Can the Open Stance Forehand Increase the Risk of Hip Injuries in Tennis Players?

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Background: The open stance forehand has been hypothesized by tennis experts (coaches, scientists, and clinicians) to be more traumatic than the neutral stance forehand as regards hip injuries in tennis. However, the influence of the forehand stance (open or neutral) on hip kinematics and loading has not been assessed.

Purpose: To compare the kinematics and kinetics at the hip joint during 3 common forehand stances (attacking neutral stance [ANS], attacking open stance [AOS], defensive open stance [DOS]) in advanced tennis players to determine whether the open stance forehand induces higher hip loading.

Study Design: Descriptive laboratory study.

Methods: The ANS, AOS, and DOS forehand strokes of 8 advanced right-handed tennis players were recorded with an optoelectronic motion capture system. The flexion-extension, abduction-adduction, and external-internal rotation angles as well as intersegmental forces and torques of the right hip were calculated using inverse dynamics.

Results: The DOS demonstrated significantly higher values than both the ANS and AOS for anterior ($P < .001$), medial ($P < .001$), and distractive ($P < .001$) forces as well as extension ($P = .004$), abduction ($P < .001$), and external rotation ($P < .001$) torques. The AOS showed higher distractive forces than the ANS ($P = .048$). The DOS showed more extreme angles of hip flexion ($P < .001$), abduction ($P < .001$), and external rotation ($P = .010$).

Conclusion: The findings of this study imply that the DOS increased hip joint angles and loading, thus potentially increasing the risk of hip overuse injuries. The DOS-induced hip motion could put players at a higher risk of posterior-superior hip impingement compared with the ANS and AOS.

Clinical Relevance: Coaches and clinicians with players who have experienced hip pain or sustained injuries should encourage them to use a more neutral stance and develop a more aggressive playing style to avoid the DOS, during which hip motion and loading are more extreme.

Keywords: tennis; biomechanics; hip; femoroacetabular impingement; general sports trauma; forehand stance

Tennis is a sport that induces high loading in the hip joint[34] because it involves quick, intense, and repeated start-stop movements, during which players perform sudden changes of direction while running and striking a ball at high speeds.[26] The forehand stroke places high demands on the hips and knees.[23] When hitting forehands, players can use different types of stances, which refer to feet and hip placement during the stroke: the neutral, semi-open, and open stances. For the neutral stance, the player's feet and hips are perpendicular to the net, while they are parallel to the net for the open stance. The semi-open stance describes any foot positioning between the neutral and open stances. When the ball speed is reduced and players are in attacking position on the court, the majority of forehand shots are played in the neutral stance.[27] However, with the game accelerating over recent decades, high-level tennis players give priority to open stances to save time during defensive baseline forehands.[41] Tennis experts (including scientists and clinicians) have hypothesized that the prevalence of the open stance forehand during the past few decades could explain the increase in hip injuries in high-level tennis players.[10,45]

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Hip pain and injuries are a growing problem for tennis players, coaches, and medical staff.[45] These injuries have been reported to occur in 8% to 27% of tennis players.[1] The number of hip injuries in male professional tennis players increased from fewer than 10 in 2012 to more than 150 in 2016.[16] In 2012, 18% of the 125 professional female tennis players examined on the WTA Tour noted a history of hip or groin pain.[44] On the ATP Tour, several famous top 10–ranked professional players (including Magnus Norman, Gustavo Kuerten, Andy Murray, Bob Bryan, and Tommy Haas) sustained severe hip injuries and required surgery, thereby affecting their subsequent career paths.[38]

In elite tennis, the prevalence of femoroacetabular impingement (FAI) has been reported to be 1.3 per 100 players.[21] When there is abnormal contact of the femur with the acetabular rim, FAI can occur anteriorly or posteriorly.[5,14,19] With repetitive loading, this femoroacetabular mismatch can be a source of labral and chondral damage.[9] Cotorro et al[8] clinically examined the hips of 148 young elite tennis players and showed that 62% of them were identified as having a hip that would be considered at risk for FAI.

To improve diagnosis and rehabilitation strategies, the estimation of forces across the hip joint is relevant because it can provide insight into the cause of hip pain in athletes.[29] Abnormal or excessive hip loading can cause anterior pain, acetabular labral tears, and subtle hip instability.[32,47,48] In the literature, it is believed that the open stance forehand places the player more at risk than the neutral stance by causing higher joint loading and could be responsible for shoulder, trunk, and hip injuries in elite tennis players.[10,45] However, studies have demonstrated no effect of stance on lumbar, trunk, or upper-extremity mechanics.[3,6,25] As regards hip injuries in tennis players, no scientific study has focused on the biomechanical effect of the forehand stance on lower limb biomechanics. Consequently, the link between forehand stance and hip joint pain and injuries is still unclear. Yet, such scientific information is crucial for tennis experts to improve the prevention, management, and rehabilitation of hip injuries in tennis players.

Therefore, the purpose of this study was to measure the 3-dimensional kinematics and kinetics at the hip joint during 3 common forehand stances (attacking neutral stance [ANS], attacking open stance [AOS], and defensive open stance [DOS]) to determine whether the open stance forehand induces higher hip loading that could explain some overuse injuries. It was hypothesized that the DOS would involve the greatest magnitudes of flexion, abduction, and external rotation at the hip and greater loading (forces and torques) in the dominant hip.

METHODS

Participants

A total of 8 right-handed advanced male tennis players (mean age, 26.3 ± 11.0 years; mean height, 1.76 ± 0.02 m; mean weight, 65.9 ± 4.6 kg), with an International Tennis Number of 4 or better, participated voluntarily in this study. Prior to their participation, the players were fully informed of the experimental procedure. At the time of testing, all the players were considered healthy with no pain or injuries. Written consent was obtained from each player. The study was approved by the local ethics committee and conducted in accordance with the 1975 Declaration of Helsinki.

Experimental Protocol

Before motion capture, participants viewed a demonstration of the experimental procedure and the 3 forehand stances (ANS, AOS, and DOS), which were performed by a professional coach. They had all the time they needed to familiarize themselves with the testing environment and the landmarks set as well as to test all forehand stances (ANS, AOS, and DOS). After a warm-up of 10 minutes, each player performed 8 forehand strokes with each stance at maximal effort. The order of the forehand 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 could. The foam tennis ball was fixed and attached to a scaffold with a rope, allowing investigators to adapt the impact height according to the player's height and type of forehand stroke (Figure 1).

For the DOS, the players performed a 9.6-m shuttle run. Players started from a standing position. After a split step, they ran laterally toward the force plate (Figure 1C). The distance between the starting point and the middle of the force plate was 4.8 m. Then, they ran back to the starting point. The height of the foam ball was adjusted to the height of each player's right pocket to simulate a defensive forehand. Such lateral movements and forehand strokes have been reported to occur frequently in tennis.[43] For the AOS, the players ran forward along a 45° lane on the left side of the force plate. Once the force plate was reached, they stepped onto the plate with the right foot, hit the foam ball with an open stance, and left the plate at a 45° angle toward the left until the finishing point (Figure 1B). For the ANS, the running motion was similar to the AOS, but the players were asked to hit the ball with a neutral stance (Figure 1A). For the AOS and the ANS, the players ran a total distance of 6.40 m. The height of the foam ball was adjusted to the height of each player's right shoulder to simulate attacking forehand conditions. The ability of the players to properly perform each forehand stance was confirmed by a professional tennis coach.

Players were equipped with 38 retroreflective markers placed on anatomic landmarks determined in agreement with previously published data.[28,40,50] A motion capture system (Vicon) was used to record the 3-dimensional trajectories of retroreflective markers on the landmarks. The system was composed of 20 high-resolution cameras (4 megapixels) operating at a nominal frame rate of 200 Hz. Players were shirtless and wore only tight shorts to limit movement of the markers. After motion capture, the 3-dimensional coordinates of the landmarks were reconstructed with Blade software (Vicon) with a residual error of less than 1 mm. A force platform operating at 2000 Hz ($0.60 \times 1.20 \times 0.06$ m; AMTI) was used to measure

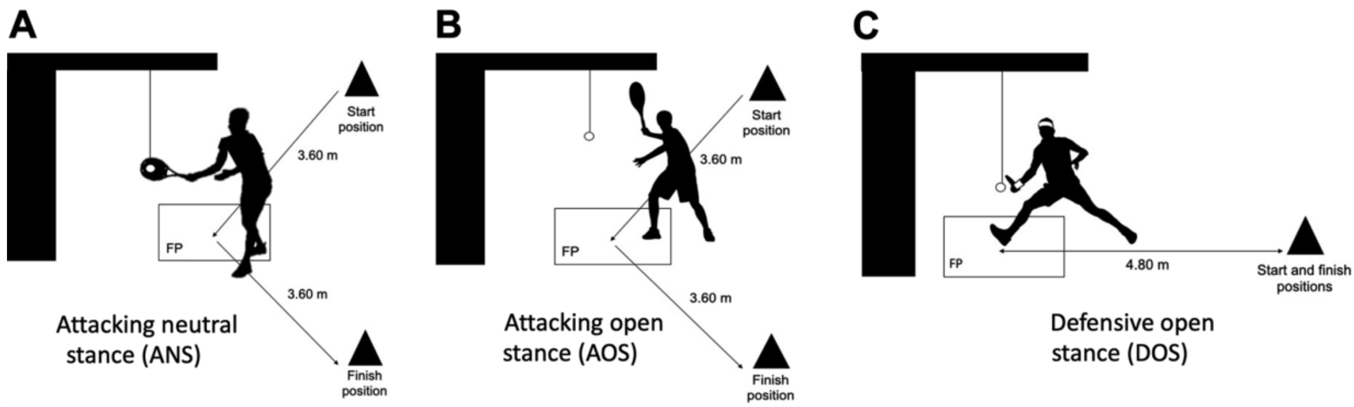

Figure 1. Experimental setup protocol with the 3 forehand stances. FP, force plate.

TABLE 1
GRF Peaks Across the 3 Forehand Stances[a]

	ANS	AOS	DOS	*P* Value (ANOVA)	Effect Size (*d*)	*P* Value (Post Hoc Difference)
Anterior	7.1 ± 2.7	7.0 ± 1.5	5.8 ± 1.3	.264	—	—
Lateral	12.0 ± 3.7	15.8 ± 3.9	21.1 ± 2.8	<.001	0.738	<.001 (DOS vs ANS) .002 (DOS vs AOS) .019 (ANS vs AOS)
Vertical	25.4 ± 4.5	28.4 ± 5.6	32.9 ± 7.1	.034	0.383	.011 (DOS vs ANS)

[a]Values are expressed as mean ± SD in N/kg. Effect size and post hoc difference were not calculated for anterior GRF. Dashes indicate that the effect size and post hoc tests were not performed since the ANOVA results were not significant. ANOVA, analysis of variance; ANS, attacking neutral stance; AOS, attacking open stance; DOS, defensive open stance; GRF, ground-reaction force.

ground-reaction forces (GRFs) on the dominant step (right one) during forehand strokes. All the kinetic and kinematic data of the right hip were processed with CusToM in Matlab software (MathWorks), which is a Customizable Toolbox for Musculoskeletal simulation allowing users to calculate inverse kinematics and inverse dynamics from motion capture data.[35] In each of the 3 forehand stances, the minimum, maximum, and range of motion were computed for each rotation axis of the right hip during right foot support on the force plate. Intersegmental forces and torques at the right hip were also computed.

Statistical Analysis

One-way analysis of variance with repeated measures was used to analyze differences in GRFs and hip kinematics and kinetics between the 3 forehand stances (ANS, AOS, and DOS). Significant main effects were calculated using the post hoc Holm-Sidak test to determine the source of difference. To determine the statistical relevance of differences, each post hoc contrast was presented as the mean difference (MD). Where data were not normally distributed, significance was determined using analysis of variance with repeated measures on ranks and a post hoc Tukey test. Mean and standard deviation values were computed for all parameters. The effect sizes were calculated, and the clinical significance of the differences was classified as small ($d < 0.2$), medium ($d = 0.5$), or large ($d > 0.8$) according to the Cohen scale. The level of significance was established at $P < .05$ (SigmaStat Version 3.1; Systat Software).

RESULTS

Ground-Reaction Forces

As shown in Table 1, there were significant main effects of the type of forehand stance on lateral and vertical GRFs. Post hoc comparisons showed that the DOS caused a significantly greater peak of lateral GRF than the ANS (MD, 9.1 N/kg; $P < .001$) and AOS (MD, 5.3 N/kg; $P = .002$). Post hoc tests also demonstrated a significant difference between the ANS and AOS concerning the peak of lateral GRF (MD, 3.8 N/kg; $P = .019$). The peak of vertical GRF was significantly higher in the DOS than in the ANS (MD, 7.5 N/kg; $P = .011$).

Hip Kinematics

Results showed significant main effects of the type of forehand stance on minimal and maximal hip flexion. Post hoc results revealed that the minimal and maximal hip flexion angles were significantly higher in the DOS compared with the ANS (MD, 11.4°; $P = .006$ and MD, 15.1°; $P < .001$, respectively) and AOS (MD, 10.5°; $P = .010$ and MD, 10.9; $P < .001$, respectively). Moreover, there were significant

TABLE 2
Range of Hip Motion Across the 3 Forehand Stances[a]

	ANS	AOS	DOS	*P* Value (ANOVA)	Effect Size (*d*)	*P* Value (Post Hoc Difference)
Hip flexion						
Minimum	10 ± 8	11 ± 8	21 ± 10	.010	0.484	.006 (DOS vs ANS) .010 (DOS vs AOS)
Maximum	53 ± 9	58 ± 9	68 ± 8	<.001	0.759	<.001 (DOS vs ANS) <.001 (DOS vs AOS)
Flexion-extension ROM	43 ± 7	47 ± 12	47 ± 8	.465	—	—
Hip abduction						
Minimum	−7 ± 7	6 ± 5	10 ± 8	<.001	0.747	<.001 (DOS vs ANS) <.001 (ANS vs AOS)
Maximum	25 ± 5	18 ± 7	34 ± 7	<.001	0.788	.001 (DOS vs ANS) <.001 (DOS vs AOS) .007 (ANS vs AOS)
Adduction-abduction ROM	32 ± 8	12 ± 4	24 ± 6	<.001	0.761	.015 (DOS vs ANS) .002 (DOS vs AOS) <.001 (ANS vs AOS)
Hip external rotation						
Minimum	−19 ± 19	−19 ± 15	−17 ± 12	.917	—	—
Maximum	1 ± 22	10 ± 20	24 ± 14	.010	0.324	.004 (DOS vs ANS)
Internal-external rotation ROM	20 ± 7	29 ± 13	41 ± 13	.006	0.519	.002 (DOS vs ANS)

[a]Values are expressed as mean ± SD in degrees. Effect size and post hoc difference were not calculated for flexion-extension ROM and minimum external rotation. Dashes indicate that the effect size and post hoc tests were not performed since the ANOVA results were not significant. ANOVA, analysis of variance; ANS, attacking neutral stance; AOS, attacking open stance; DOS, defensive open stance; ROM, range of motion.

TABLE 3
Maximum Hip Joint Forces Across the 3 Forehand Stances[a]

	ANS	AOS	DOS	*P* Value (ANOVA)	Effect Size (*d*)	*P* Value (Post Hoc Difference)
Posterior	11.9 ± 3.1	14.6 ± 4.8	17.9 ± 5.2	.023	0.419	.007 (DOS vs ANS)
Anterior	2.5 ± 0.4	2.7 ± 0.8	5.1 ± 0.9	<.001	0.805	<.001 (DOS vs ANS) <.001 (DOS vs AOS)
Compressive	16.3 ± 3.1	19.9 ± 5.0	22.0 ± 5.4	.015	0.449	.005 (DOS vs ANS)
Distractive	2.6 ± 0.5	3.3 ± 1.0	4.2 ± 0.5	<.001	0.690	<.001 (DOS vs ANS) .006 (DOS vs AOS) .048 (ANS vs AOS)
Medial	1.6 ± 0.3	2.3 ± 1.1	4.6 ± 0.8	<.001	0.816	<.001 (DOS vs ANS) <.001 (DOS vs AOS)
Lateral	5.8 ± 3.5	6.3 ± 3.7	8.0 ± 5.4	.035	0.379	.014 (DOS vs ANS)

[a]Values are expressed as mean ± SD in N/kg. ANOVA, analysis of variance; ANS, attacking neutral stance; AOS, attacking open stance; DOS, defensive open stance.

main effects of the type of forehand stance on minimal and maximal hip abduction and adduction-abduction hip range of motion (Table 2). Post hoc comparisons showed that maximal hip abduction (DOS-AOS: MD, 15.8°; $P < .001$) (DOS-ANS: MD, 8.8°; $P = .001$) (ANS-AOS: MD, 7.0°; $P = .007$) and range of motion angles (DOS-AOS: MD, 11.6°; $P < .002$) (DOS-ANS: MD, 8.3°; $P = .015$) (ANS-AOS: MD, 19.9°; $P < .001$) were significantly different between the 3 forehand stances. Post hoc tests showed that the minimal hip abduction angle was significantly different between the DOS and ANS (MD, 17.1°; $P < .001$) and between the ANS and AOS (MD, 12.9°; $P < .001$). Results indicated significant main effects of the type of forehand stance on maximal hip external rotation and internal-external hip range of motion. Post hoc comparisons revealed that maximal hip external rotation (MD, 23.0°; $P = .004$) and internal-external hip range of motion angles (MD, 22.5°; $P = .002$) were significantly different between the DOS and ANS (Table 2).

Hip Kinetics

Hip Joint Forces. Significant main effects were recorded for posterior, anterior, compressive, distractive, medial, and lateral forces between the forehand stances (Table 3). Post hoc tests indicated that the DOS involved a significantly greater peak of anterior hip joint force than the ANS (MD, 2.6 N/kg; $P < .001$) and AOS (MD, 2.4 N/kg; $P < .001$). Post hoc comparisons showed that the peak of posterior,

TABLE 4
Maximum Hip Torques Across the 3 Forehand Stances[a]

	ANS	AOS	DOS	*P* Value (ANOVA)	Effect Size (*d*)	*P* Value (Post Hoc Difference)
Flexion	5.0 ± 0.8	6.2 ± 1.6	7.6 ± 2.9	.064	—	—
Extension	1.3 ± 0.3	1.1 ± 0.4	1.8 ± 0.4	.004	0.556	.016 (DOS vs ANS) .001 (DOS vs AOS)
Adduction	1.8 ± 0.5	1.7 ± 0.4	2.1 ± 1.0	.498	—	—
Abduction	1.4 ± 0.3	1.3 ± 0.8	3.6 ± 0.8	<.001	0.844	<.001 (DOS vs ANS) <.001 (DOS vs AOS)
External rotation	1.1 ± 0.3	1.0 ± 0.3	2.1 ± 0.4	<.001	0.914	<.001 (DOS vs ANS) <.001 (DOS vs AOS)
Internal rotation	0.5 ± 0.4	0.7 ± 0.3	0.9 ± 0.6	.341	—	—

[a]Values are expressed as mean ± SD in N·m/kg. Effect size and post hoc difference were not calculated for flexion, adduction, or internal rotation torques. Dashes indicate that the effect size and post hoc tests were not performed since the ANOVA results were not significant. ANOVA, analysis of variance; ANS, attacking neutral stance; AOS, attacking open stance; DOS, defensive open stance.

compressive, and lateral hip joint forces were significantly greater during the DOS compared with the ANS (posterior: MD, 6.0 N/kg; $P = .007$) (compressive: MD, 5.7 N/kg; $P = .005$) (lateral: MD, 2.3 N/kg; $P = .014$). Post hoc results showed a significant gradual increase in the peak of distractive hip joint force across the 3 forehand stances (DOS-ANS: MD, 1.5 N/kg; $P < .001$) (DOS-AOS: MD, 0.9 N/kg; $P = .006$) (ANS-AOS: MD, 0.6 N/kg; $P = .048$). According to the post hoc tests, the peak of medial hip joint force was significantly higher in the DOS than in the ANS (MD, 3.0 N/kg; $P < .001$) and AOS (MD, 2.3 N/kg; $P < .001$).

Hip Joint Torques. Significant main effects were recorded for hip extension, abduction, and external rotation torques between the forehand stances (Table 4). Post hoc tests showed that the DOS involved a significantly greater peak of hip extension torque than the AOS (MD, 0.8 N·m/kg; $P = .001$) and ANS (MD, 0.5 N·m/kg; $P = .016$). There was a post hoc difference in the peak of hip abduction torque between the DOS and ANS (MD, 2.2 N·m/kg; $P < .001$) and AOS (MD, 2.3 N·m/kg; $P < .001$). Post hoc comparisons revealed that the peak of hip external rotation torque was significantly higher in the DOS than in the ANS (MD, 1.0 N·m/kg; $P < .001$) and AOS (MD, 1.1 N·m/kg; $P < .001$) (Table 4).

DISCUSSION

Our results showed that the DOS significantly increased lateral and vertical GRFs. During the AOS and DOS, flexion, abduction, and external rotation occurred in the right hip. Of the 2 open forehand stances studied, the DOS induced the highest magnitude of flexion, abduction, and external rotation of the hip. Moreover, the DOS induced the greatest hip joint loading. All of these results confirmed the hypothesis that the hip was more loaded with the open stance forehand than the neutral stance forehand. Consequently, the DOS may increase the risk of hip injuries in tennis players.

Kinematic Data

In tennis, the forehand stroke involves a sequence of movements referred to as a "kinetic chain" that begins with the lower limb and is followed by the trunk and then the upper limb. The hip plays a crucial role in the forehand kinetic chain, as it allows a transfer of a maximum of energy from the lower limb to the trunk. During the forehand, the player's hip is put under a lot of stress during flexion/extension and rotational maneuvers (abduction/adduction and external/internal rotation) performed to powerfully hit the ball.[11,37]

The maximal hip abduction angle was significantly higher in the DOS in comparison with the ANS and AOS. The mean maximal hip abduction angle in the DOS was similar to the passive or active maximal hip abduction range of motion reported in the literature in male tennis players.[33,44] Those results have clinical relevance because it is well-known that the likelihood of hip lateral rim impingement increases with the magnitude of the hip abduction angle.[24] Consequently, the DOS seems more likely to cause hip lateral acetabular rim injuries for hip lateral acetabular rim injuries.

The results of the current study showed that during the open stance forehand the right hip first went into external rotation, which was significantly higher in the DOS than in the AOS and ANS (Table 2). The maximal hip external rotation angle in the DOS (24° ± 14°) was similar to the hip external rotation end range of motion measured in female professional tennis players (23° ± 24°)[49] and soccer players (24° ± 6°).[7] However, our data are different from hip external rotation end range of motion measured in other studies about tennis players (40°-60°).[33,44] Methodological differences in the protocol used by these studies may explain the differences. According to the literature, the pathomechanics of FAI involves abutment of the femur against the acetabular rim during the end range of hip external motion.[13] As a consequence, the DOS could increase the risk of FAI in tennis players by placing the hip in extreme external rotation.

Concerning hip flexion, it has been reported that the right hip flexes during the forehand backswing and then produces a violent extension to initiate pelvis and trunk rotation toward the ball.[27,46] In our study, players showed a significantly higher maximal hip flexion angle in the DOS than in the AOS and ANS. This result is logical because the ball height was reduced in the DOS to simulate defensive forehand strokes. Our values of maximal hip flexion angles are in accordance with previously published results that have reported a maximal hip flexion angle between 41° and 55° during the forehand backswing in highly skilled male tennis players.[12,46] In the literature, sport movements that are associated with a higher incidence of FAI are those involving repeated and excessive flexion of the hip.[51] By causing a higher hip flexion than the AOS and ANS, the DOS could increase the risk of FAI in tennis players, especially as our findings showed that this hip flexion was concomitant with high abduction and external rotation angles.

Our results demonstrated that the DOS combined the highest maximal angles of hip flexion, abduction, and external rotation (FABER). The hip posture in the DOS with flexion and extreme abduction and external rotation resembles the traditional FABER test. Among the physical examination tests used by clinicians, the FABER test is considered to involve one of the most provocative hip impingement postures.[39] Indeed, it has been shown that the FABER test is the most sensitive hip provocation maneuver to predict the presence of an intra-articular hip abnormality.[31] During the FABER test, the patient is in the supine position. The hip is flexed, abducted, and externally rotated with the lateral ankle resting on the contralateral thigh proximal to the knee. While stabilizing the opposite side of the pelvis, external rotation, abduction, and posterior forces are then lightly applied by the examiner to the ipsilateral knee until hip end range of motion is achieved. The combination of these movements (flexion, abduction, and external rotation) during the FABER test can induce mechanical conflict between the femur and the acetabulum. Consequently, hip abduction and external rotation in the DOS may provide the most plausible mechanical precursor to hip injuries in tennis players. Conversely, none of the ANS and AOS movements involved magnitudes of hip kinematics that were close to the end range of passive flexion, external rotation, and abduction values that have been reported in tennis players. Considering these mechanics in the context of previous clinical research, it is difficult to argue that the ANS and AOS may account for the high incidence of hip injuries in tennis players.

Torque Data

The peak hip extension, abduction, and external rotation torques were significantly higher for the DOS than the ANS and AOS. The magnitudes of hip torques obtained in the current study were similar or higher than those measured in golf swings[15] or in forehand table tennis.[22] It has been shown that these right hip joint torques are very important for forehand performance because they contribute to produce high racket speeds.[22,23] However, the repetition of these high joint torques may increase the risk of hip injuries. Indeed, the increased torsional maneuvers caused by excessive extension, abduction, and external rotation torques at the hip in the DOS may increase the risk of chondral injuries, hindering recovery and placing the player at risk for further degenerative changes.[18] Moreover, the highest maximal hip external rotation and abduction torques measured for the DOS could potentially lead to posterior and lateral impingement and stress along the anterior capsule of the hip and could explain hip injuries in tennis players.[24] The increased external rotation torque measured in the DOS in comparison with the ANS may also lead to laxity and instability of the anterior capsule and could be responsible for a higher hip injury risk.[30]

Force Data

In our study, the DOS induced the highest shear forces (anterior, posterior, medial, and lateral) on the hip joint. Concerning maximal hip anterior force, our results are in line with a previous unpublished study (E. Bondi, oral presentation at the Society for Tennis Medicine & Science, Amelia Island, December 5, 2016) revealing that the open stance forehand increases anterior translational forces in the dominant hip. The combination of higher anterior hip joint force and external rotation observed in the DOS could cause anterior femoral head translation and subsequent stretching of the anterior labrum, leading to labral tears.[20] Moreover, the acetabular cartilage is subject to excessive shear forces.[2,17] Consequently, labral tears and acetabular cartilage injuries could be more likely to appear with the repetition of the DOS in tennis players.

Our results showed that the peak of hip compressive force was significantly higher in the DOS. It has been described in the literature that the hip labrum is susceptible to compression injuries as a result of compressive forces, while the acetabular cartilage is subject to excessive shear forces.[2,17] As a consequence, in light of maximal hip joint forces measured in the present study, the DOS and AOS are more likely to cause compressive hip trauma than the ANS.

Long-term Implications

In tennis, the most common sources of pain in players include overuse injuries caused by repeated and excessive joint loading. For example, for FAI in tennis players, the inciting event of injury is not usually the single forehand stroke when pain becomes evident but rather all the previous repetitions of forehand strokes that the player performed over the previous weeks or months of training and competitions.[4] At first, it seems logical that a significant MD of 1.0 N·m/kg of hip external rotation torque or 2.2 N·m/kg of hip abduction torque between the DOS and ANS is weak and would have no influence on the hip injury risk if we consider an isolated forehand stroke. However, expert tennis players might expect to play in excess of 1000 shots per match.[42] High-level junior players hit 40 to 388 shots per training session.[36] Expert players can hit tens of thousands of forehands per year. Consequently, one could speculate that the small difference of 1.0 N·m/kg of hip external rotation torque or 2.2 N·m/kg of hip abduction torque between the DOS and ANS for 1 single forehand becomes a huge difference if we consider a tennis season or career and could increase the risk of hip overuse injuries.

Limitations

Our study has some limitations. First, the sample size is small because we included only advanced tennis players; moreover, their participation was voluntary. Second, we evaluated hip joint loading using the inverse dynamics method, but we did not use musculoskeletal modeling and computer simulations to predict the hip muscle and ligament forces during the forehand strokes. Insight into how hip muscles interact to produce motion may be of importance for a better understanding of possible hip injury mechanisms. Moreover, we restricted the study to biomechanical comparisons of hip kinematics and kinetics across 3 common forehand stances. We did not combine our results with clinical testing (individual hip range of motion and anatomy) and/or prospective registration of hip or groin injuries to specifically assess the relation between specific forehand stance patterns and the hip injury risk. Consequently, the results of this study should be interpreted with caution because the influence of forehand stances has not been clinically verified. We are aware that hip injuries are likely caused not only by excessive joint kinetics but also by the interaction between joint loading and several factors such as anatomy, hip range of motion, playing surface, and overuse (training and competitive planning).[45] As a consequence, further studies based on clinical measurements, musculoskeletal modeling, and simulations taking into account all these potential risk factors are necessary to enhance the etiological knowledge of tennis hip injuries related to the 3 common forehand stances.

CONCLUSION

The results of this study seem to support the hypothesis that the DOS was riskier for hip injuries in tennis because it caused higher loading than the ANS and AOS. The combination of extreme motion of hip flexion, abduction, and external rotation observed in the DOS were critical movements that may put players at risk for hip injuries such as posterior-superior impingement. Consequently, the growing problem of hip injuries among tennis players could be related to the increasing use of the open stance in groundstrokes. Coaches with players who sustain hip pain or injuries (especially posterior-superior impingement) should encourage them to use a more neutral stance and to develop an aggressive playing style to avoid the DOS, during which hip motion and loading are more extreme. After a rehabilitation program following a hip injury, players should favor the use of the neutral stance to lighten the load on the hip during forehand strokes. Further research is needed to clarify the influence of other injury risks, such as the playing surface (hard, clay, and grass courts), match duration, or fatigue, on hip joint loading to enhance the etiological knowledge of tennis hip injuries related to the 3 common forehand stances.

REFERENCES

1. Abrams G, Renstrom P, Safran M. Epidemiology of musculoskeletal injury in the tennis player. *Br J Sports Med*. 2012;46(7):492-498.
2. Anderson LA, Peters CL, Park BB, Stoddard GJ, Erickson JA, Crim JR. Acetabular cartilage delamination in femoroacetabular impingement: risk factors and magnetic resonance imaging diagnosis. *J Bone Joint Surg Am*. 2009;91(2):305-313.
3. Bahamonde R, Knudson D. Kinetics of the upper extremity in the open and square stance tennis forehand. *J Sci Med Sport*. 2003;6(1): 88-101.
4. Bahr R, Holme I. Risk factors for sports injuries: a methodological approach. *Br J Sports Med*. 2003;37(5):384-392.
5. Bharam S. Labral tears, extra-articular injuries, and hip arthroscopy in the athlete. *Clin Sports Med*. 2006;25(2):279-292.
6. Campbell A, Straker L, Whiteside D, O'Sullivan P, Elliott B, Reid M. Lumbar mechanics in tennis groundstrokes: differences in elite adolescent players with and without low back pain. *J Appl Biomech*. 2016;32(1):32-39.
7. Chiaia TA, Maschi R, Stuhr R, et al. A musculoskleletal profile of elite female soccer players. *Musculoskelet J Hosp Spec Surg*. 2009;5(2): 186-195.
8. Cotorro A, Philippon M, Briggs K, Boykin R, Dominguez D. Hip screening in elite youth tennis players. *Br J Sports Med*. 2014;48:582.
9. Egger A, Frangiamore S, Rosneck J. Femoroacetabular impingement: a review. *Sports Med Arthrosc Rev*. 2016;24(4):e53-e58.
10. Ellenbecker T. The relationship between stroke mechanics and injuries in tennis. *USTA Newsl Tennis Coach*. 2006;8(2):4-9.
11. Elliott B. Biomechanics and tennis. *Br J Sports Med*. 2006;40(5): 392-396.
12. Elliott B, Marsh T, Overheu P. A biomechanical comparison of the multisegment and single unit topspin forehand drives in tennis. *Int J Sports Biomech*. 1989;5:350-364.
13. Emary P. Femoroacetabular impingement syndrome: a narrative review for the chiropractor. *J Can Chiropr Assoc*. 2010;54(3):164-176.
14. Felix I, Draovitch P, Ellenbecker T, Dines J. Tennis injuries of the hip and thigh. In: Di Giacomo G, Ellenbecker TS, Kibler WB, eds. *Tennis Medicine: A Complete Guide to Evaluation, Treatment, and Rehabilitation*. Springer; 2018:381-399.
15. Foxworth JL, Millar AL, Long BL, Way M, Vellucci MW, Vogler JD. Hip joint torques during the golf swing of young and senior healthy males. *J Orthop Sports Phys Ther*. 2013;43(9):660-665.
16. Fu MC, Ellenbecker TS, Renstrom PA, Windler GS, Dines DM. Epidemiology of injuries in tennis players. *Curr Rev Musculoskelet Med*. 2018;11(1):1-5.
17. Ganz R, Leunig M, Leunig-Ganz K, Harris WH. The etiology of osteoarthritis of the hip. *Clin Orthop Relat Res*. 2008;466(2):264-272.
18. Ganz R, Parvizi J, Beck M, Leunig M, Nötzli H, Siebenrock KA. Femoroacetabular impingement: a cause for osteoarthritis of the hip. *Clin Orthop Relat Res*. 2003;417:112-120.
19. Grant AD, Sala DA, Schwarzkopf R. Femoro-acetabular impingement: the diagnosis. A review. *J Child Orthop*. 2012;6(1):1-12.
20. Groh MM, Herrera J. A comprehensive review of hip labral tears. *Curr Rev Musculoskelet Med*. 2009;2(2):105-117.
21. Hutchinson MR, LaPrade RF, Burnett QM, Moss R, Terpstra J. Injury surveillance at the USTA Boys' Tennis Championships: a 6-yr study. *Med Sci Sports Exerc*. 1995;27(6):826-830.
22. Iino Y. Hip joint kinetics in the table tennis topspin forehand: relationship to racket velocity. *J Sports Sci*. 2018;36(7):834-842.
23. Iino Y, Kojima T. Torque acting on the pelvis about its superior-inferior axis through the hip joints during a tennis forehand stroke. *J Hum Mov Stud*. 2001;40:269-290.
24. Klingenstein GG, Martin R, Kivlan B, Kelly BT. Hip injuries in the overhead athlete. *Clin Orthop Relat Res*. 2012;470(6):1579-1585.
25. Knudson D, Blackwell J. Trunk muscle activation in open stance and square stance tennis forehands. *Int J Sports Med*. 2000;21(5): 321-324.
26. Kovacs MS. Applied physiology of tennis performance. *Br J Sports Med*. 2006;40(5):381-386.
27. Landlinger J, Lindinger S, Stoggl T, Wagner H, Muller E. Key factors and timing patterns in the tennis forehand of different skill levels. *J Sports Sci Med*. 2010;9(4):643-651.

28. Leardini A, Cappozzo A, Catani F, et al. Validation of a functional method for the estimation of hip joint centre location. *J Biomech*. 1999;32(1):99-103.
29. Madeti B, Rao C, Rao S. Biomechanics of hip joint: a review. *Int J Biomed Eng Technol*. 2014;15(4):341-359.
30. Martin RL, Sekiya JK. The interrater reliability of 4 clinical tests used to assess individuals with musculoskeletal hip pain. *J Orthop Sports Phys Ther*. 2008;38(2):71-77.
31. Maslowski E, Sullivan W, Harwood J, et al. The diagnostic validity of hip provocation maneuvers to detect intra-articular hip pathology. *PM R*. 2010;2(3):174-181.
32. Mason JB. Acetabular labral tears in the athlete. *Clin Sports Med*. 2001;20(4):779-790.
33. Moreno-Pérez V, Ayala F, Fernandez-Fernandez J, Vera-Garcia FJ. Descriptive profile of hip range of motion in elite tennis players. *Phys Ther Sport*. 2016;19:43-48.
34. Moreno-Pérez V, Nakamura FY, Sánchez-Migallón V, et al. The acute effect of match-play on hip range of motion and isometric strength in elite tennis players. *PeerJ*. 2019;7:e7940.
35. Muller A, Pontonnier C, Puchaud P, Dumont G. CusToM: a Matlab toolbox for musculoskeletal simulation. *J Open Source Softw*. 2019; 4(33):927.
36. Murphy AP, Duffield R, Kellett A, Reid M. A descriptive analysis of internal and external loads for elite-level tennis drills. *Int J Sports Physiol Perform*. 2014;9(5):863-870.
37. Nesbit SM, Serrano M, Elzinga M. The role of knee positioning and range-of-motion on the closed-stance forehand tennis swing. *J Sports Sci Med*. 2008;7(1):114-124.
38. Newman P. Is this the end for Andy Murray? Hopefully not, but the road back to the top will not be smooth. Published January 4, 2018. Accessed May 5, 2020. https://www.independent.co.uk/sport/tennis/australian-open-andy-murray-hip-injury-withdrawal-draw-roger-federer-a8141876.html
39. Philippon M, Maxwell B, Johnston T, Schenker M, Briggs K. Clinical presentation of femoroacetabular impingement. *Knee Surg Sports Traumatol Arthrosc*. 2007;15:1041-1047.
40. Reed MP, Manary MA, Schneider LW. Methods for measuring and representing automobile occupant posture. Technical Paper 990959. *SAE Trans J Passeng Cars*. 1999;108(4):1-15.
41. Reid M, Elliott B, Crespo M. Mechanics and learning practices associated with the tennis forehand: a review. *J Sports Sci Med*. 2013; 12(2):225-231.
42. Reid M, Schneiker K. Strength and conditioning in tennis: current research and practice. *J Sci Med Sport*. 2008;11(3):248-256.
43. Roetert EP, Kovacs M, Knudson DV, Groppel J. Biomechanics of the tennis groundstrokes: implications for strength training. *Strength Cond J*. 2009;31(4):41-49.
44. Safran M. Evaluation of the painful hip in the tennis players. *Aspetar Sports Med J*. 2014;3:516-525.
45. Safran M, Costantini A. Treatment of femoroacetabular impingement and labral injuries in tennis players. In: Di Giacomo G, Ellenbecker TS, Kibler WB, eds. *Tennis Medicine: A Complete Guide to Evaluation, Treatment, and Rehabilitation*. Springer; 2018:369-380.
46. Seeley MK, Funk MD, Denning WM, Hager RL, Hopkins JT. Tennis forehand kinematics change as post-impact ball speed is altered. *Sports Biomech Int Soc Biomech Sports*. 2011;10(4): 415-426.
47. Shindle MK, Ranawat AS, Kelly BT. Diagnosis and management of traumatic and atraumatic hip instability in the athletic patient. *Clin Sports Med*. 2006;25(2):309-326.
48. Smith CD, Masouros S, Hill AM, Amis AA, Bull AMJ. A biomechanical basis for tears of the human acetabular labrum. *Br J Sports Med*. 2009;43(8):574-578.
49. Young SW, Dakic J, Stroia K, Nguyen ML, Harris AHS, Safran MR. Hip range of motion and association with injury in female professional tennis players. *Am J Sports Med*. 2014;42(11):2654-2658.
50. Zatsiorsky V, Seluyanov V, Chugunova L. Methods of determining mass-inertial characteristics of human body segments. In: Chernyi GG, Regirer SA, eds. *Contemporary Problems of Biomechanics*. Florida: CRC Press; 1990:272-291.
51. Zhang C, Li L, Forster B, et al. Femoroacetabular impingement and osteoarthritis of the hip. *Can Fam Phys*. 2015;61:1055-1060.