Journal of Sports Sciences

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/rjsp20

Influence of the forehand stance on knee biomechanics: Implications for potential injury risks in tennis players

Caroline Martin , Anthony Sorel , Pierre Touzard , Benoit Bideau , Ronan Gaborit , Hugo DeGroot & Richard Kulpa

To cite this article: Caroline Martin , Anthony Sorel , Pierre Touzard , Benoit Bideau , Ronan Gaborit , Hugo DeGroot & Richard Kulpa (2020): Influence of the forehand stance on knee biomechanics: Implications for potential injury risks in tennis players, Journal of Sports Sciences, DOI: 10.1080/02640414.2020.1853335

To link to this article: https://doi.org/10.1080/02640414.2020.1853335

JOURNAL OF SPORTS SCIENCES
https://doi.org/10.1080/02640414.2020.1853335

Influence of the forehand stance on knee biomechanics: Implications for potential injury risks in tennis players

Caroline Martin, Anthony Sorel, Pierre Touzard, Benoit Bideau, Ronan Gaborit, Hugo DeGroot and Richard Kulpa

M2S Laboratory, Rennes 2 University, Rennes, France

ABSTRACT

The open stance forehand has been hypothesized to be more traumatic for knee injuries in tennis than the neutral stance forehand. This study aims to compare kinematics and kinetics at the knee during three common forehand stroke stances (attacking neutral stance ANS, attacking open stance AOS, defensive open stance DOS) to determine if the open stance forehand induces higher knee loadings and to discuss its potential relationship with given injuries. Eight advanced tennis players performed eight repetitions of forehand strokes with each stance (ANS: forward run and stroke with feet parallel with the hitting direction, AOS: forward run and stroke with feet perpendicular to the hitting direction, DOS: lateral run and stroke with feet perpendicular to the hitting direction) at maximal effort. All the trials were recorded with an optoelectronic motion capture system. The flexion-extension, abduction-adduction, external-internal rotation angles, intersegmental forces and torques of the right knee were calculated. Ground reaction forces were measured with a forceplate. The DOS increases vertical GRF, maximum knee flexion and abduction angles, range of knee flexion-extension, peak of compressive, distractive and medial knee forces, peak of knee abduction and external rotation torques. Consequently, the DOS appears potentially more at risk for given knee injuries.

ARTICLE HISTORY
Accepted 16 November 2020

KEYWORDS
Knee injuries; knee kinematics; knee loadings

1. Introduction

Tennis players execute repetitive lateral, start/stop and turning motions with quick anterior or posterior transitions followed by powerful strokes, which can induce tremendous stress on the musculoskeletal system of the lower limbs (Kovacs, 2006; Manske & Paterno, 2018). Each change of direction creates a load of 1.5 to 2.7 times body weight on the planted knee and ankle (Kibler & Safran, 2012). Due to the repetitive loadings during matches, which can last up to 5 hours, lower limb injuries are very common in tennis players (Okholm Kryger et al., 2015; Renström, 1995).

Knee injuries concern 19% of tennis injuries (Kibler & Safran, 2005; O'Connor et al., 2020). For professional players, it has been shown that the knee is the most common injury region in male and the 3rd in female at the 2011–2016 Australian Open Grand Slam (Gescheit et al., 2017). For junior tennis players, ankle sprain, low back pain and knee injuries are the most common (Hjelm et al., 2010). In recreational competitive players, the knee concerns 12% of all injuries (Jayanthi et al., 2005). The majority (60–74%) of the knee injuries in tennis players are classified as overuse (Chard & Lachmann, 1987; Hjelm et al., 2010) including patella-femoral tendinopathies or pain, patella dislocation, quadriceps tendinopathy, iliotibial band friction syndrome and Osgood Schlatter's disease. The traumatic injuries such as collateral ligament, anterior cruciate ligament and meniscal injuries less often occur in tennis players but represent around 30–40% of knee injuries (Chard & Lachmann, 1987; Hjelm et al., 2010; Renstrom & Lynch, 2002). These knee injuries can be particularly problematic not only for players' performance and career but also for their work and daily quality of life (De Vries et al., 2017). Indeed, for example, more than 50% of athletes with patellar tendinopathy were forced to retire from sport but continue to have pain with stairs climbing (15 years later) (Kettunen et al., 2002; Leong et al., 2018). The dominant knee is involved in 57% of injuries in tennis players (Hjelm et al., 2010).

Indeed, the dominant knee is a crucial joint allowing the energy transfer from the ankle to the hip during tennis strokes such as serves or groundstrokes. The knee helps to generate force and absorb impact during specific movements allowing tennis players to hit the ball with efficiency. Indeed, there is a significant relationship between the peak angular velocity of dominant-side knee joint extension and post-impact ball speed in the forehand (Seeley et al., 2011). Moreover, it has been shown that initial knee positioning and range-of-motion are positively related to racket velocity during the forehand (Nesbit et al., 2008).

Concerning feet and knee positioning in forehands, players can use different stances: the neutral, the semi-open and the open stances. For the neutral stance, the player's feet and knees are perpendicular to the net while they are parallel to the net for the open stance. The semi-open stance concerns any feet positioning between the neutral and open stances. When the ball speed is reduced and the players are in attacking position into the court, the majority of forehand shots are played in a neutral stance (Landlinger et al., 2010). However, with the game acceleration during the last decades, high-level tennis players give priority to open stances for saving time during defensive baseline forehands (Reid et al., 2013). For example, it

CONTACT Caroline Martin caromartin@numericable.fr M2S Laboratory, ENS de Rennes, Avenue Robert Schuman, Bruz 35170, France

has been reported that Federer hit 77% of his forehands with an open stance during a set played against Falla (Reid et al., 2013) during the 2010 French Open. Moreover, in the 2010 Miami Open Final between Clijsters and Williams, 68% of all forehands were executed in open stance and only 32% of all forehands were executed in neutral stance (Zusa et al., 2010). In advanced tennis players, data about the ratios of stances are really limited. According to Schonborn (1999), about 90% of all forehands are played by advanced players in an open stance position (Schönborn, 2000). The open stance forehand is thought to be more traumatic than the neutral one because it could increase loadings on the dominant side leg and consequently favour injuries appearance in lower limb injuries of tennis players (Ellenbecker, 2006). However, there is no data in the literature about the influence of the forehand stance on lower limb biomechanics and injury risks for the dominant knee. Consequently, it remains unclear if one of the forehand stances could increase knee injuries. Yet, such scientific information is crucial for coaches, scientists, physiotherapists and medical staff to improve the prevention, management and rehabilitation of knee injuries in players.

Consequently, this study aims to evaluate knee kinematics and kinetics during three common forehand stroke stances (attacking neutral stance ANS[1], attacking open stance AOS, defensive open stance DOS) to know if the open stance forehand induces higher knee loadings and to discuss its potential relationship with given knee injuries

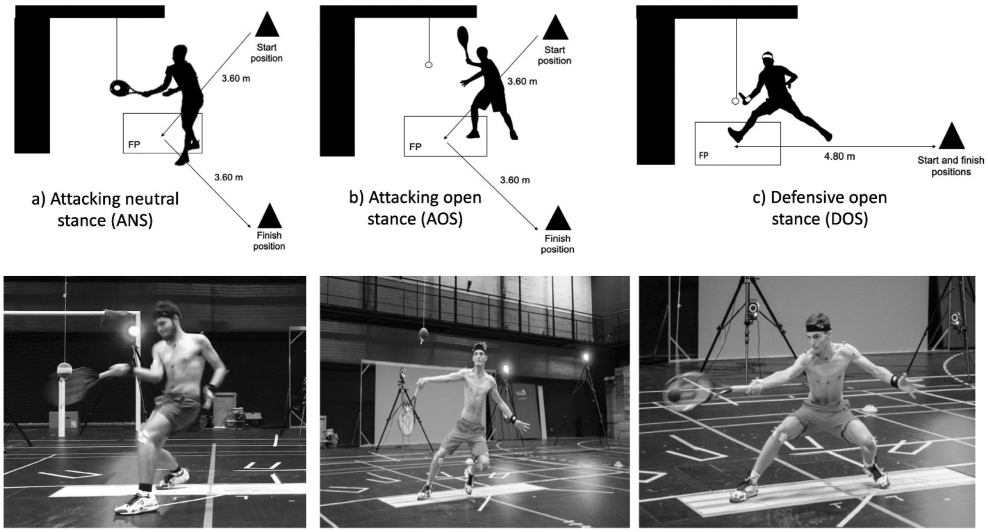
2. Materials and methods

8 right-handed male tennis players (age: 26.3 ± 11.0 years; height: 1.76 ± 0.02 m; weight: 65.9 ± 4.6 kg) voluntarily participated in this study. Inclusion criteria consisted of uninjured advanced tennis players with an International Tennis Number (ITN) of 4 or 5 (International Tennis Federation, 2009) and the ability to properly perform each forehand stroke stance (ANS, AOS, DOS). The ITN is a tennis rating, internationally recognized, that represents a player's general level of play. The International Tennis Federation (2009) describes the level of ITN 4 and ITN 5 players as follows: "*ITN 4 players can use power and spins and have begun to handle pace. They have sound footwork, can control depth of shots, and can vary game plan according to opponents." "ITN 5 players have dependable strokes, including directional control and depth on both groundstrokes and on moderate shots. The players have the ability to use lobs, overheads, approach shots and volleys with some success*." The ability of the players to properly perform each forehand stroke stance was confirmed by a professional tennis coach.

Before participation, they were fully informed of the experimental procedures. At the time of the experiment, all players were considered healthy, with no pain or injury. Written consent was obtained for each player. The study respected all local laws for studies involving human participants and was approved by the Local Ethics Board.

Before the motion capture, participants viewed a demonstration of the experimental procedure and the three forehand stroke stances (ANS, AOS, DOS) performed by a professional coach. They had sufficient time to familiarize themselves with the testing environment and the landmarks set, as well as to test all forehand stroke stances (ANS, AOS, DOS). After a warm-up of 10 minutes, each player performed eight forehand strokes with each stance at maximal effort. The order of the forehand stroke stances was randomly assigned. The players were asked to move as quickly as possible and to hit a foam tennis ball as hard as they can. The foam tennis ball was fixed and attached to a scaffold with a rope, allowing the investigators to adapt the impact height according to the players' height and the type of forehand strokes (Figure 1).

For the AOS and the ANS, the players ran a total distance of 6.2 m. For the ANS, the players ran along a 45° line (3.6 m) on the left side of the force plate before stepping onto the plate with the right leg to execute a jab run. Then, they placed their left leg in front of the right leg. Consequently, they hit the foam ball with a neutral stance (feet parallel with the hitting



a) Attacking neutral stance (ANS)

b) Attacking open stance (AOS)

c) Defensive open stance (DOS)

Figure 1. Experimental set-up protocol with the three forehand stances. FP: force plate.

---

[1] ANS: attacking neutral stance, AOS: attacking open stand, DOS: defensive open stance

direction, left leg in front of the right leg located on the force plate). They left the plate at 45° angle towards the left until the finishing point (Figure 1(a)). The height of the foam ball was adjusted to the right hip' height of each player to simulate an attacking neutral stance forehand.

For the AOS, the running motion was similar to the ANS but the players were asked to hit the ball with an open stance with the feet perpendicular to the hitting direction (Figure 1(b)). The right leg was located on the force plate and the left leg was beside the right leg. The height of the foam ball was adjusted to the right shoulder' height of each player to simulate an attacking open stance forehand.

For the DOS, the players performed a 9.6 m lateral shuttle run. First, they started from a standing position. After a split step, they laterally ran towards the force plate (Figure 1(c)). When the force plate was reached, they stepped onto the plate with the right leg, performed an open stance with the feet perpendicular to the hitting direction (left leg beside the right leg), and hit the foam ball. Then, they ran back to the starting point. The distance between the starting point and the middle of the force plate was 4.8 m. The height of the foam ball was adjusted to the right pocket's height of each player to simulate a defensive forehand. The characteristics of the movement patterns (covered distances, lateral shuttle run in DOS, jab run in ANS and AOS) and forehands strokes (attacking and defensive strokes) have been validated by a professional tennis coach and have been chosen because they are reported to occur frequently in tennis (Hughes & Meyers, 2005; Reid et al., 2013; Roetert et al., 2009). For the DOS, five steps were performed before landing on the force plate while for the ANS and AOS, four steps were performed before landing on the force plate to ensure that a maximal speed was achieved, as recommended in the literature (Graf & Stefanyshyn, 2013).

Players were equipped with 38 retroreflective markers placed on anatomical landmarks determined in agreement with previously published data (Leardini et al., 1999; Reed & Manary, 1999; Zatsiorsky et al., 1990). A Vicon motion capture system (Oxford Metrics Inc., Oxford, UK) was used to record the trajectories of the 3-dimensional anatomical landmarks. The system was composed of 20 high-resolution cameras (4 megapixels) operating at a nominal frame of 200 Hz. Players were shirtless and wore only tight short to limit movement of the markers. After the capture, the 3D coordinates of the landmarks were reconstructed with Blade software (Blade; Vicon, Oxford, UK) with a residual error of less than 1 mm. A force platform operating at 2000 Hz (60 x 120 × 5.7 cm, Advanced Mechanical Technology Incorporation, Watertown, MA, USA) was used to measure peak of ground reaction forces (GRF) on the right step during forehand strokes. All the right knee kinetic and kinematic data were processed with CusTom in Matlab software (Mathworks, Natick, Massachussetts, USA), which is a Customizable Toolbox for Musculoskeletal simulation allowing to solve inverse kinematics and inverse dynamics from motion capture data (Muller et al., 2019).

In each of the three forehand stances, the minimum, maximum, and range of motion were computed in each plane of motion at the dominant (right) knee during the right foot standing on the force plate. Intersegmental forces and torques at the dominant knee were also computed.

One-way analyses of variance (ANOVAs) with repeated measures were used to analyse differences in GRF, knee kinematics and kinetics between the 3 forehand stances (ANS, AOS, DOS). Significant main effects were decomposed using post hoc Holm-Sidak method to determine the source of difference. To determine the clinical relevance of differences, each post hoc contrast was presented using a mean difference (MD). Where data were not normally distributed, significance was determined using ANOVA with repeated measures on ranks and a post hoc Tukey test. Mean and SD values were computed for all parameters. The effect sizes were calculated and the clinical significance of the differences was classified as small (Cohen's d < 0.2), medium (Cohen's d = 0.5), or large (Cohen's d > 0.8), according to the Cohen scale. The level of significance was established at $p < 0.05$ (SigmaStat 3.1; Jandel Corporation, San Rafael, CA). In accordance with Altman (1991), statistical result with p value between 0.05 and 0.1 is reported as tendency towards a difference (Altman, 1991).

3. Results

3.1. Absolute running velocity of the centre of mass at the instant of the first contact between the right foot and the force plate

Results show a significant main effect of the type of forehand stances on the absolute running velocity of the centre of mass at the instant of the first contact between the right foot and the force plate ($p < 0.002$; retrospective statistical power = 0.949). Post hoc tests reveal that the absolute running velocity was significantly higher in ANS (3.7 $m.s^{-1}$) and AOS (3.6 $m.s^{-1}$) than in DOS (3.2 $m.s^{-1}$) (respectively, MD: 0.5 $m.s^{-1}$; $p < 0.001$; respectively, MD: 0.4 $m.s^{-1}$; $p = 0.006$).

3.2. Ground reaction forces

There are significant main effects of the type of forehand stances on lateral GRF ($p < 0.001$; retrospective statistical power = 1) and vertical GRF ($p = 0.035$; retrospective statistical power = 0.524). Post hoc comparisons show that the DOS involved significant greater peak of lateral GRF than ANS (MD: 599 N; $p < 0.001$) and AOS (MD: 350 N; $p = 0.002$) (Table 1). Post hoc test demonstrates also a significant difference between ANS and AOS concerning peak of lateral GRF (MD: 249 N; $p = 0.018$). The peak of vertical GRF is significantly higher in DOS than in ANS (MD: 488 N; $p = 0.011$, d = 1.26). There is also a tendency towards a difference concerning peak of vertical GRF between DOS and AOS (MD: 298 N; $p = 0.097$).

3.3. Knee kinematics

Results show significant main effects of the type of forehand stances maximal knee flexion ($p < 0.001$; retrospective statistical power = 0.999) and knee flexion range of motion ($p = 0.003$; retrospective statistical power = 0.913). Post hoc results reveal that the maximal knee flexion angle is significantly higher in DOS compared with ANS (MD: 13.3°; $p < 0.001$) and AOS (MD: 16.4°; $p < 0.001$). Post-hoc analyses show that the range of knee

Table 1. Statistical comparison of GRF peaks across the 3 forehand stances.

GRF (N)	ANS	AOS	DOS	ANOVA *p* value	Effect size d	Post Hoc Differences *p* value
Anterior GRF	468 ± 195	458 ± 86	382 ± 92	0.256	/	/
Lateral GRF	786 ± 235	1035 ± 229	1385 ± 165	< 0.001	0.748	DOS-ANS DOS-AOS ANS-AOS
Vertical GRF	1684 ± 370	1873 ± 387	2171 ± 513	0.035	0.380	DOS-ANS DOS-AOS^{T}

Values are expressed as mean ± SD. Abbreviations: ANS = attacking neutral stance, AOS = attacking open stance, DOS = defensive open stance. DOS-ANS, significant difference between defensive open stance and attacking neutral stance forehands. DOS-AOS, significant difference between defensive open stance and attacking open stance forehands. ANS-AOS, significant difference between attacking neutral stance and attacking open stance forehands. DOS-AOS^{T}, tendency towards a difference between defensive open stance and attacking open stance forehands.

flexion is significantly lower in AOS than in ANS (MD: 10.5°; $p = 0.008$) and DOS (MD: 13.7°; $p = 0.001$).

Moreover, there are significant main effects of the type of forehand stances on maximal knee abduction ($p < 0.001$; retrospective statistical power = 0.999) and adduction-abduction knee range of motion ($p = 0.004$; retrospective statistical power = 0.884). Post hoc comparisons show that DOS induces higher values of knee abduction angle in comparison with ANS (MD: 23.0°; $p < 0.05$) and AOS (MD: 13.0°; $p < 0.05$). ANS is the only stance that shows maximal knee adduction angle, in comparison with AOS (MD: 24.0°; $p < 0.001$) and DOS (MD: 29.0°; $p < 0.001$). Post hoc test shows that ANS has higher knee adduction-abduction range of motion than AOS (MD: 13.6°; $p = 0.001$). There is also a tendency towards a difference concerning the knee adduction-abduction range of motion between DOS and AOS (MD: 7.8°; $p = 0.058$) and between ANS and DOS (MD: 5.9°; $p = 0.098$). No significant difference exists between the three forehand stances concerning maximal knee internal and external rotation angles and knee internal – external rotation range of motion (Table 2).

3.4. Knee kinetics

3.4.1. Knee joint forces

Results only show tendencies across the three forehand stances concerning maximal posterior ($p = 0.091$, retrospective statistical power = 0.313) and anterior knee joint forces ($p = 0.052$, retrospective statistical power = 0.438) (Table 3). Significant main effects are recorded in compressive ($p = 0.023$, retrospective statistical power = 0.614), distractive ($p < 0.001$, retrospective statistical power = 0.994) and medial forces ($p < 0.002$, retrospective statistical power = 0.933) between the forehand stances. Post hoc test reveals that the ANS involves significantly lower peak of compressive knee joint force than DOS (MD: 564.6 N; $p = 0.007$). There is also a tendency for this variable with AOS (MD: 330.8 N; $p < 0.086$). According to post hoc results, the peak of distractive knee force is significantly increased in DOS than in ANS (MD: 82.3 N; $p < 0.001$) and AOS (MD: 90.6 N; $p < 0.001$). The peak of medial knee joint force is significantly higher in DOS than in ANS (MD: 117.6 N and $p = 0.001$) and AOS (MD: 101.3 N and $p = 0.004$).

Table 2. Statistical comparison of the ranges of knee motion across the 3 forehand stances.

Knee kinematics (°)	ANS	AOS	DOS	ANOVA *p* value	Effect size d	Post Hoc Differences *p* value
Knee flexion						
Minimum	30 ± 6	27 ± 7	30 ± 9	0.306	/	/
Maximum	83 ± 8	70 ± 6	86 ± 7	< 0.001	0.732	DOS-ANS DOS-AOS
Flexion-extension range of motion	53 ± 7	42 ± 8	56 ± 7	0.003	0.566	DOS-AOS ANS-AOS
Knee abduction/adduction						
Minimum	−12 ± 12	−22 ± 15	−35 ± 19	0.008	0.432	DOS-ANS DOS-AOS
Maximum	13 ± 16	−11 ± 11	−16 ± 16	< 0.001	0.546	DOS-ANS AOS-ANS
Adduction-abduction range of motion	25 ± 7	11 ± 5	19 ± 7	0.004	0.543	ANS-AOS DOS-ANS^{T} DOS-AOS^{T}
Knee internal/external rotation						
Minimum	−18 ± 11	−12 ± 12	−21 ± 8	0.355	/	/
Maximum	12 ± 19	13 ± 16	15 ± 23	0.591	/	/
Internal – external rotation range of motion	30 ± 22	25 ± 10	37 ± 23	0.245	/	/

Values are expressed as mean ± SD. Abbreviations: ANS = attacking neutral stance, AOS = attacking open stance, DOS = defensive open stance. DOS-ANS, significant difference between defensive open stance and attacking neutral stance forehands. DOS-AOS, significant difference between defensive open stance and attacking open stance forehands. ANS-AOS, significant difference between attacking neutral stance and attacking open stance forehands. DOS-AOS^{T}, tendency towards a difference between defensive open stance and attacking open stance forehands. DOS-ANS^{T}, tendency towards a difference between defensive open stance and attacking neutral stance forehands.

Table 3. Statistical comparison of the maximal values of knee forces across the 3 forehand stances.

Knee joint forces (N)	ANS	AOS	DOS	ANOVA *p* value	Effect size d	Post Hoc Differences *p* value
Posterior force	149 ± 45	234 ± 126	243 ± 109	0.091	/	/
Anterior force	604 ± 148	755 ± 168	580 ± 227	0.052	/	/
Compressive force	1475 ± 335	1806 ± 400	2040 ± 445	0.023	0.417	DOS-ANS AOS-ANS^{T}
Distractive force	107 ± 24	99 ± 26	189 ± 60	< 0.001	0.680	DOS-ANS DOS-AOS
Medial force	204 ± 40	221 ± 71	322 ± 112	< 0.002	0.579	DOS-ANS DOS-AOS
Lateral force	94 ± 36	68 ± 35	97 ± 73	0.654	/	/

Values are expressed as mean ± SD. Abbreviations: ANS = attacking neutral stance, AOS = attacking open stance, DOS = defensive open stance. DOS-ANS, significant difference between defensive open stance and attacking neutral stance forehands. DOS-AOS, significant difference between defensive open stance and attacking open stance forehands. DOS-ANS^{T}, tendency towards a difference between defensive open stance and attacking neutral stance forehands.

Table 4. Statistical comparison of the maximal values of knee torques across the 3 forehand stances.

Knee flexion torques (Nm)	ANS	AOS	DOS	ANOVA *p* value	Effect size d	Post Hoc Differences *p* value
Extension	189 ± 30	179 ± 45	182 ± 75	0.901	/	/
Flexion	51 ± 13	80 ± 32	112 ± 46	0.013	0.464	DOS-ANS DOS-AOS^{T}
Adduction (varus)	55 ± 36	58 ± 23	59 ± 76	0.985	/	/
Abduction (valgus)	83 ± 24	101 ± 20	230 ± 41	< 0.001	0.899	DOS-ANS DOS-AOS
Internal torque	27 ± 12	9 ± 7	10 ± 7	< 0.001	0.703	DOS-ANS ANS-AOS
External torque	28 ± 5	32 ± 11	52 ± 13	< 0.001	0.631	DOS-ANS DOS-AOS

Values are expressed as mean ± SD. Abbreviations: ANS = attacking neutral stance, AOS = attacking open stance, DOS = defensive open stance. DOS-ANS, significant difference between defensive open stance and attacking neutral stance forehands. DOS-AOS, significant difference between defensive open stance and attacking open stance forehands. ANS-AOS, significant difference between attacking neutral stance and attacking open stance forehands. DOS-AOS^{T}, tendency towards a difference between defensive open stance and attacking open stance forehands.

3.4.2. *Knee joint torques*

Significant main effects are recorded in knee flexion ($p = 0.013$, retrospective statistical power = 0.728), abduction ($p < 0.001$, retrospective statistical power = 1.000), internal ($p < 0.001$, retrospective statistical power = 0.998) and external torques ($p < 0.001$, retrospective statistical power = 0.976) between the forehand stances (Table 4). Post hoc tests show that the DOS involves significantly greater peak of flexion knee torque than ANS (MD: 60.3 Nm and $p = 0.004$) (Table 4). There is a tendency towards a difference in comparison with AOS (MD: 31.9 Nm and $p = 0.087$). The peak of internal knee joint torque is significantly higher in ANS than in DOS (MD: 17.2 Nm and $p < 0.001$) and AOS (MD: 18.7 Nm and $p < 0.001$). Conversely, the peak of external knee joint torque is increased in DOS in comparison with ANS (MD: 24.0 Nm and $p < 0.001$) and AOS (MD: 20.5 Nm and $p < 0.001$). The peak of abduction knee joint torque is significantly higher in DOS than in ANS (MD: 146.5 Nm and $p < 0.001$) and AOS (MD: 128.5 Nm and $p < 0.001$).

4. Discussion

This study aims to evaluate 3-dimensional knee kinematics and kinetics during three common forehand stroke stances (attacking neutral stance ANS, attacking open stance AOS, defensive open stance DOS) to determine if the open stance forehands induces higher knee loadings and to discuss its potential relationship with several well-known knee injuries.

The DOS significantly increases lateral and vertical GRF. Among the three forehand stances, the DOS induces the highest magnitude of flexion and abduction at the dominant knee. Moreover, the DOS produces the greatest peak of compressive, distractive and medial forces at the dominant knee. Knee abduction, flexion and external torques are significantly increased with DOS in comparison with ANS and AOS. All these results confirm the formulated hypothesis that the dominant knee is more loaded with the open stance forehand during defensive shots. Consequently, the DOS could increase the risk of having knee injuries for tennis players.

4.1. *Forehand stance effects on knee biomechanics*

The magnitude of running velocity, knee kinematics and kinetics measured in the current study are similar or slightly higher than previous published results during side-step or shuttle run cutting in young athletes (Ishii et al., 2011; Sigward & Powers, 2006; Zaslow et al., 2016). However, our results demonstrate clear knee kinematic and kinetic differences between the three common forehand stroke stances which can be explained in the light of literature. The forehand stroke involves a sequence of motions referred to as a “kinetic chain” that begins with the lower limb action and is followed by the trunk and then the upper limb. The knee joint allows to transfer a maximum of energy from the lower limb to the hips and trunk. During the forehand, the vigorous flexion and extension of the knee contributes to the subsequent rotational drive of the hips and trunk to increase racket velocity during ball impact (Iino & Kojima, 2003). Our results show that knee flexion angle and torque are significantly higher in DOS than in AOS and ANS. This is logical since the ball height was lower in DOS to simulate defensive forehand strokes in our protocol. Moreover, the DOS significantly increases lateral and vertical GRF. One plausible explanation is the difference in the movement plane of study, which was executed predominantly in the medial-lateral and vertical directions during defensive forehand open stance strokes (DOS), compared with attacking forehand neutral stance strokes (ANS) that was executed in the anterior-posterior directions (Bahamonde, 2001; Elliott, 2003). Knee abduction and external torques are significantly increased with DOS. This result seems logical because, during open stance strokes, players need to create higher amount of angular momentum about the longitudinal axis, than in neutral stance strokes, from greater knee and hip rotations to generate power at impact (Bahamonde, 2001; Elliott, 2003).

4.2. Forehand stance effects on risks of knee injuries

4.2.1. Patellar tendinopathy and knee osteoarthritis

During tennis practice, players can suffer from anterior knee pain, which is commonly called jumper's knee (Hale, 2005). This pain is also referred to as patellar tendinopathy that is a pathology affecting the bone-tendon junction during jumping, bending, cutting or pivoting actions performed by tennis players (Leong et al., 2018). In the literature, the mechanisms of patellar tendinopathy are multifactorial, both intrinsic and extrinsic factors have been identified. Among them, knee joint kinematics and loadings are considered as extrinsic risks for athletes. Indeed, for example, in elite volleyball players, it has been shown that maximum vertical GRF, maximum knee flexion angle, and peak knee external-rotation moment during spike-jump and block-jump takeoff or landing are strong and reliable indicators of patellar tendinitis in the dominant knee (Richards et al., 1996). In our study, the magnitude of vertical GRF and maximal knee flexion angle in DOS are similar to the values measured during the take-off phase of both spike and block jumps in volleyball players (Richards et al., 1996). Our results show that the DOS significantly increases vertical GRF in comparison with ANS and AOS. Moreover, the DOS induced higher maximum knee flexion angle than the two other stances, higher range of knee flexion-extension than AOS, and higher peak of compressive knee force than ANS. All these elements may lead to focal degeneration and microtears in the patellar tendon of athletes (Hale, 2005). Consequently, one may argue that the continual repetition of compressive forces on the dominant knee during DOS in tennis players could increase the risk of patellar tendinopathy and joint osteoarthritis.

4.2.2. Osgood-Schlatter's disease

The Osgood-Schlatter's disease is a highly common knee injury in junior tennis players (Georgevia et al., 2015; Hjelm et al., 2010). The pain is located at the insertion of the patellar tendon into the tibia. In growing individuals, the soft tissues such as tendon and muscles are stronger than the bone (Renström, 1995). It is known that excessive and repetitive tensile or distractive forces may cause Osgood-Schlatter's disease by fragmenting the tendon's insertion (Renstrom & Lynch, 2002). Our results show that the peak of distractive knee force is significantly more important during DOS than during ANS and AOS. Consequently, the repetition of DOS forehands could be riskier for Osgood-Schlatter's disease in tennis players.

4.2.3. Meniscus tears

The meniscus aims to absorb shock and distribute stress to protect the knee. It allows joint stabilization and margins protection. Moreover, it facilitates joint gliding and provides articular cartilage lubrication and nutrition (Brindle et al., 2001). As a result of excessive knee pivoting motion, meniscus tears are very common among tennis players (Fu et al., 2018), especially in middle-aged and elderly players (Renström, 1995). Injury risks for the meniscus include loadings that exceeds the structural integrity of the tissue (Rattner et al., 2011). In athletes, menisci injuries are mainly produced by a compressive force coupled with tibiofemoral external or internal rotation as the knee moves from flexion to extension during rapid change of direction (Brindle et al., 2001). While it is known that excessive loading of the menisci can lead to degenerative changes, it is not known at what magnitude compressive forces and rotation torques become injurious to cartilage (Escamilla et al., 2001). In this study, the results show that the peak of compressive knee force, the maximal knee flexion angle and the external rotation knee torque are significantly higher in DOS than in ANS. Moreover, while some areas of the meniscus aim to absorb compressive loads (inner sections), other meniscus areas deal with distractive loads (outer areas) (Hellio Le Graverand et al., 2001). DOS induces more extreme distractive knee force than the two other stances. Consequently, all these results lead us to believe that the DOS could be potentially more traumatic for meniscus in tennis players.

4.2.4. Anterior cruciate ligament (ACL)

ACL injuries often occur without physical contact between athletes in sports with sudden deceleration, landing and pivoting motions (Yu & Garrett, 2007). From a mechanical point of view, it can be the case when an athlete himself produces great forces and moments on his knee, generating excessive loading on the ACL which can break. In tennis, the ACL injury is usually induced by a cutting motion towards one side, followed by a quick twisting motion towards the other side (Renstrom & Lynch, 2002). However, ACL rupture is not a common injury during tennis playing. Indeed, a study reported a 2% overall ACL rupture incidence from tennis related injuries (Kuhne et al., 2004). Another study reported that 11% of knee injuries in tennis players concern ACL injury (Majewski et al., 2006). Knee abduction or valgus, internal rotation and anterior shear force at the tibia have been associated with non-contact ACL injuries in video studies describing ACL mechanisms during sport motions (Hewett et al., 2005, 2009; Olsen et al., 2004) but also in cadaver studies (Berns et al., 1992; Markolf et al., 1995). Hewett et al. (2005, 2009) reported that maximal knee flexion and abduction angles, maximal knee abduction torque and maximal vertical GRF were significantly higher in ACL-injured than in injured athletes during a jump-landing task (Hewett et al., 2005) or a cutting task (Hewett et al., 2009). Consequently, all these parameters are considered as predictors of anterior cruciate ligament injury risk in athletes. Our results demonstrate that maximal knee flexion angle, maximal knee abduction angle and torque, and peak of vertical GRF are significantly higher in DOS. All these values measured in DOS are similar or higher than those reported by Hewett et al. (2005, 2009).

Moreover, it has been reported that excessive compressive loads caused by impact loads along the tibial shaft (e.g., load from a powerful stroke) may contribute to ACL injuries, especially when the knee is flexed (Meyer et al., 2008; Meyer & Haut, 2005). In our study, the peak of compressive knee force is significantly higher in DOS and is close to the peak compression loads for ACL failure measured in human cadavers (2900 N) (Meyer et al., 2008; Meyer & Haut, 2005). There is a tendency towards a difference between the three stances concerning peak of anterior knee force with the highest values observed in AOS. AOS also tends to produce higher peak of compressive knee force than ANS. There is no significant difference concerning internal and external rotation knee angles between the three stances. But the internal rotation knee torque is significantly higher in ANS, even if the values are quite small. All these results suggest that DOS and AOS could be potentially more at risk for ACL injuries. However, they have to be interpreted with caution because among knee abduction, internal rotation torques, anterior and compressive forces, some debates exist about the main biomechanical contributor in non-contact ACL injuries (Quatman & Hewett, 2009; Yu & Garrett, 2007).

4.2.5. Medial collateral ligament (MCL)

The main function of the MCL is to stabilize the medial side of the knee joint. Its role is very important for providing support against valgus stress, rotational forces, and anterior translational forces on the tibia (Andrews et al., 2017). In tennis, the MCL is the most commonly injured knee ligament (Renstrom & Lynch, 2002). The injury usually occurs during a twisting situation when the knee is forced into a valgus position with external rotation (Rattner et al., 2011). For example, it has been reported that MCL strain increases with the increase of knee abduction moment (between 2 and 115 $N.m^{-1}$) in cadavers (Bates et al., 2019) and in a simulation study (Shin et al., 2009). Moreover, in ski accidents, it has been reported that the moments required to rupture the MCL were estimated at 92 $N.m^{-1}$ for knee abduction moment and 123 $N.m^{-1}$ for external moment through a simple model (Johnson et al., 1979). In our study, the results show that maximal knee abduction angle, peak of knee abduction and external rotation torques are significantly higher in DOS (16°, 230 $N.m^{-1}$, 52 $N.m^{-1}$, respectively). Moreover, the peak of knee medial force increases significantly in DOS. As a result, DOS seems riskier for MCL injuries.

4.3. Limitations

This study has some limitations. First, our sample size is limited because we only included advanced tennis players and their participation was voluntary. Some results tend to show differences between forehand stances' biomechanics. It seems reasonable to assume that nonsignificant results are due to lack of power caused by the small number of subjects involved in the study. Second, players were asked to hit a foam tennis ball and the forehand strokes were simulated and not played "under time pressure" as it is the case during training sessions or matches. Since the data were collected in simulated stroking conditions with ITN 4 or 5 skilled players, the results may not be generalizable to other skills levels or march play conditions.

Moreover, knee joint kinetics were measured using the inverse dynamics method. Musculoskeletal modelling and computer simulations could have been provided complementary results on knee muscle and ligament forces during the forehand strokes. Finally, the aetiology of the injuries in tennis players reveals that numerous extrinsic (playing surface, racquet properties) and intrinsic (age, sex, volume of play, skill level, biomechanics, anatomy, range of motion) risk factors are implied in the occurrence of injuries (Abrams et al., 2012). In this study, we restricted our research to biomechanical data concerning knee kinematics and kinetics across three common forehand stances. It could be interesting for further studies to combine biomechanical analysis and prospective registration of knee injuries to specifically assess the relation between specific forehand stance patterns and knee injury risks. Furthermore, it could be relevant to also analyse the influence of semi-open stance on knee kinetics and kinematics.

4.4. Conclusion

To conclude, this study aimed to compare knee kinematics and kinetics in tennis players during three common forehand stroke stances (attacking neutral stance ANS, attacking open stance AOS, defensive open stance DOS). Tennis experts generally believe that the forehand open stance constitutes a risk factor for dominant leg injuries in tennis (Ellenbecker, 2006). Our findings are in line with this hypothesis by showing that the DOS increases vertical GRF, maximum knee flexion and abduction angles, range of knee flexion-extension, peak of compressive, distractive and medial knee forces, peak of knee abduction and external rotation torques. Consequently, the DOS appears potentially more at risk for given knee injuries: patellar tendinopathy, knee osteoarthritis, Osgood-Schlatter's disease, meniscus tears, ACL and MCL. Coaches with players suffering from knee pain or injuries should encourage them to use more neutral stance and to develop aggressive playing style to avoid defensive open stance where knee motions and loadings are more extreme, especially in young or elderly players. After knee rehabilitation programme, players should favour the use of neutral stance to reduced loadings on the dominant knee during forehand strokes.

Disclosure statement

The authors report no conflict of interest.

References

Abrams, G., Renstrom, P., & Safran, M. (2012). Epidemiology of musculoskeletal injury in the tennis player. *British Journal of Sports Medicine*, *46*(7), 492–498. https://doi.org/10.1136/bjsports-2012-091164

Altman, D. (1991). *Practical statistics for medical research*. Chapman&Hall.

Andrews, K., Lu, A., Mckean, L., & Ebraheim, N. (2017). Review: Medial collateral ligament injuries. *Journal of Orthopaedics*, *14*(4), 550–554. https://doi.org/10.1016/j.jor.2017.07.017

Bahamonde, R. E. (2001). Biomechanics of the forehand stroke. *ITF Coaching and Sport Science Review*, 24,6–8.

Bates, N., Schilaty, N., Nagelli, C., Krych, A., & Hewett, T. (2019). Multiplanar loading of the knee and its influence on anterior cruciate ligament and medial collateral ligament strain during simulated landings and non-contact tears. *The American Journal of Sports Medicine*, *47*(8), 1844–1853. https://doi.org/10.1177/0363546519850165

Berns, G. S., Hull, M. L., & Patterson, H. A. (1992). Strain in the anteromedial bundle of the anterior cruciate ligament under combination loading. *Journal of Orthopaedic Research*, *10*(2), 167–176. https://doi.org/10.1002/jor.1100100203

Brindle, T., Nyland, J., & Johnson, D. L. (2001). The meniscus: Review of basic principles with application to surgery and rehabilitation. *Journal of Athletic Training*, *36*(2), 160–169. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC155528/

Chard, M., & Lachmann, S. (1987). Racquet sports–patterns of injury presenting to a sports injury clinic. *British Journal of Sports Biomechanics*, *21* (4), 150–153. http://dx.doi.org/10.1136/bjsm.21.4.150

De Vries, A., Koolhaas, W., Zwerver, J., Diercks, R., Nieuwenhuis, K., Van Der Worp, H., Brouwer, S., & Van Den Akker-Scheek, I. (2017). The impact of patellar tendinopathy on sports and work performance in active athletes. *Research in Sports Medicine*, *25*(3), 253–265. https://doi.org/10.1080/15438627.2017.1314292

Ellenbecker, T. (2006). The relationship between stroke mechanics and injuries in tennis. *The USTA Newsletter for Tennis Coaches*, *8*(2), 4–9. http://www.revolutionarytennis.com/Resources/usta-high-performance-vol-8-no-2.pdf

Elliott, B. (2003). *Biomécanique du tennis de haut niveau*. B. Elliott, M. Reid, & M. Crespo (Eds.), (p. 221). International Tennis Federation.

Escamilla, R., Fleisig, G., Zheng, N., Lander, J., Barrentine, S., Andrews, J., Bergemann, B. W., & Moorman, C. T. (2001). Effects of technique variations on knee biomechanics during the squat and leg press. *Medicine and Science in Sports and Exercise*, *33*(9), 1552–1566. https://doi.org/10.1097/00005768-200109000-00020

Fu, M. C., Ellenbecker, T. S., Renstrom, P. A., Windler, G. S., & Dines, D. M. (2018). Epidemiology of injuries in tennis players. *Current Reviews in Musculoskeletal Medicine*, *11*(1), 1–5. https://doi.org/10.1007/s12178-018-9452-9

Georgevia, D., Poposka, A., Dzoleva-Tolevska, R., Maneva-Kuzevska, K., Georgiev, A., & Vujica, Z. (2015). Osgood-Schlatter disease: A common problem in young athletes. *Research in Physical Education, Sport & Health*, *4*(2), 47–49. http://www.pesh.mk/PDF/Vol_4_No_2/8.pdf

Gescheit, D. T., Cormack, S. J., Duffield, R., Kovalchik, S., Wood, T. O., Omizzolo, M., & Reid, M. (2017). Injury epidemiology of tennis players at the 2011-2016 Australian Open Grand Slam. *British Journal of Sports Medicine*, *51*(17), 1289–1294. https://doi.org/10.1136/bjsports-2016-097283

Graf, E. S., & Stefanyshyn, D. (2013). The effect of footwear torsional stiffness on lower extremity and kinetics during lateral cutting movements. *Footwear Science*, *5*(2), 101–109. https://doi.org/10.1080/19424280.2013.789561

Hale, S. (2005). Etiology of patellar tendinopathy in athletes. *Journal of Sport Rehabilitation*, *14*(3), 258–272. https://doi.org/10.1123/jsr.14.3.259

Hellio Le Graverand, M. P., Ou, Y., Schield-Yee, T., Barclay, L., Hart, D., Natsume, T., & Rattner, J. B. (2001). The cells of the rabbit meniscus: Their arrangement, interrelationship, morphological variations and cytoarchitecture. *Journal of Anatomy*, *198*(5), 525–535. https://doi.org/10.1046/j.1469-7580.2000.19850525.x

Hewett, T. E., Myer, G. D., Ford, K. R., Heidt, R. S., Colosimo, A. J., McLean, S. G., van den Bogert, A. J., Paterno, M. V., & Succop, P. (2005). Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes: A prospective study. *The American Journal of Sports Medicine*, *33*(4), 492–501. https://doi.org/10.1177/0363546504269591

Hewett, T. E., Torg, J. S., & Boden, B. P. (2009). Video analysis of trunk and knee motion during non-contact anterior cruciate ligament injury in female athletes: Lateral trunk and knee abduction motion are combined components of the injury mechanism. *British Journal of Sports Medicine*, *43*(6), 417–422. https://doi.org/10.1136/bjsm.2009.059162

Hjelm, N., Werner, S., & Renstrom, P. (2010). Injury profile in junior tennis players: A prospective two year study. *Knee Surgery, Sports Traumatology, Arthroscopy*, *18*(6), 845–850. https://doi.org/10.1007/s00167-010-1094-4

Hughes, M., & Meyers, R. (2005). Movement patterns in elite men's singles tennis. *International Journal of Performance Analysis in Sport*, *5*(2), 110–134. https://doi.org/10.1080/24748668.2005.11868331

Iino, Y., & Kojima, T. (2003). Role of knee flexion and extension for rotating the trunk in a tennis forehand stroke. *Journal of Human Movement Studies*, *45*(2), 133–152. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3761834/pdf/jssm-12-339.pdf

Ishii, H., Nagano, Y., Ida, H., Fukubayashi, T., & Maruyama, T. (2011). Knee kinematics and kinetics during shuttle run cutting: Comparison of the assessments performed with and without the point cluster technique. *Journal of Biomechanics*, *44*(10), 1999–2003. https://doi.org/10.1016/j.jbiomech.2011.05.001

Jayanthi, N., Sallay, P., Hunker, P., & Przybylski, M. (2005). Skill-level related injuries in recreational competition tennis players. *Journal of Medicine and Science in Tennis*, *10*(1), 12–15.

Johnson, R., Pope, M., Weisman, G., & Ettlinger, C. (1979). Knee injury in skiing: A multifaceted approach. *The American Journal of Sports Medicine*, *7*(6), 321–327. https://doi.org/10.1177/036354657900700603

Kettunen, J. A., Kvist, M., Alanen, E., & Kujala, U. M. (2002). Long-term prognosis for jumper's knee in male athletes. A prospective follow-up study. *The American Journal of Sports Medicine*, *30*(5), 689–692. https://doi.org/10.1177/03635465020300051001

Kibler, B., & Safran, M. (2005). Tennis injuries. In Dennis J. Caine, Nicola Maffulli, (Eds). *Epidemiology of pediatric sports injuries. individual sports* (Vol. 48, pp. 120–137). Karger. (Medicine and Sport Science; vol. 48).

Kibler, W., & Safran, M. (2012). Musculoskeletal injuries in the young tennis player. *Clinics in Sports Medicine*, *19*(4), 781–792. https://doi.org/10.1016/S0278-5919(05)70237-4

Kovacs, M. S. (2006). Applied physiology of tennis performance. *British Journal of Sports Medicine*, *40*(5), 381–386. https://doi.org/10.1136/bjsm.2005.023309

Kuhne, C., Zettl, R., & Nast-Kolb, D. (2004). Injuries and frequency of complaints in competitive tennis and leisure sports. *Sportverletzung Sportschaden: Organ der Gesellschaft fur Orthopadisch-Traumatologische Sportmedizin*, *18*(2), 85–89. https://doi.org/10.1055/s-2004-813049.

Landlinger, J., Lindinger, S., Stoggl, T., Wagner, H., & Muller, E. (2010). Key factors and timing patterns in the tennis forehand of different skill levels. *Journal of Sports Science & Medicine*, *9*(4), 643–651. https://www.jssm.org/abstresearchajssm-09-643.xml.xml

Leardini, A., Cappozzo, A., Catani, F., Toksvig-Larsen, S., Petitto, A., Sforza, V., Cassanelli, G., & Giannini, S. (1999). Validation of a functional method for the estimation of hip joint centre location. *Journal of Biomechanics*, *32*(1), 99–103. https://doi.org/10.1016/S0021-9290(98)00148-1

Leong, H. T., Cook, J., Docking, S., & Rio, E. (2018). Physiotherapy management of patellar tendinopathy in tennis players. In Di Giacomo, Giovanni, Ellenbecker, Todd, Kibler, W. Ben (Eds.). *Tennis medicine: A complete guide to evaluation, treatment and rehabilitation* (pp. 401–414).

Majewski, M., Susanne, H., & Klaus, S. (2006). Epidemiology of athletic knee injuries: A 10-year study. *The Knee*, *13*(3), 184–188. https://doi.org/10.1016/j.knee.2006.01.005

Manske, R., & Paterno, M. (2018). Rehabilitation of knee injuries. In Di Giacomo, Giovanni, Ellenbecker, Todd, Kibler, W. Ben (Eds.). *Tennis medicine: A complete guide to evaluation, treatment, and rehabilitation* (pp. 415–438). Springer.

Markolf, K. L., Burchfield, D. M., Shapiro, M. M., Shepard, M. F., Finerman, G. A., & Slauterbeck, J. L. (1995). Combined knee loading states that generate high anterior cruciate ligament forces. *Journal of Orthopaedic Research*, *13*(6), 930–935. https://doi.org/10.1002/jor.1100130618

Meyer, E., Baumer, T., Slade, J., Smith, W., & Haut, R. (2008). Tibiofemoral contact pressures and osteochondral microtrauma during anterior cruciate ligament rupture due to excessive compressive loading and internal torque of the human knee. *The American Journal of Sports Medicine*, *36* (10), 1966–1977. https://doi.org/10.1177/0363546508318046

Meyer, E. G., & Haut, R. C. (2005). Excessive compression of the human tibio-femoral joint causes ACL rupture. *Journal of Biomechanics*, *38*(11), 2311–2316. https://doi.org/10.1016/j.jbiomech.2004.10.003

Muller, A., Pontonnier, C., Puchaud, P., & Dumont, G. (2019). CusToM: A Matlab toolbox for musculoskeletal simulation. *Journal of Open Source Software*, *4*(33), 927. https://doi.org/10.21105/joss.00927

Nesbit, S. M., Serrano, M., & Elzinga, M. (2008). The role of knee positioning and range-of-motion on the closed-stance forehand tennis swing. *Journal of Sports Science & Medicine*, *7*(1), 114–124. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3763335/

O'Connor, S., Huseyin, O. R., Whyte, E. F., & Lacey, P. (2020). A 2-year prospective study of injuries and illness in an elite national junior tennis program. *The Physician and Sportsmedicine*, *48*(3), 1–7. https://doi.org/10.1080/00913847.2020.1714512

Okholm Kryger, K., Dor, F., Guillaume, M., Haida, A., Noirez, P., Montalvan, B., & Toussaint, J.-F. (2015). Medical reasons behind player departures from male and female professional tennis competitions. *The American Journal of Sports Medicine*, *43*(1), 34–40. https://doi.org/10.1177/0363546514552996

Olsen, O., Myklebust, G., Engebretsen, L., & Bahr, R. (2004). Injury mechanisms for anterior cruciate ligament injuries in team handball: A systematic video analysis. *American Journal of Sports Medicine*, *32*(4), 1002–1012. https://doi.org/10.1177/0363546503261724

Quatman, C. E., & Hewett, T. E. (2009). The anterior cruciate ligament injury controversy: Is "valgus collapse" a sex-specific mechanism? *British Journal of Sports Medicine*, *43*(5), 328–335. https://doi.org/10.1136/bjsm.2009.059139

Rattner, J. B., Matyas, J. R., Barclay, L., Holowaychuk, S., Sciore, P., Lo, I. K. Y., Shrive, N. G., Frank, C. B., Achari, Y., & Hart, D. A. (2011). New understanding of the complex structure of knee menisci: Implications for injury risk and repair potential for athletes. *Scandinavian Journal of Medicine & Science in Sports*, *21*(4), 543–553. https://doi.org/10.1111/j.1600-0838.2009.01073.x

Reed, M., & Manary, M. L. S. (1999). Methods for measuring and representing automobile occupant posture. Technical Paper 990959. *SAE Transactions Journal of Passengers Cars*, *108*, 1–15.

Reid, M., Elliott, B., & Crespo, M. (2013). Mechanics and learning practices associated with the tennis forehand: A review. *Journal of Sports Science & Medicine*, *12*(2), 225–231. https://pubmed.ncbi.nlm.nih.gov/24149800/

Renström, A. (1995). Knee pain in tennis players. *Clinics in Sports Medicine*, *14*(1), 163–175. https://doi.org/10.1016/S0278-5919(20)30263-5

Renstrom, P., & Lynch, S. (2002). Knee injuries in tennis. In *Handbook of sports medicine and science: Tennis* (pp. 186–203). Great Britain, Wiley.

Richards, D. P., Ajemian, S. V., Wiley, J. P., & Zernicke, R. F. (1996). Knee joint dynamics predict patellar tendinitis in elite volleyball players. *The American Journal of Sports Medicine*, *24*(5), 676–683. https://doi.org/10.1177/036354659602400520

Roetert, E. P., Kovacs, M., Knudson, D. V., & Groppel, J. (2009). Biomechanics of the tennis groundstrokes: Implications for strength training. *Strength and Conditioning Journal*, *31*(4), 41–49. https://doi.org/10.1519/SSC.0b013e3181aff0c3

Schönborn, R. (2000). *Advanced techniques for competitive tennis*. Meyer & Meyer Sport, Limited.

Seeley, M. K., Funk, M. D., Denning, W. M., Hager, R. L., & Hopkins, J. T. (2011). Tennis forehand kinematics change as post-impact ball speed is altered. *Sports Biomechanics*, *10*(4), 415–426. https://doi.org/10.1080/14763141.2011.629305

Shin, C., Chaudhari, A., & Andriacchi, T. (2009). The effect of isolated valgus moments on ACL strain during single-leg standing: A simulation study. *Journal of Biomechanics*, *42*(3), 280–285. https://doi.org/10.1016/j.jbiomech.2008.10.031

Sigward, S., & Powers, C. M. (2006). The influence of experience on knee mechanics during side-step cutting in females. *Clinical Biomechanics*, *21*(7), 740–747. https://doi.org/10.1016/j.clinbiomech.2006.03.003

Yu, B., & Garrett, W. E. (2007). Mechanisms of non-contact ACL injuries. *British Journal of Sports Medicine*, *41*(Suppl. 1), i47–51. https://doi.org/10.1136/bjsm.2007.037192

Zaslow, T., Pace, J. L., Mueske, N., Chua, M., Katzel, M., Dennis, S., & Wren, T. A. L. (2016). Comparison of lateral shuffle and side-step cutting in young recreational athletes. *Gait & Posture*, *44*, 189–193. https://doi.org/10.1016/j.gaitpost.2015.12.019

Zatsiorsky, V., Seluyanov, V., & Chugunova, L. (1990). Methods of determining mass-inertial characteristics of human body segments. In G. Chernyi & S. Regirer (Eds.), *Contemporary problems of biomechanics*. (pp. 272–291). CRC Press.

Zusa, A., Lanka, J., & Vagin, A. (2010). Biomechanical analysis of forehand in modern tennis. *LASE Journal of Sport Science*, *1*(1), 13–17. http://journal.lspa.lv/files/Archive/LASE_JOURNAL_OF_SPORT_SCIENCE_V_1_2010_No_1.pdf