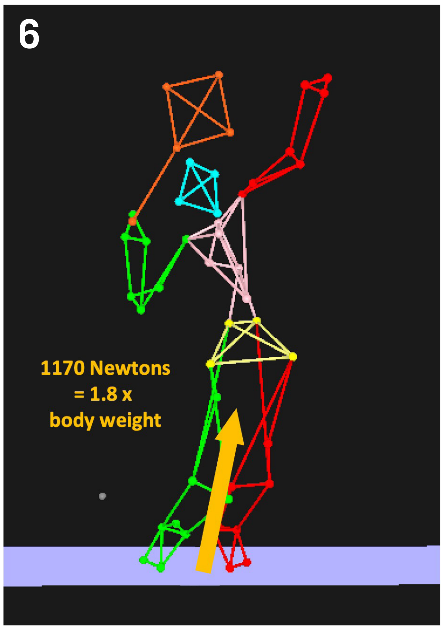


Figure 5: Maximal separation angle between the shoulders and the hips during the cocking phase.

Figure 6: Maximal ground reaction forces produced during the leg drive.

the shoulders and the hips can predict and/or differentiate between players with and without a history of lower back pain in other sporting populations, including cricket fast bowlers[19].

- the maximal vertical ground reaction forces (GRF) and power produced by the leg drive (Figure 6). According to Kibler[20], an inefficient leg drive characterized by a low value of maximal vertical GRF during the serve would force the player to produce a "pull" mechanism, in which the trunk and arm muscles, respectively, tow and pull the lower back and the back hip upwards and the dominant arm and the racket towards the hitting zone. On the contrary, a "push" serve mechanism is characterized by high maximal vertical GRF and a powerful leg extension enabling the player to lift off well above the ground to hit the ball as high as possible, while limiting the pulling actions on the lower back, the back hip, the trunk and the arm.

BIOMECHANICAL RESULTS AND RECOMMENDATIONS

Concerning performance indicators, the player hit the ball at mean speed of 129.4 km/h at a height corresponding to 1.46 x her body height. We analyzed the player's biomechanical data and compared it with a data base including female players at the same level of skills, in the same age category (under 18 – U18) and with no previous lower back injuries. The results (table 1) show that the lateral flexion angles of the player's upper trunk and pelvis in trophy position were within the range of our reference data, and therefore did not appear to be associated with a risk of injury in the lumbar region. In the same way, the player's maximal trunk extension was similar to what we usually observed in our reference values. Consequently, the player's trunk extension did not seem to be responsible for her injury.

On the contrary, she demonstrated:

- a low angle between the pelvis and the baseline in the transverse plane at the beginning of the cocking phase showing a premature opening of the hips towards the net
- a high maximal hips/shoulders separation angle during the cocking phase. It is likely that the lumbar spine is exposed to a significant torque due to the counter-rotation, or "closing", of the shoulder line away from the baseline and the rotation, or "opening", of the hip line towards the baseline during the cocking phase.
- low values of maximal vertical GRF and power during the leg drive. In this player's case, the results show that the leg drive appears inefficient, theoretically forcing her to use a "pull" serve technique that may over-stress her lumbar muscles and increased tension loads on her lower back.

Based on our team experience, technical instructions were given to the player in order to modify the biomechanical elements potentially involved in the onset of her injury[21]. Figure 7 demonstrates a comparison between the player's usual technique and the post-intervention (new) technique; we asked her to change her stance technique from foot-up (FU) to a foot-back (FB) stance, where the feet do not move during the wind-up and the cocking phase, in order to:

1. delay the rotation of the hips towards the net
2. limit the maximal hips/shoulder separation angle during the cocking phase
3. facilitate a "push" serve mechanism in order to reduce the traction mechanism on the right region of her lumbar spine.

After a period of familiarization with this modified technique during the test, we recorded new serve trials. She managed to modify her technique quite easily and all the parameters of interest in relation to her injury improved by the end of the test (Table 1). Concerning performance parameters, her mean ball speed increased by 8.4 km/h to reach 137.8 km/h and her impact height remained relatively similar (1.47 x body height) with the new FB technique. As a result, the technical change seems to have optimized her serve kinetic chain since all biomechanical variables related to lower-back injury improved (except the vertical GRF and power) and the performance factors increased.

A few days after the test, a full biomechanical report including injury risk

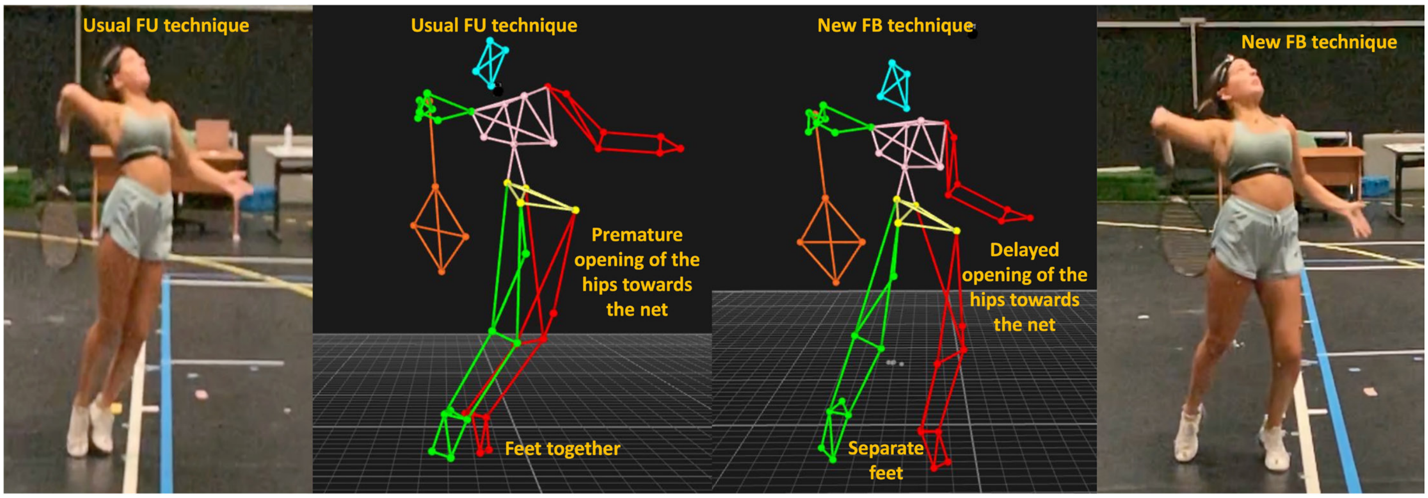


Figure 7: Comparison between the player's usual and the new techniques.

TABLE 1

	Player – usual FU technique (mean value)	*Player – new FB technique (mean value)*	*Data base U18 (mean ± SD)*
Angle of upper trunk lateral flexion at time of trophy position	*33°*	*33°*	*31 ± 9°*
Angle of pelvis lateral flexion at time of trophy position	*8°*	*10°*	*5 ± 5°*
Maximal angle of trunk extension during the cocking phase	*139°*	*138°*	*135 ± 9°*
Angle between the pelvis and the baseline in the transverse plane at the beginning of the cocking phase	*61°*	*76°*	*75 ± 13°*
Maximal hips/shoulders separation angle during the cocking phase	*36°*	*28°*	*30 ± 7°*
Maximal vertical GRF during the leg drive	*1.8 (BW)*	*1.8 (BW)*	*2.1 ± 0.4 (BW)*
Maximal vertical power during the leg drive	*21.0 W/kg*	*21.0 W/kg*	*21.6 ± 5.9 W/kg*

Table 1: Biomechanical parameters for the player and our U18 data base. FU=foot-up technique, FB=foot-back technique, SD=standard deviation, W=watts, kg=kilograms, BW=bodyweight.

factors and serve performance data was sent to the player and her team. One month after the test, a video debriefing was held with the player, her parents, her physiotherapist and her tennis coach to review the technical modifications made. We have suggested to the player's staff (coach, physical trainer, doctor, and physiotherapist) a corrective program based on our particular observations. Subsequently in the few months following implementation of new serving technique, the player was able to return to competition pain free, with no injury recurrence.

CONCLUSION

When it comes to serve-related persistent or recurrent injuries, biomechanical evaluation constitutes an interesting solution in a complex system approach. Of course, biomechanical assessment alone is not sufficient, and must be coupled with other methods of athlete management (physical conditioning, musculoskeletal screening, training load considerations, medical care, equipment, etc.). The success of the biomechanical assessment obviously depends on the involvement and commitment of the player and coach. Our work also highlights the need for awareness by medical staff of the importance of biomechanical analysis in reducing the risk of injury in tennis players.

References

1. *Kovacs M, Ellenbecker T. An 8-stage model for evaluating the tennis serve: implications for performance enhancement and injury prevention. Sports Health. 2011;3(6):504-13.*
2. *Pluim BM, Windler GS. Epidemiology of tennis injuries. In: Tennis Medicine A complete guide to evaluation, treatment, and rehabilitation. Cham, Switzerland: Springer International Publishing; 2018. p. 43-51.*
3. *Maquirriain J, Ghisi JP, Kokalj AM. Rectus abdominis muscle strains in tennis players. Br J Sports Med. 2007;41(11):842-8.*
4. *Robison HJ, Boltz AJ, Morris SN, Collins CL, Chandran A. Epidemiology of injuries in National Collegiate Athletic Association men's tennis: 2014–2015 through 2018–2019. J Athl Train. 2021;56(7):773-9.*
5. *Kekelekis A, Nikolaidis PT, Moore IS, Rosemann T, Knechtle B. Risk Factors for Upper Limb Injury in Tennis Players: A Systematic Review. Int J Environ Res Public Health. 16 avr 2020;17(8):2744.*
6. *Campbell A, O'Sullivan P, Straker L, Elliott B, Reid M. Back pain in tennis players: a link with lumbar serve kinematics and range of motion. Med Sci Sports Exerc. févr 2014;46(2):351-7.*
7. *Fleisig G, Nicholls R, Elliott B, Escamilia R. Kinematics used by world class tennis players to produce high-velocity serves. Sports Biomech. 2003;2(1):51-64.*
8. *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. Scand J Med Sci Sports. 2014;24(4):60-75.*
9. *Martin C, Kulpa R, Ropars M, Delamarche P, Bideau B. Identification of temporal pathomechanical factors during the tennis serve. Med Sci Sports Exerc. nov 2013;45(11):2113-9.*
10. *Girard O, Micallef J, Millet G. Influence of restricted knee motion during the flat first serve in tennis. J Strength Cond Res. 2007;21(3):950-7.*
11. *Tubez F, Forthomme B, Croisier JL, Cordonnier C, Brüls O, Denoël V, et al. Biomechanical analysis of abdominal injury in tennis serves. A case report. J Sports Sci Med. 8 mai 2015;14(2):402-12.*
12. *Elliott B, Fleisig G, Nicholls R, Escamilia R. Technique effects on upper limb loading in the tennis serve. J Sci Med Sport. 2003;6(1):76-87.*
13. *Touzard P, Kulpa R, Bideau B, Montalvan B, Martin C. Biomechanical analysis of the « waiter's serve » on upper limb loads in young elite tennis players. Eur J Sport Sci. juill 2019;19(6):765-73.*
14. *Cools AM, Maenhout AG, Vanderstukken F, Declève P, Johansson FR, Borms D. The challenge of the sporting shoulder: From injury prevention through sport-specific rehabilitation toward return to play. Ann Phys Rehabil Med. juill 2021;64(4):101384.*
15. *Schwank A, Blazey P, Asker M, Møller M, Hägglund M, Gard S, et al. 2022 Bern Consensus Statement on Shoulder Injury Prevention, Rehabilitation, and Return to Sport for Athletes at All Participation Levels. J Orthop Sports Phys Ther. janv 2022;52(1):11-28.*
16. *Maquirriain J. Low back pain in the young tennis player: The risk of spondylolysis. Aspetar Sports Med J. 2014;3:508-14.*
17. *Connolly M, Middleton K, Spence G, Cant O, Reid M. Effects of Lumbar Spine Abnormality and Serve Types on Lumbar Kinematics in Elite Adolescent Tennis Players. Sports Med - Open. 11 janv 2021;7(1):7.*
18. *Connolly M, Middleton K, Spence G, Cant O, Reid M. Effects of lumbar spine abnormality and serve types on lumbar kinematics in elite adolescent tennis players. Sports Med - Open. 2021;7(7).*
19. *Farhart P, Beakley D, Diwan A, Duffield R, Rodriguez EP, Chamoli U, et al. Intrinsic variables associated with low back pain and lumbar spine injury in fast bowlers in cricket: a systematic review. BMC Sports Sci Med Rehabil. 20 sept 2023;15(1):114.*
20. *Kibler B. The kinetic chain in tennis: do you push or pull? Aspetar Sports Med J. 2012;1(1):40-3.*
21. *Touzard P. L'évolution biomécanique du service des jeunes joueurs de tennis élites : identification des facteurs de performance et de risque de blessures [Internet] [PhD Thesis]. 2021. Disponible sur: http://www.theses.fr/2021REN20013/document*

Caroline Martin Ph.D.
Associate Professor of Sports Science
M2S Laboratory, Rennes 2 University
France

Pierre Touzard Ph.D.
Research Engineer in Sports Science
M2S Laboratory, Rennes 2 University
France

Loïc Fourel Ph.D.
Research Engineer in Sports Science
MS2 Laboratory, Rennes 2 University
France

Contact: Caroline.martin@univ-rennes2.fr