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

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20 17
21 18
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23 20
24 21 **Word count:** 4917 words

25 22 **Abstract**

26 23 The open stance forehand has been hypothesized to be more traumatic for knee injuries in tennis than
27 24 the neutral stance forehand. This study aims to compare kinematics and kinetics at the knee during three
28 25 common forehand stroke stances (attacking neutral stance ANS, attacking open stance AOS, defensive
29 26 open stance DOS) to determine if the open stance forehand induces higher knee loadings and to discuss
30 27 its potential relationship with given injuries. Eight advanced tennis players performed eight repetitions
31 28 of forehand strokes with each stance (ANS: forward run and stroke with feet parallel with the hitting
32 29 direction, AOS: forward run and stroke with feet perpendicular to the hitting direction, DOS: lateral run
33 30 and stroke with feet perpendicular to the hitting direction) at maximal effort. All the trials were recorded
34 31 with an optoelectronic motion capture system. The flexion-extension, abduction-adduction, external-
35 32 internal rotation angles, intersegmental forces and torques of the right knee were calculated. Ground
36 33 reaction forces were measured with a forceplate. The DOS increases vertical GRF, maximum knee
37 34 flexion and abduction angles, range of knee flexion-extension, peak of compressive, distractive and
38 35 medial knee forces, peak of knee abduction and external rotation torques. Consequently, the DOS
39 36 appears potentially more at risk for given knee injuries.

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63 30 **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^{1 2}. Each change of direction creates a load of 1.5 to 2.7 times body weight on the planted knee and ankle³. Due to the repetitive loadings during matches, which can last up to 5 hours, lower limb injuries are very common in tennis players^{4 5}.

Knee injuries concern 19% of tennis injuries^{6 7}. 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 Slam⁸. For junior tennis players, ankle sprain, low back pain and knee injuries are the most common⁹. In recreational competitive players, the knee concerns 12% of all injuries¹⁰. The majority (60 – 74%) of the knee injuries in tennis players are classified as overuse^{9 11} 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^{9 11 12}. These knee injuries can be particularly problematic not only for players' performance and career but also for their work and daily quality of life¹³. 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)^{14 15}. The dominant knee is involved in 57% of injuries in tennis players⁹.

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 forehand¹⁶. Moreover, it has been shown that initial knee positioning and range-of-motion are positively related to racket velocity during the forehand¹⁷.

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 stance¹⁸. However, with the game acceleration during the last decades, high-level tennis players give priority to open stances for saving time during defensive baseline forehands¹⁹. For example, it has been reported that Federer hit 77% of his forehands with an open stance during a set played against Falla¹⁹ 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 stance²⁰. 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 position²¹. The open stance forehand is thought to be more traumatic than the neutral one because it could

70 increase loadings on the dominant side leg and consequently favor injuries appearance in lower limb
71 injuries of tennis players²². However, there is no data in the literature about the influence of the forehand
72 stance on lower limb biomechanics and injury risks for the dominant knee. Consequently, it remains
73 unclear if one of the forehand stances could increase knee injuries. Yet, such scientific information is
74 crucial for coaches, scientists, physiotherapists and medical staff to improve the prevention,
75 management and rehabilitation of knee injuries in players.

76 Consequently, this study aims to evaluate knee kinematics and kinetics during three common
77 forehand stroke stances (attacking neutral stance ANS¹, attacking open stance AOS, defensive open
78 stance DOS) to know if the open stance forehand induces higher knee loadings and to discuss its
79 potential relationship with given knee injuries

81 2. Materials and methods

82 8 right-handed male tennis players (age: 26.3 ± 11.0 years; height: 1.76 ± 0.02 m; weight: 65.9
83 ± 4.6 kg) voluntarily participated in this study. Inclusion criteria consisted of uninjured advanced tennis
84 players with an International Tennis Number (ITN) of 4 or 5 (International Tennis Federation, 2009)
85 and the ability to properly perform each forehand stroke stance (ANS, AOS, DOS). The ITN is a tennis
86 rating, internationally recognized, that represents a player's general level of play. The International
87 Tennis Federation (2009) describes the level of ITN 4 and ITN 5 players as follows: "*ITN 4 players can*
88 *use power and spins and have begun to handle pace. They have sound footwork, can control depth of*
89 *shots, and can vary game plan according to opponents.*" "*ITN 5 players have dependable strokes,*
90 *including directional control and depth on both groundstrokes and on moderate shots. The players have*
91 *the ability to use lobs, overheads, approach shots and volleys with some success.*" The ability of the
92 players to properly perform each forehand stroke stance was confirmed by a professional tennis coach.

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

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

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

104 allowing the investigators to adapt the impact height according to the players' height and the type of
105 forehand strokes (Fig. 1).

106
107 ***** Fig. 1 near here*****

108 For the AOS and the ANS, the players ran a total distance of 6.2m. For the ANS, the players
109 ran along a 45° line (3.6m) on the left side of the force plate before stepping onto the plate with the right
110 leg to execute a jab run. Then, they placed their left leg in front of the right leg. Consequently, they hit
111 the foam ball with a neutral stance (feet parallel with the hitting direction, left leg in front of the right
112 leg located on the force plate). They left the plate at 45° angle towards the left until the finishing point
113 (Fig. 1a). The height of the foam ball was adjusted to the right hip' height of each player to simulate an
114 attacking neutral stance forehand.

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

119 For the DOS, the players performed a 9.6m lateral shuttle run. First, they started from a standing
120 position. After a split step, they laterally ran towards the force plate (Fig. 1c). When the force plate was
121 reached, they stepped onto the plate with the right leg, performed an open stance with the feet
122 perpendicular to the hitting direction (left leg beside the right leg), and hit the foam ball. Then, they ran
123 back to the starting point. The distance between the starting point and the middle of the force plate was
124 4.8m. The height of the foam ball was adjusted to the right pocket's height of each player to simulate a
125 defensive forehand. The characteristics of the movement patterns (covered distances, lateral shuttle run
126 in DOS, jab run in ANS and AOS) and forehands strokes (attacking and defensive strokes) have been
127 validated by a professional tennis coach and have been chosen because they are reported to occur
128 frequently in tennis ^{19 23 24}. For the DOS, five steps were performed before landing on the force plate
129 while for the ANS and AOS, four steps were performed before landing on the force plate to ensure that
130 a maximal speed was achieved, as recommended in the literature ²⁵.

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132 Players were equipped with 38 retroreflective markers placed on anatomical landmarks determined
133 in agreement with previously published data ^{26 27 28}. A Vicon motion capture system (Oxford Metrics
134 Inc., Oxford, UK) was used to record the trajectories of the 3-dimensional anatomical landmarks. The
135 system was composed of 20 high-resolution cameras (4 megapixels) operating at a nominal frame of
136 200 Hz. Players were shirtless and wore only tight short to limit movement of the markers. After the
137 capture, the 3D coordinates of the landmarks were reconstructed with Blade software (Blade; Vicon,
138 Oxford, UK) with a residual error of less than 1 mm. A force platform operating at 2000 Hz (60 x 120
139 x 5.7 cm, Advanced Mechanical Technology Incorporation, Watertown, MA, USA) was used to
140 measure peak of ground reaction forces (GRF) on the right step during forehand strokes. All the right

141 knee kinetic and kinematic data were processed with CusTom in Matlab software (Mathworks, Natick,
142 Massachusetts, USA), which is a Customizable Toolbox for Musculoskeletal simulation allowing to
143 solve inverse kinematics and inverse dynamics from motion capture data ²⁹.

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

147 One-way analyses of variance (ANOVAs) with repeated measures were used to analyze differences
148 in GRF, knee kinematics and kinetics between the 3 forehand stances (ANS, AOS, DOS). Significant
149 main effects were decomposed using post hoc Holm-Sidak method to determine the source of difference.
150 To determine the clinical relevance of differences, each post hoc contrast was presented using a mean
151 difference (MD). Where data were not normally distributed, significance was determined using ANOVA
152 with repeated measures on ranks and a post hoc Tukey test. Mean and SD values were computed for all
153 parameters. The effect sizes were calculated and the clinical significance of the differences was
154 classified as small (Cohen's $d < 0.2$), medium (Cohen's $d = 0.5$), or large (Cohen's $d > 0.8$), according
155 to the Cohen scale. The level of significance was established at $p < 0.05$ (SigmaStat 3.1; Jandel
156 Corporation, San Rafael, CA). In accordance with Altman (1991), statistical result with p value between
157 0.05 and 0.1 is reported as tendency towards a difference³⁰.

159 2. Results

160 2.1 Absolute running velocity of the center of mass at the instant of the first contact between the right 161 foot and the force plate

162 Results show a significant main effect of the type of forehand stances on the absolute running velocity
163 of the center of mass at the instant of the first contact between the right foot and the force plate (p
164 < 0.002 ; retrospective statistical power = 0.949). Post hoc tests reveal that the absolute running velocity
165 was significantly higher in ANS ($3.7 \text{ m}\cdot\text{s}^{-1}$) and AOS ($3.6 \text{ m}\cdot\text{s}^{-1}$) than in DOS ($3.2 \text{ m}\cdot\text{s}^{-1}$) (respectively,
166 MD: $0.5 \text{ m}\cdot\text{s}^{-1}$; $p < 0.001$; respectively, MD: $0.4 \text{ m}\cdot\text{s}^{-1}$; $p = 0.006$).

168 2.2. Ground reaction forces

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

177 ***** Table 1 near here *****

2.3. 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 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 toward 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).

***** Table 2 near here *****

2.4. Knee kinetics

3.3.1. 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 $p = 0.004$).

214 ***** Table 3 near here *****

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3 216 *3.3.2. Knee joint torques*

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5 217 Significant main effects are recorded in knee flexion ($p = 0.013$, retrospective statistical power
6 218 = 0.728), abduction ($p < 0.001$, retrospective statistical power = 1.000), internal ($p < 0.001$, retrospective
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8 219 statistical power = 0.998) and external torques ($p < 0.001$, retrospective statistical power = 0.976)
9
10 220 between the forehand stances (Table 4). Post hoc tests show that the DOS involves significantly greater
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12 221 peak of flexion knee torque than ANS (MD: 60.3 Nm and $p = 0.004$) (Table 4). There is a tendency
13 222 toward a difference in comparison with AOS (MD: 31.9 Nm and $p = 0.087$). The peak of internal knee
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15 223 joint torque is significantly higher in ANS than in DOS (MD: 17.2 Nm and $p < 0.001$) and AOS (MD:
16 224 18.7 Nm and $p < 0.001$). Conversely, the peak of external knee joint torque is increased in DOS in
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18 225 comparison with ANS (MD: 24.0 Nm and $p < 0.001$) and AOS (MD: 20.5 Nm and $p < 0.001$). The peak
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20 226 of abduction knee joint torque is significantly higher in DOS than in ANS (MD: 146.5 Nm and $p < 0.001$)
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22 227 and AOS (MD: 128.5 Nm and $p < 0.001$).

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25 229 ***** Table 4 near here *****

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28 231 **4. Discussion**

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30 232 This study aims to evaluate 3-dimensional knee kinematics and kinetics during three common
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32 233 forehand stroke stances (attacking neutral stance ANS, attacking open stance AOS, defensive open
33 234 stance DOS) to determine if the open stance forehands induces higher knee loadings and to discuss its
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35 235 potential relationship with several well-known knee injuries.

36 236 The DOS significantly increases lateral and vertical GRF. Among the three forehand stances, the
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38 237 DOS induces the highest magnitude of flexion and abduction at the dominant knee. Moreover, the DOS
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40 238 produces the greatest peak of compressive, distractive and medial forces at the dominant knee. Knee
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42 239 abduction, flexion and external torques are significantly increased with DOS in comparison with ANS
43 240 and AOS. All these results confirm the formulated hypothesis that the dominant knee is more loaded
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45 241 with the open stance forehand during defensive shots. Consequently, the DOS could increase the risk of
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47 242 having knee injuries for tennis players.

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50 244 *4.1. Forehand stance effects on knee biomechanics*

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52 245 The magnitude of running velocity, knee kinematics and kinetics measured in the current study are
53 246 similar or slightly higher than previous published results during side-step or shuttle run cutting in young
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55 247 athletes^{31 32 33}. However, our results demonstrate clear knee kinematic and kinetic differences between
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57 248 the three common forehand stroke stances which can be explained in the light of literature. The forehand
58 249 stroke involves a sequence of motions referred to as a 'kinetic chain' that begins with the lower limb
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60 250 action and is followed by the trunk and then the upper limb. The knee joint allows to transfer a maximum

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251 of energy from the lower limb to the hips and trunk. During the forehand, the vigorous flexion and
1 252 extension of the knee contributes to the subsequent rotational drive of the hips and trunk to increase
2 racket velocity during ball impact ³⁴. Our results show that knee flexion angle and torque are
3 253 significantly higher in DOS than in AOS and ANS. This is logical since the ball height was lower in
4 254 DOS to simulate defensive forehand strokes in our protocol. Moreover, the DOS significantly increases
5 lateral and vertical GRF. One plausible explanation is the difference in the movement plane of study,
6 255 which was executed predominantly in the medial-lateral and vertical directions during defensive
7 256 forehand open stance strokes (DOS), compared with attacking forehand neutral stance strokes (ANS)
8 257 that was executed in the anterior-posterior directions ^{35 36}. Knee abduction and external torques are
9 significantly increased with DOS. This result seems logical because, during open stance strokes, players
10 258 need to create higher amount of angular momentum about the longitudinal axis, than in neutral stance
11 259 strokes, from greater knee and hip rotations to generate power at impact ^{35 36}.

21 264 *4.2. Forehand stance effects on risks of knee injuries*

23 265 *4.2.1. Patellar tendinopathy and knee osteoarthritis*

25 266 During tennis practice, players can suffer from anterior knee pain, which is commonly called
26 267 jumper's knee ³⁷. This pain is also referred to as patellar tendinopathy that is a pathology affecting the
27 bone-tendon junction during jumping, bending, cutting or pivoting actions performed by tennis players
28 268 ¹⁴. In the literature, the mechanisms of patellar tendinopathy are multifactorial, both intrinsic and
29 269 extrinsic factors have been identified. Among them, knee joint kinematics and loadings are considered
30 270 as extrinsic risks for athletes. Indeed, for example, in elite volleyball players, it has been shown that
31 271 maximum vertical GRF, maximum knee flexion angle, and peak knee external-rotation moment during
32 272 spike-jump and block-jump takeoff or landing are strong and reliable indicators of patellar tendinitis in
33 273 the dominant knee ³⁸. In our study, the magnitude of vertical GRF and maximal knee flexion angle in
34 274 DOS are similar to the values measured during the take-off phase of both spike and block jumps in
35 275 volleyball players ³⁸. Our results show that the DOS significantly increases vertical GRF in comparison
36 276 with ANS and AOS. Moreover, the DOS induced higher maximum knee flexion angle than the two
37 277 other stances, higher range of knee flexion-extension than AOS, and higher peak of compressive knee
38 278 force than ANS. All these elements may lead to focal degeneration and microtears in the patellar tendon
39 279 of athletes ³⁷. Consequently, one may argue that the continual repetition of compressive forces on the
40 280 dominant knee during DOS in tennis players could increase the risk of patellar tendinopathy and joint
41 281 osteoarthritis.

54 284 *4.2.2 Osgood-Schlatter's disease*

56 285 The Osgood-Schlatter's disease is a highly common knee injury in junior tennis players ^{39 9}. The
57 286 pain is located at the insertion of the patellar tendon into the tibia. In growing individuals, the soft tissues
58 287 such as tendon and muscles are stronger than the bone ⁵. It is known that excessive and repetitive tensile

288 or distractive forces may cause Osgood-Schlatter's disease by fragmenting the tendon's insertion ¹². Our
1 289 results show that the peak of distractive knee force is significantly more important during DOS than
2
3 290 during ANS and AOS. Consequently, the repetition of DOS forehands could be riskier for Osgood-
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5 291 Schlatter's disease in tennis players.

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8 293 4.2.3. *Meniscus tears*

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10 294 The meniscus aims to absorb shock and distribute stress to protect the knee. It allows joint
11 295 stabilization and margins protection. Moreover, it facilitates joint gliding and provides articular cartilage
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13 296 lubrication and nutrition ⁴⁰. As a result of excessive knee pivoting motion, meniscus tears are very
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15 297 common among tennis players ⁴¹, especially in middle-aged and elderly players ⁵. Injury risks for the
16 298 meniscus include loadings that exceeds the structural integrity of the tissue ⁴². In athletes, menisci
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18 299 injuries are mainly produced by a compressive force coupled with tibiofemoral external or internal
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20 300 rotation as the knee moves from flexion to extension during rapid change of direction ⁴⁰. While it is
21 301 known that excessive loading of the menisci can lead to degenerative changes, it is not known at what
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23 302 magnitude compressive forces and rotation torques become injurious to cartilage⁴³. In this study, the
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25 303 results show that the peak of compressive knee force, the maximal knee flexion angle and the external
26 304 rotation knee torque are significantly higher in DOS than in ANS. Moreover, while some areas of the
27
28 305 meniscus aim to absorb compressive loads (inner sections), other meniscus areas deal with distractive
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30 306 loads (outer areas) ⁴⁴. DOS induces more extreme distractive knee force than the two other stances.
31 307 Consequently, all these results lead us to believe that the DOS could be potentially more traumatic for
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33 308 meniscus in tennis players.

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36 310 4.2.4. *Anterior cruciate ligament (ACL)*

38 311 ACL injuries often occur without physical contact between athletes in sports with sudden
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40 312 deceleration, landing and pivoting motions ⁴⁵. From a mechanical point of view, it can be the case when
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42 313 an athlete himself produces great forces and moments on his knee, generating excessive loading on the
43 314 ACL which can break. In tennis, the ACL injury is usually induced by a cutting motion toward one side,
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45 315 followed by a quick twisting motion toward the other side ¹². However, ACL rupture is not a common
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47 316 injury during tennis playing. Indeed, a study reported a 2% overall ACL rupture incidence from tennis
48 317 related injuries ⁴⁶. Another study reported that 11% of knee injuries in tennis players concern ACL injury
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50 318 ⁴⁷. Knee abduction or valgus, internal rotation and anterior shear force at the tibia have been associated
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52 319 with non-contact ACL injuries in video studies describing ACL mechanisms during sport motions ^{48 49}
53 320 ⁵⁰ but also in cadaver studies ^{51 52}. Hewett et al. (2005, 2009) reported that maximal knee flexion and
54
55 321 abduction angles, maximal knee abduction torque and maximal vertical GRF were significantly higher
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57 322 in ACL-injured than in injured athletes during a jump-landing task ⁴⁸ or a cutting task ⁴⁹. Consequently,
58 323 all these parameters are considered as predictors of anterior cruciate ligament injury risk in athletes. Our
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60 324 results demonstrate that maximal knee flexion angle, maximal knee abduction angle and torque, and

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325 peak of vertical GRF are significantly higher in DOS. All these values measured in DOS are similar or
1 326 higher than those reported by Hewett et al. (2005, 2009) ^{48 49}.

3 327 Moreover, it has been reported that excessive compressive loads caused by impact loads along the
4 328 tibial shaft (e.g., load from a powerful stroke) may contribute to ACL injuries, especially when the knee
5 329 is flexed ^{53 54}. In our study, the peak of compressive knee force is significantly higher in DOS and is
6 330 close to the peak compression loads for ACL failure measured in human cadavers (2900 N) ^{53 54}. There
7 331 is a tendency toward a difference between the three stances concerning peak of anterior knee force with
8 332 the highest values observed in AOS. AOS also tends to produce higher peak of compressive knee force
9 333 than ANS. There is no significant difference concerning internal and external rotation knee angles
10 334 between the three stances. But the internal rotation knee torque is significantly higher in ANS, even if
11 335 the values are quite small. All these results suggest that DOS and AOS could be potentially more at risk
12 336 for ACL injuries. However, they have to be interpreted with caution because among knee abduction,
13 337 internal rotation torques, anterior and compressive forces, some debates exist about the main
14 338 biomechanical contributor in non-contact ACL injuries ^{55 45}.

23 339 24 25 340 4.2.5 Medial collateral ligament (MCL)

26 341 The main function of the MCL is to stabilize the medial side of the knee joint. Its role is very
27 342 important for providing support against valgus stress, rotational forces, and anterior translational forces
28 343 on the tibia ⁵⁶. In tennis, the MCL is the most commonly injured knee ligament ¹². The injury usually
29 344 occurs during a twisting situation when the knee is forced into a valgus position with external rotation⁴².
30 345 For example, it has been reported that MCL strain increases with the increase of knee abduction moment
31 346 (between 2 and 115 N.m⁻¹) in cadavers⁵⁷ and in a simulation study ⁵⁸. Moreover, in ski accidents, it has
32 347 been reported that the moments required to rupture the MCL were estimated at 92 N.m⁻¹ for knee
33 348 abduction moment and 123 N.m⁻¹ for external moment through a simple model ⁵⁹. In our study, the
34 349 results show that maximal knee abduction angle, peak of knee abduction and external rotation torques
35 350 are significantly higher in DOS (16°, 230 N.m⁻¹, 52 N.m⁻¹, respectively). Moreover, the peak of knee
36 351 medial force increases significantly in DOS. As a result, DOS seems riskier for MCL injuries.

37 352 38 353 4.3. Limitations

39 354 This study has some limitations. First, our sample size is limited because we only included
40 355 advanced tennis players and their participation was voluntary. Some results tend to show differences
41 356 between forehand stances' biomechanics. It seems reasonable to assume that nonsignificant results are
42 357 due to lack of power caused by the small number of subjects involved in the study. Second, players were
43 358 asked to hit a foam tennis ball and the forehand strokes were simulated and not played "under time
44 359 pressure" as it is the case during training sessions or matches. Since the data were collected in simulated
45 360 stroking conditions with ITN 4 or 5 skilled players, the results may not be generalizable to other skills
46 361 levels or match play conditions.

362 Moreover, knee joint kinetics were measured using the inverse dynamics method.
1 363 Musculoskeletal modeling and computer simulations could have been provided complementary results
2 364 on knee muscle and ligament forces during the forehand strokes. Finally, the etiology of the injuries in
3 365 tennis players reveals that numerous extrinsic (playing surface, racquet properties) and intrinsic (age,
4 366 sex, volume of play, skill level, biomechanics, anatomy, range of motion) risk factors are implied in the
5 367 occurrence of injuries⁶⁰. In this study, we restricted our research to biomechanical data concerning knee
6 368 kinematics and kinetics across three common forehand stances. It could be interesting for further studies
7 369 to combine biomechanical analysis and prospective registration of knee injuries to specifically assess
8 370 the relation between specific forehand stance patterns and knee injury risks. Furthermore, it could be
9 371 relevant to also analyze the influence of semi-open stance on knee kinetics and kinematics.

16 372 17 373 4.4. Conclusion

18 374 To conclude, this study aimed to compare knee kinematics and kinetics in tennis players during
19 375 three common forehand stroke stances (attacking neutral stance ANS, attacking open stance AOS,
20 376 defensive open stance DOS). Tennis experts generally believe that the forehand open stance constitutes
21 377 a risk factor for dominant leg injuries in tennis²². Our findings are in line with this hypothesis by
22 378 showing that the DOS increases vertical GRF, maximum knee flexion and abduction angles, range of
23 379 knee flexion-extension, peak of compressive, distractive and medial knee forces, peak of knee abduction
24 380 and external rotation torques. Consequently, the DOS appears potentially more at risk for given knee
25 381 injuries: patellar tendinopathy, knee osteoarthritis, Osgood-Schlatter's disease, meniscus tears, ACL and
26 382 MCL. Coaches with players suffering from knee pain or injuries should encourage them to use more
27 383 neutral stance and to develop aggressive playing style to avoid defensive open stance where knee
28 384 motions and loadings are more extreme, especially in young or elderly players. After knee rehabilitation
29 385 program, players should favor the use of neutral stance to reduced loadings on the dominant knee during
30 386 forehand strokes.

31 387 32 388 **Disclosure of interest**

33 389 The authors report no conflict of interest.
34 390

35 391 **References**

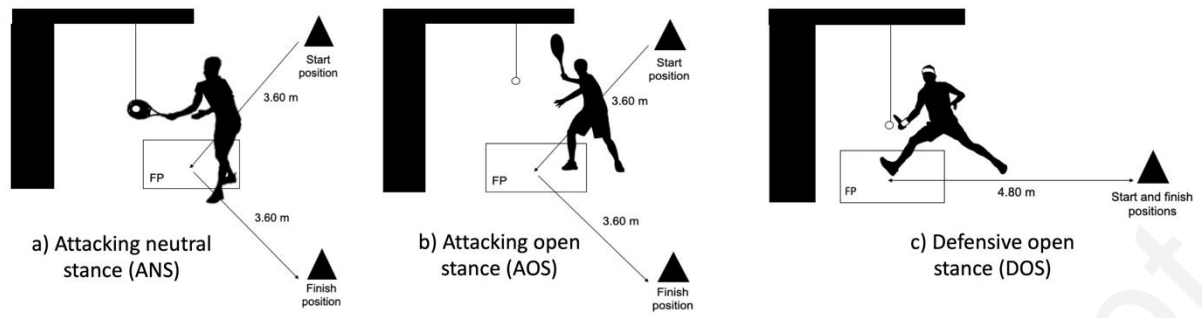
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551 Figure 1



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554 Figure caption

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

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Figure 1

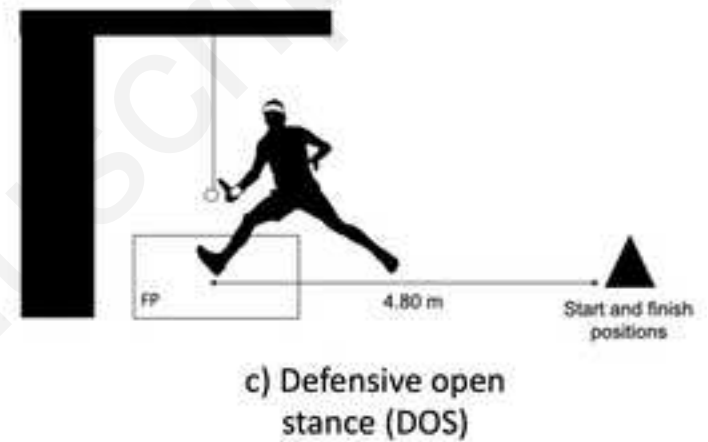
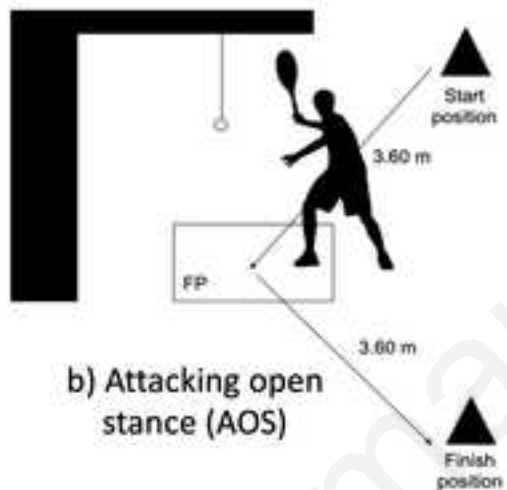
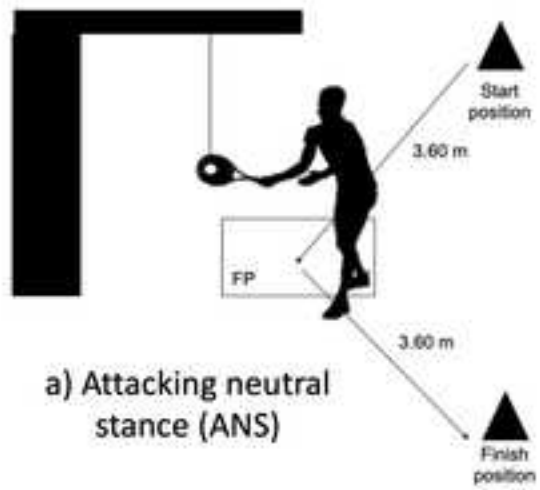


Table 1

Statistical comparison of GRF peaks across the 3 forehand stances.

GRF (N)	ANS	AOS	DOS	ANOVA <i>p</i> value	Effect size <i>d</i>	Post Hoc Differences <i>p</i> 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 toward a difference between defensive open stance and attacking open stance forehands.

Table 2

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

Knee kinematics (°)	ANS	AOS	DOS	ANOVA <i>p</i> value	Effect size <i>d</i>	Post Hoc Differences <i>p</i> 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 toward a difference between defensive open stance and attacking open stance forehands. DOS-ANS^T, tendency toward 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 <i>p</i> value	Effect size <i>d</i>	Post Hoc Differences <i>p</i> 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 toward 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 <i>p</i> value	Effect size <i>d</i>	Post Hoc Differences <i>p</i> 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 toward a difference between defensive open stance and attacking open stance forehands.