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Influence of shoe torsional stiffness on foot and ankle biomechanics during tennis forehand strokes

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ABSTRACT

Tennis shoe characteristics need to minimise the risk of athletes suffering ankle injuries and improve players' feet performance. This study aims to evaluate the influence of shoe torsional stiffness on running velocity, stance duration, ground reaction forces and ankle biomechanics during two different tennis forehand runs and strokes. Ten right-handed advanced male tennis players performed two specific tennis forehand runs and strokes at maximal effort (a shuttle run with a defensive open stance forehand – SRDF and a lateral jab run with an offensive open stance forehand - JROF) with four different pairs of tennis shoes with different torsional stiffness. A force platform measured ground reaction forces (GRF). A motion capture system recorded the 3D trajectories of markers located on players' anatomical landmarks. The minimum, maximum angle value, and range of motion were computed using inverse kinematics for each rotation axis of the right ankle. Normalised maximal ankle torques were also computed using inverse dynamics. Shoe torsional stiffness had no effect on running velocity, on stance duration and maximal values of GRF. Shoe torsional stiffness influenced forefoot inversion which was significantly higher for the most flexible shoes. For SRDF, the maximal ankle inversion angle was significantly and largely increased for the stiffest shoe. The stiffest shoe may put the ankle at a higher risk of lateral sprains during SRDF while it was not the case during JROF.

Highlights

- Shoe torsional stiffness has no effect on performance parameters (running velocity of the centre of mass, ground reaction forces, and stance duration) during tennis forehand strokes.
- Decreased shoe torsional stiffness increased the maximal forefoot inversion angle and the range of motion of forefoot inversion–eversion during tennis forehand strokes and movements.
- Increased footwear torsional stiffness causes higher maximal ankle inversion angle which may increase the risk for ankle sprains in SRDF.

KEYWORDS
Performance; injury and prevention; 3D analysis

Introduction

Tennis is a sport that involves quick, intense, and repeated start-stop movements, during which players perform sudden changes of direction while running and striking the ball at high speeds (Kovacs, 2006). During all these runs, changes of direction and strokes, the player's feet and ankles are always the foundation for tennis performance (Avagnina, 2018) because they interact with the ground to generate ground reaction forces (GRF) that influence stroke performance. For example, it has been reported that lateral, antero-posterior, and vertical GRF positively influenced ball speed during tennis forehands (Shimokawa et al., 2020).

The interaction between the feet and the ground induces also high plantar pressures and loadings (Girard et al., 2007) that can be responsible for foot and ankle injuries that are very common in tennis players (Hjelm et al., 2010). Indeed, injury statistics from the ATP World Tour show foot and ankle injuries comprise 12% of all injuries evaluated by physiotherapists during the 2014 and 2015 seasons (Sniteman & Suzuki, 2018). Other results show ankle injuries represent 21% of all injuries reported by the National Collegiate Athletic Association Injury Surveillance Program for men's and women's tennis during the 2009/2010–2014/2015 academic years (Lynall et al., 2015). Among

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all injuries, ankle sprains are very common in the lower extremity in tennis players (Sniteman & Suzuki, 2018) (Pluim & Windler, 2018).

Many different variables such as ground-surface, fatigue, poor physical condition and tennis shoe characteristics influence the risks of ankle injuries (Pluim et al., 2006) (Beynnon et al., 2002). Tennis shoe characteristics need to minimise the risk of athletes suffering ankle injuries Among all tennis shoe characteristics, the shoe's lateral stability and torsional stiffness are important for ankle injury prevention (Pluim et al., 2006). Torsional shoe stiffness quantifies the resistance of a shoe to twisting about its long axis between the heel and the toe (Zifchock et al., 2017). Results about the effect of shoe torsional stiffness on ankle injury risks in sports are contradictory in the literature. On the one hand, Graf and Stefanyshyn (2013) have evaluated the effect of footwear torsional stiffness on knee and ankle kinematics and kinetics during lateral cutting movements often used in basketball, handball or soccer (Graf & Stefanyshyn, 2013). Their results showed that increased footwear torsional stiffness causes higher ankle eversion torque, increasing the risk for ankle injuries. On the other hand, Luethi et al. (1986) have evaluated the effect of two different shoes (a soft and flexible one vs. a harder and stiffer one) on ankle biomechanics during side-ways shuffle runs in tennis players. They reported lower lateral ground reaction force, lower ankle inversion angle and lower internal resistive force with the stiffer shoe (Luethi et al., 1986). According to Luethi et al. (1986), too much or too little shoe torsional stiffness can induce too much or too little inversion movement at the ankle, disturb the equilibrium of force absorption and cause ankle injuries.

Tennis shoe characteristics also need to improve players' comfort and performance. The studies concerning the effect of shoe torsional stiffness on performance are very limited and controversial (Kulessa et al., 2017). While Llana-Belloch et al. (2013) reported that shoes limiting supination (i.e. shoes with more torsional stiffness) allowed tennis players to perform faster sideward cutting movements (Llana-Belloch et al., 2013), Graf and Stefanyshyn (2013) observed no effect of the shoe torsional stiffness on two performance parameters (stance duration and ground reaction impulses) during cutting movements. Moreover, the optimal torsional stiffness of tennis shoes for increasing tennis performance and reducing ankle and foot injury risks is unknown.

Consequently, this study aims to evaluate, during two different tennis forehand runs and strokes, the influence of shoe torsional stiffness on ground reaction forces and stance time, which are related to sports performance, and ankle biomechanics which have been related to ankle sprain injury mechanisms. It is hypothesised that shoes with a high torsional stiffness have no effect on ground reaction forces, stance time and running velocity but decrease maximal ankle inversion angle, angular velocity and torque.

Materials and methods

Ten right-handed advanced male tennis players (age: 26.8 ± 10.9 years; height: 1.77 ± 0.03 m; weight: 65.3 ± 4.3 kg), with an International Tennis Number of 4 or better, participated voluntarily in this study. Before experiments, participants were fully informed of the experimental procedures. At the testing time, all the players were considered healthy, with no pain or injuries. Each player signed a written consent. The local Ethical Committee approved the study which was conducted under the 1975 Declaration of Helsinki.

Before the start of the movement protocol, participants viewed a demonstration of the experimental procedure and the two specific tennis movements and forehands performed by a professional coach. Such movements and forehand strokes occur frequently in tennis (Roetert et al., 2009). For both movements, the players were asked to move as quickly as possible until a force plate (0.60 × 1.20 × 0.06 m, AMTI, Watertown, MA, USA) and hit a foam tennis ball as hard as possible they could. A foam tennis ball was fixed and attached to a scaffold with a rope (Figure 1). The first movement was a lateral jab run (JR) during which players performed an offensive open stance forehand (OF). Firstly, the players ran forward along a 45° lane on the left side of the force plate. Once the force plate reached, they stepped onto the plate with the right foot, hit a foam ball with an open stance, and left the plate at a 45° angle towards the left until the finishing point (Figure 1(a)). The players ran a total distance of 6.40 m. The height of the foam ball was adjusted to the right shoulder's height of each player to simulate attacking forehand conditions. The other movement was a sideways shuttle run (SR), during which players performed a defensive open stance forehand (Figure 1(b)) (DF). For the SRDF, players performed a split step and then laterally ran towards the force plate (Figure 1(b)). 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. Consequently, the players ran a 9.6-m distance. The height of the foam ball was adjusted to the right pocket's height of each player to simulate a defensive forehand. The players had all the time they needed to familiarise themselves with the testing environment and the landmarks set and, test the two specific tennis movements (SRDF, JROF). After a warm-up of ten

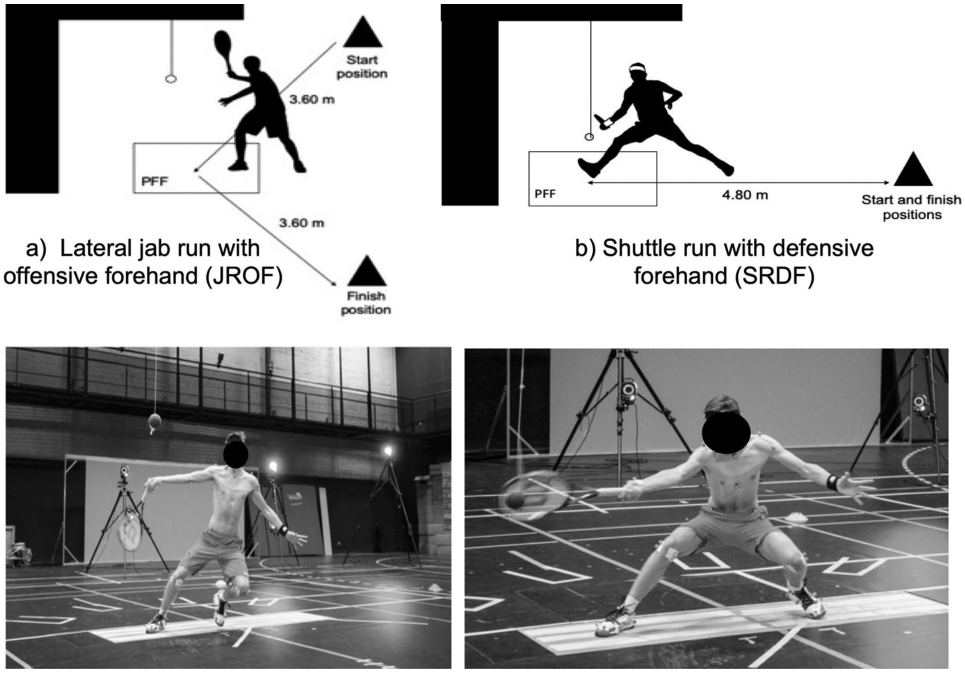

Figure 1. Experimental set-up protocol for the SRDF and the JROF. PFF: force plate.

minutes, the participants performed eight repetitions of SRDF and JROF at maximal effort with four different pairs of tennis shoes with different torsional stiffness (32 repetitions in total). The order of the tennis shoes and movements was randomly assigned. A professional tennis coach confirmed the ability of the players to properly perform each forehand stroke movement.

Three tennis shoes were chosen for the study covered high-quality levels and prices: Wilson "Kaos 3.0", Babolat "Propulse Fury", Asics "Solution Speed". The fourth tennis shoe was a new prototype developed by Wilson. This prototype has the same characteristics than the "Rush Pro 3.0" model, excepted a decreased torsional stiffness. The heel-toe drop (9 mm) was similar between the four tennis shoes. The stiffness of the shoes was determined using a testing device that measures the amount of torque necessary to twist the forefoot part of the shoe to 30 degrees of inversion and eversion, respectively (ISO norm 17707:2005). An average torque was computed based on three consecutive trials. The test was validated since the difference between the three trials was less than 2%. The four types of shoes had different internal and external torsional stiffness. The internal torsion torque was 2.2 Nm for shoe 1, 2.9 Nm for shoe 2, 3.7 Nm for shoe 3 and 4.2 Nm for shoe 4. The external torsion torque was 2.9 Nm for S1, 4.2 Nm for S2, 4.2 Nm for S3 and 5.3 Nm for S4. S3 and S4 are considered as stiffer shoes while S1 and S2 are more flexible shoes. For the purpose of this study, shoe 1 will be referred to as "high flexible", shoe 2 to "flexible", shoe 3 to "stiff" and shoe 4 to "high stiff".

Players were equipped with 52 retro-reflective markers placed on anatomical landmarks determined in agreement with previously published data (Leardini et al., 1999) (Reed et al., 1999) (Zatsiorsky et al., 1990). On the feet, landmarks were placed according to the Oxford foot model (Stebbins et al., 2006). A Vicon motion capture system (Oxford Metrics Inc., Oxford, UK) recorded the 3D trajectories of retro-reflective markers located on anatomical landmarks with a residual error less than 1 mm. The system was composed of 20 high-resolution cameras (4 megapixels) operating at a nominal framerate of 200 Hz. Players were shirtless and wore only tight shorts to limit unwanted markers' movements. After motion 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. The force platform (operating at 2000 Hz) measured vertical, horizontal and lateral ground reaction forces (GRF) on the dominant step (right side) and stance time during forehand strokes. GRF were normalised by the mass of the subjects. All the kinetic and kinematic data was processed with CusToM in Matlab software (Mathworks, Natick, Massachusetts, USA). CusToM is a Customizable Toolbox for Musculoskeletal simulation which solves inverse kinematics and inverse dynamics from motion capture data (Muller et al., 2019). For both tennis-specific movements (SRDJ and JROF), the inversion/eversion rotation of the forefoot with respect to the rearfoot (minimum, maximum and range of motion) was determined about the long axis of the foot. Moreover, the minimum, maximum angle value, and range of motion were computed for each rotation axis of the right ankle during the right foot support on the force plate. Maximal ankle torques (plantar flexion/dorsiflexion, external rotation/internal rotation, and inversion/eversion) were computed and normalised by the mass of the subjects. Absolute approach running velocity of the centre of mass at the instant of the first contact between the right foot and the force plate was also computed. This approach running velocity also called the "entry speed" (Giles & Reid, 2021) corresponds to the velocity at which the player's body arrives to hit the forehand stroke.

Mean and SD values were computed for all parameters. For SRDF and JROF, one-way analyses of variance (ANOVAs) with repeated measures were used to analyse differences in maximal GRF, forefoot and ankle kinematics, and ankle torques between the four shoe conditions. Partial eta squared (η^2p), defined as small (.10–.24), moderate (.25–.39), or large (≥.40) were also calculated to determine effect sizes. Significant main effects were decomposed using the *post-hoc* Holm-Sidak correction method to determine the source of difference. Where data were not normally distributed, significance was determined using a Friedman analysis of variance with repeated measures on ranks and a *post-hoc* Durbin-Conover test. Kendall's W, defined as small (.10-.29), moderate (0.30-0.49) and large (≥0.50) were also calculated to determine effect sizes for ANOVA with repeated measures on ranks. The level of significance was established at $P < 0.05$ (Jamovi, version 1.6.23).

Results

Stance time and GRF peaks

As revealed in Table 1, the absolute running velocity of the centre of mass at the instant of the first contact between the right foot and the force plate, the stance duration and the peaks of GRF are not significantly influenced by the shoe torsional stiffness in both tennis forehands (SRDF and JROF). There was a trivial or small effect sizes among the four shoe conditions for absolute running velocity of the centre of mass, stance duration and maximal GRF (Table 1).

Ankle and forefoot angles and ranges of motion

For the SRDF, the shoe torsional stiffness significantly and largely affected the maximal angle of ankle inversion [F(3,27) = 7.57; $P < 0.001$; $\eta^2_p = 0.486$] that was significantly higher in "high stiff" shoes compared with "stiff" shoes (P =0.001), "flexible" shoes ($P < 0.05$) and "high flexible" shoes (P =0.01) (Table 2). The results showed significant and large main effects of the shoe torsional stiffness on the maximal angle of forefoot inversion [$\chi^2(3) = 20.76$, $P < 0.001$, $W = 0.692$] and on the range of motion of forefoot inversion–eversion [*F* (3,27) = 15.5, $P < 0.001$, $\eta^2_p = 0.632$]. The maximal angle of forefoot inversion was significantly higher in "flexible" than in "stiff" ($P < 0.001$), "high stiff" ($P < 0.01$) and "high flexible" shoes ($P < 0.05$). The maximal angle of forefoot inversion was significantly higher in "high flexible" shoes than in "stiff" and "high stiff" shoes ($P <$ 0.05). The range of motion of forefoot inversion–eversion was significantly higher in "flexible" than in "stiff" ($P < 0.001$) and "high stiff" shoes ($P < 0.05$) and in "high flexible" than in "stiff" shoes ($P < 0.001$).

For the JROF, the shoe torsional stiffness significantly and moderately affected the maximal angle of forefoot inversion [$F(3,27) = 4.49$; $P = 0.011$; $\eta^2_p = 0.333$] and the range of motion of forefoot inversion–eversion [$F(3,27)$ = 5.34, $P < 0.005$, $\eta^2_p = 0.372$] (Table 2). The maximal angle of forefoot inversion was significantly higher in "flexible" than in "stiff" and "high stiff" shoes ($P < 0.05$). The range of motion of forefoot inversion–eversion was significantly lower in "stiff" than in "high flexible" ($P < 0.05$) and "flexible" ($P < 0.05$).

Maximal ankle inversion angular velocity

For JROF, the shoe torsional stiffness has no effect on the maximal velocity of ankle inversion. For the SRDF, the shoe torsional stiffness significantly and moderately affected the maximal velocity of ankle inversion [F (3,27) = 3.69; $P = 0.037$; $\eta^2_p = 0.292$]. However, *post-hoc* test reveals no significant difference between the four shoes (Table 2).

Ankle and forefoot torques

For the SRDF, the shoe torsional stiffness significantly and largely affected the maximal torque of ankle plantar flexion [F(3,27) = 12.02; $P < 0.001$; $\eta^2_p = 0.600$] that was significantly higher in "high flexible" compared with "high stiff" ($P < 0.001$) and "stiff" shoes ($P < 0.01$) (Table 2) and in "flexible" compared with "high stiff" shoes ($P < 0.001$) (Table 3). The results showed a significant and large main effect of the shoe torsional stiffness on the maximal torque of ankle dorsiflexion [$\chi^2(3) =$ 17.93, $P < 0.001$, $W = 0.598$]. *Post-hoc* results demonstrated that the maximal torque of ankle dorsiflexion was significantly lower in "high flexible" than in "high

Table 1. Statistical comparison of absolute running velocity of the centre of mass at the instant of the first contact between the right foot and the force plate, stance duration, and maximal ground reaction force values across the four shoes for the shuttle run defensive forehand (SRDF) and the jab run offensive forehand (JROF).

	SRDF						JROF					
	"High flexible"	"Flexible"	"Stiff"	"High stiff"	*P* value	Effect size	"High flexible"	"Flexible"	"Stiff"	"High stiff"	*P* value	Effect size
Running velocity of the centre of mass ($m.s^{-1}$)	3.1 ± 2.1	3.1 ± 2.3	3.1 ± 2.7	3.1 ± 2.3	0.359	0.111	3.5 ± 3.0	3.4 ± 3.0	3.5 ± 3.2	3.6 ± 3.0	0.472	0.068
Stance duration (ms)	645 ± 84	643 ± 86	648 ± 93	635 ± 83	0.757	0.042	314 ± 93	312 ± 90	309 ± 97	301 ± 71	0.724	0.044
Anterior GRF ($N.kg^{-1}$)	5.2 ± 1.4	5.6 ± 2.0	5.6 ± 1.4	5.5 ± 1.6	0.169	0.168	14.1 ± 5.2	13.6 ± 4.8	15.0 ± 4.6	14.7 ± 5.3	0.263	0.135
Lateral GRF ($N.kg^{-1}$)	20.2 ± 2.9	20.6 ± 2.8	20.6 ± 2.7	20.3 ± 3.0	0.868	0.024	6.2 ± 2.4	6.1 ± 1.7	6.7 ± 2.0	6.3 ± 2.4	0.528	0.078
Vertical GRF ($N.kg^{-1}$)	30.7 ± 7.9	30.3 ± 6.3	31.6 ± 6.5	30.7 ± 6.0	0.672	0.055	25.8 ± 8.0	25.5 ± 7.1	26.1 ± 6.4	26.7 ± 8.1	0.589	0.068

Values are expressed as mean ± SD.

stiff", "stiff" ($P < 0.001$) and "flexible" ($P < 0.01$) and also significantly reduced in "flexible" ($P < 0.001$) and "stiff" than in "high stiff" shoes ($P < 0.01$).

For the JROF, a significant and moderate main effect of the shoe torsional stiffness was observed on the maximal torque of ankle plantar flexion [$\chi^2(3) = 12.60$, $P = 0.006$, $W = 0.413$]. *Post-hoc* results demonstrate that the maximal torque of ankle plantar flexion was significantly lower in "high flexible" than in "high stiff" and "stiff shoes" ($P < 0.001$).

Discussion

This study aimed to evaluate, during two tennis forehand runs and strokes, the influence of shoe torsional stiffness on absolute running velocity of the centre of mass at the instant of the first contact between the right foot and the force plate, ground reaction forces and stance duration, which are considered as performance indicators, and on ankle kinematic and kinetic variables which have been related to ankle sprain mechanisms.

Our results showed that shoe torsional stiffness had no significant influence on foot performance since absolute running velocity of the centre of mass at the instant of the first contact between the right foot and the force plate, stance duration, and maximal values of GRF are similar for the four shoe conditions for both SRDF and JROF. These findings confirm the results of Graf and Stefanyshyn (2013) who reported no effect of shoe torsional stiffness on performance for lateral cutting movements in team sports (Graf & Stefanyshyn, 2013). However, our results did not confirm that shoes with more torsional stiffness limiting supination allowed tennis players to perform faster sideward cutting movements (Llana-Belloch et al., 2013). In the study of Llana-Belloch et al. (2013), the range of footwear models studied ($n = 10$ shoes, longitudinal flexibility from 8 to 21°, different quality levels and prices) was more important than in the current protocol ($n = 4$ shoes, shoe internal torsional stiffness from 2.2 to 4.2 Nm, high-quality levels and prices). The lower range of footwear may explain the contradictory results between our study and those of Llana-Belloch et al. (2013).

The typical lateral ankle ligamentous sprain mechanism corresponds to a combined motion with ankle inversion, internal rotation and plantar flexion (Garrick, 1977) (Fong et al., 2012) (Purevsuren et al., 2018). Lysdal et al. (2022) published a quantitative review of published case reports documenting the kinematics of acute lateral ankle sprains aiming to provide a comprehensive and hierarchical description of the ankle sprains mechanisms. They reported that excessive ankle inversion angle and angular velocity were the most pronounced kinematic pattern observed across all included cases. Other studies considered that excessive ankle inversion angle and velocity appear to be the primary factors of the lateral ankle sprain mechanism (Purevsuren et al., 2018) (Fong et al., 2012) (Mok et al., 2011) (Delahunt & Remus, 2019).

In our study, the maximum ankle inversion angle and angular velocity showed no differences between the shoes for JROF. However, for SRDF, the maximal ankle inversion angle was significantly and largely influenced by shoe torsional stiffness. Moreover, for SRDF, the shoe torsional stiffness has a small significant effect on the maximal ankle inversion angular velocity, even if the *post-hoc* test reveals no significant difference between the four shoes. The lack of statistical power caused by the small sample size ($n = 10$) of our study can explain the non-significant *post-hoc* test result. Indeed, when pairwise comparison tests are not statistically powerful, it is less likely to detect significant differences. One may argue that the differences in results

Table 2. Maximal ankle and forefoot angles and ranges of motion across the four shoes for the shuttle run defensive forehand (SRDF) and the jab run offensive forehand (JROF).

	SRDF							JROF						
Maximal values	"High flexible"	"Flexible"	"Stiff"	"High stiff"	*P* value	Effect size	*Post-hoc* difference	"High flexible"	"Flexible"	"Stiff"	"High stiff"	*P* value	Effect size	*Post-hoc* difference
Ankle external rotation (°)	3.2 ± 2.9	6.4 ± 5.8	4.8 ± 5.1	4.2 ± 3.1	0.205	0.171	/	2.7 ± 6.7	5.9 ± 6.0	5.0 ± 6.0	4.9 ± 5.6	0.298	0.125	/
Ankle internal rotation (°)	12.4 ± 4.0	10.8 ± 4.1	11.7 ± 4.8	11.2 ± 4.2	0.506	0.078	/	12.7 ± 5.9	9.0 ± 5.7	10.9 ± 7.3	10.2 ± 5.3	0.392	0.100	/
ROM (°)	15.7 ± 4.3	17.2 ± 4.2	16.5 ± 5.8	15.4 ± 4.7	0.644	0.056	/	16.6 ± 4.0	16.1 ± 5.2	16.4 ± 5.6	16.8 ± 6.5	0.940	0.014	/
Ankle plantar flexion (°)	24.5 ± 7.1	25.2 ± 5.4	24.3 ± 6.5	24.6 ± 5.7	0.684	0.053	/	16.0 ± 7.9	16.8 ± 7.7	15.7 ± 7.5	16.4 ± 7.4	0.472	0.084	/
Ankle dorsiflexion (°)	18.7 ± 10.5	19.0 ± 8.7	19.9 ± 10.6	19.1 ± 11.1	0.848	0.029	/	21.8 ± 6.2	21.2 ± 7.5	21.6 ± 6.1	20.9 ± 5.5	0.668	0.052	/
ROM (°)	43.2 ± 5.8	44.2 ± 5.2	44.2 ± 6.2	43.7 ± 6.9	0.800	0.036	/	37.8 ± 7.0	38.0 ± 7.7	37.3 ± 7.5	37.3 ± 6.8	0.800	0.036	/
Ankle eversion (°)	1.3 ± 3.7	0.2 ± 3.9	2.7 ± 5.2	1.6 ± 4.2	0.377	0.119	/	2.6 ± 6.1	5.2 ± 6.7	3.4 ± 3.9	5.0 ± 6.3	0.481	0.082	/
Ankle inversion (°)	37.0 ± 8.1	37.9 ± 7.1	35.6 ± 7.3	41.3 ± 7.5	**<0.001**	**0.486**	**S < HS*****(P=0.001) **HF < HS****(P=0.01) **F < HS***(P=0.048)	29.1 ± 6.5	27.2 ± 5.4	27.0 ± 6.3	29.9 ± 4.3	0.199	0.173	/
ROM (°)	38.3 ± 8.0	38.1 ± 6.0	38.3 ± 6.3	42.9 ± 8.0	0.058	0.263	/	26.4 ± 9.3	22.0 ± 9.2	23.5 ± 8.9	24.0 ± 8.9	0.247	0.155	/
Ankle inversion velocity (°/s)	402.0 ± 94.0	406.9 ± 82.9	428.3 ± 106.3	477.2 ± 131.7	**0.037**	**0.292**	**NS**	150.4 ± 61.6	163.0 ± 98.4	126.6 ± 39.4	148.7 ± 56.2	0.361	0.123	/
Forefoot eversion (°)	7.0 ± 3.3	6.0 ± 3.2	4.6 ± 1.9	5.9 ± 2.4	0.077	0.220	/	3.6 ± 3.3	2.3 ± 3.0	1.7 ± 2.3	3.2 ± 2.1	0.077	0.220	/
Forefoot inversion (°)	16.0 ± 3.3	19.3 ± 3.9	13.0 ± 2.7	14.6 ± 4.2	**<0.001**	**0.641**	**HF > HS***(P=0.045) **F > HS****(P=0.004) **F > S*****(P<0.001) **HF > S***(P=0.045) **F > HF***(P=0.039)	10.4 ± 3.2	12.5 ± 5.3	9.1 ± 3.2	10.1 ± 3.1	**0.011**	**0.333**	**F > HS*** (P=0.036) **F > S*** (P=0.017)
ROM (°)	23.1 ± 3.1	25.3 ± 3.2	17.6 ± 2.8	20.4 ± 4.9	**<0.001**	**0.632**	**F > S*****(P<0.001) **HF > S*****(P=0.001) **F > HS***(P=0.021)	13.9 ± 4.5	14.8 ± 4.9	10.8 ± 3.6	13.3 ± 2.9	**0.005**	**0.372**	**HF > S*** (P=0.034) **F > S*** (P=0.044)

Values are mean ± SD. NS: non-significant. HF: high flexible, F: flexible, S: stiff, HS: high stiff.
**P* < 0.05.
***P* < 0.01.
****P* < 0.001.

Table 3. Maximal ankle torques across the four shoes for the shuttle run defensive forehand (SRDF) and the jab run offensive forehand (JROF).

	SRDF							JROF						
Maximal values	"High flexible"	"Flexible"	"Stiff"	"High stiff"	*P* value	Effect size	*Post-hoc* difference	"High flexible"	"Flexible"	"Stiff"	"High stiff"	*P* value	Effect size	*Post-hoc* difference
Plantar flexion (Nm.kg^{-1})	2.16 ± 0.35	2.10 ± 0.38	1.96 ± 0.37	1.85 ± 0.36	**<0.001**	**0.600**	HF > HS*** (P<0.001) F > HS*** (P<0.001) HF > S**(P=0.005)	2.49 ± 0.64	2.43 ± 0.63	2.38 ± 0.62	2.33 ± 0.49	0.145	0.180	/
Dorsiflexion (Nm.kg^{-1})	0.47 ± 0.13	0.52 ± 0.16	0.56 ± 0.20	0.63 ± 0.16	<0.001	0.598	HF < HS*** (P<0.001) F < HS*** (P<0.001) S < HS** (P=0.007) HF < S*** (P<0.001) HF < F** (P=0.007)	0.38 ± 0.21	0.41 ± 0.24	0.47 ± 0.26	0.51 ± 0.22	**0.006**	**0.413**	HF < S***(P<0.001) HF < HS***(P<0.001)
External rotation (Nm.kg^{-1})	0.07 ± 0.06	0.05 ± 0.06	0.08 ± 0.10	0.06 ± 0.03	0.704	0.050	/	0.08 ± 0.06	0.08 ± 0.09	0.07 ± 0.04	0.07 ± 0.02	0.668	0.052	/
Internal rotation (Nm.kg^{-1})	0.78 ± 0.26	0.85 ± 0.28	0.82 ± 0.28	0.75 ± 0.22	0.315	0.152	/	0.58 ± 0.24	0.60 ± 0.25	0.55 ± 0.19	0.56 ± 0.13	0.989	0.004	/
Inversion (Nm.kg^{-1})	0.13 ± 0.09	0.12 ± 0.07	0.12 ± 0.07	0.12 ± 0.07	0.182	0.162	/	0.08 ± 0.08	0.09 ± 0.07	0.10 ± 0.07	0.07 ± 0.06	0.508	0.091	/
Eversion (Nm.kg^{-1})	0.59 ± 0.36	0.58 ± 0.38	0.65 ± 0.33	0.61 ± 0.35	0.415	0.110	/	0.43 ± 0.23	0.38 ± 0.17	0.40 ± 0.12	0.39 ± 0.15	0.644	0.056	/

Values are expressed as mean ± SD. HF: high flexible, F: flexible, S: stiff, HS: high stiff.
*$P < 0.05$.
**$P < 0.01$.
***$P < 0.001$.

observed between JROF and SRDF are linked to the nature of these tennis movements. The JROF is a forward and slightly lateral movement while the SRDF is a strong lateral movement that may solicit more of the ankle in the frontal plane (action of inversion/eversion). In SRDF, the “high stiff” shoes had the disadvantage of largely increasing the maximal angle of ankle inversion (+3–5°) and slightly increasing the maximal angular velocity of ankle inversion (+ 48.9–75.2 °/s) compared to other shoes. A quantitative synthesis of published case reports documenting the kinematics of acute lateral ankle sprains and episodes of “giving-way” of the ankle joint reported that excessive ankle inversion was the most pronounced kinematic pattern observed across all included cases, with great variation for peak inversion angle (range 2.0–142°) and angular velocity (range 468–1752°/s) (Lysdal et al., 2022). A study presenting five cases of ankle sprains from televised tennis competitions reported great variations in the peak inversion angle and angular velocity in the five cases, which cases ranged from 48 to 126° and from 509 to 1488°/s, respectively (Fong et al., 2012). Our results show that it is for the “high stiff” shoe that the ankle inversion values (peak angle: 42.9° and peak angular velocity: 477.2°/s) are the closest of those previously published from ankle sprain case studies. Consequently, the “high stiff” shoe seems more conducive to induce lateral ankle sprains in tennis players during SRDF.

Moreover, the literature supports that the higher the ankle eversion torque, the higher the risk of injury. Our results showed a small but not significant effect of the shoe torsional stiffness on maximal ankle eversion torque in SRDF. The maximal ankle eversion torques in “high stiff” and “stiff” shoes were 3–12% higher than in “flexible” and “high flexible” shoes. These results are partially in line with the findings of Graf et Stefanyshyn (2013) who reported a significant increased ankle eversion torque of 20% for stiff shoes in comparison with flexible shoes in typical cutting movements for team sports. Behind ankle inversion, internal rotation is considered the second factor of lateral ankle sprain (Lysdal et al., 2022). In our study, the maximal angles and torques of ankle internal rotation were not significantly influenced by the shoe torsional stiffness in SRDF and JROF.

The ankle plantar flexion angle and torque are considered minor factors of injury because it might not play a crucial role in the lateral ankle sprain mechanism (Purevsuren et al., 2018) (Lysdal et al., 2022). Indeed, high plantar flexion is not always required for an ankle sprain to occur (Mok et al., 2011) (Kristianslund et al., 2011) (Panagiotakis et al., 2017). Whereas ankle plantar flexion and dorsiflexion angles were not significantly influenced by shoe torsional stiffness in SRDF and JROF (only small or trivial effects), our results surprisingly showed large and significant effects of shoe torsional stiffness on ankle plantarflexion torques in SRDF and dorsiflexion torques in SRDF and JROF. The reason for these results remains unclear. While it has been reported that a muscular deficit in plantar flexion torque characterised unstable ankles (Fox et al., 2008), the literature lacks clear and consensual data about the potential effects of ankle plantar flexion and dorsiflexion torques on ankle injury risks and mechanisms (Lysdal et al., 2022). Further studies are necessary to understand them and to enlighten our current results.

The maximal angle of forefoot inversion and the range of motion of forefoot inversion–eversion were significantly affected by the shoe torsional stiffness for both forehand strokes and movements. The effect of the shoe torsional stiffness on these kinematic parameters was large for the SRDF and moderate for the JROF. For the SRDF, the “stiff” and the “high stiff” shoes demonstrated smaller maximal angle of forefoot inversion and range of motion of forefoot inversion–eversion. All these results are in line with the findings of (Graf & Stefanyshyn, 2013). In stiff shoes, the forefoot and the rearfoot were more rigidly coupled. This mechanism reduces the maximal angle of forefoot inversion but increases the ankle inversion angle to provide an effective angle between forefoot and shank in stiff shoes (Graf & Stefanyshyn, 2013). On the contrary, in “flexible” and “high flexible” shoes, the forefoot and the rearfoot acted and moved in a more free or independent way than in stiffer shoes. The difference between shoe conditions was small (1–6°) and it is assumed that the observed increase in forefoot movement does not increase the risk of injury in the flexible shoes (Graf & Stefanyshyn, 2013). The difference in forefoot inversion angle could explain the higher feeling of comfort associated with flexible shoes in tennis players (Herbaut et al., 2019) (Llana et al., 2002). According to Avagnina (2018), the relationship between the rearfoot and forefoot is fundamental for the comfort, the speed, the fluidity and the transfer of rotation from the foot to the lower limb during tennis motions. In running, different studies showed that the stiffer the shoe, the more the natural barefoot motion of the foot was modified (Stacoff et al., 1989) (Stacoff et al., 1991). As a consequence, by “freeing” the foot and inducing more forefoot torsion, one may hypothesise that flexible shoes could help tennis players to perform more natural foot actions during tennis forehands and strokes. Further studies comparing barefoot and different conditions of shoes’ stiffness during tennis motions are necessary to confirm this hypothesis.

Our study had several limitations. First, the comfort of the shoes was not assessed, this is a limitation of the present work. Moreover, the sample size was small because we only included male advanced tennis players able to properly perform both specific forehand stroke movements (SRDF and JROF) and their participation was voluntary. The small sample size of this exploratory study also increased the chance of type II errors and decreased statistical power. Another limitation of the current study was that the measure of foot and ankle motions was based on markers placed on the shoes' upper and on the skin of the players. This could slightly increase errors in the kinematic and kinetic calculations despite efforts to minimise them, such as by placing markers on bony prominences with the least amount of skin motion. A recent study compared ankle kinematic measures during running trials with an optoelectronic marker-based system and biplanar videoradiography (Kessler et al., 2019). Results showed a good agreement of ankle plantarflexion/dorsiflexion angles between the two systems but moderate agreements for the ankle inversion/eversion and internal/external rotation angles. As a consequence, the interpretation of ankle inversion/eversion and internal/external rotation angles in the current study should be treated with caution. Moreover, the movement of the foot inside the shoe could not be quantified with the motion capture system. One may suppose that the torsion angle of the foot in the shoe was larger than the torsion angle of the shoe (Graf & Stefanyshyn, 2013). One may hypothesise that the difference between the torsion angle of the foot in the shoe and the torsion angle of the shoe may be more important in the most flexible shoes that less constrain and less modify the natural motion of the foot (Stacoff et al., 1989) (Stacoff et al., 1991). Finally, we evaluated ankle loadings using the inverse dynamics method but we did not use musculoskeletal modelling and computer simulations to predict the ankle muscle and ligament forces during the forehand strokes. The insight into how leg and foot muscles interact to produce the motion may be of importance for a better understanding of possible ankle injury mechanisms.

In conclusion, shoe torsional stiffness had no effect on performance since absolute running velocity of the centre of mass at the instant of the first contact between the right foot and the force plate, stance duration, and maximal values of GRF are similar for the four shoe conditions for both SRDF and JROF. For SRDF and JROF, the shoe torsional stiffness influenced forefoot inversion which was significantly higher for the most flexible shoes. As a consequence, in flexible shoes, the forefoot and the rearfoot acted and moved in a freer way. For SRDF, the maximal ankle inversion angle was significantly and largely increased for the stiffest shoe. This result showed that the stiffest shoe may put the ankle at a higher risk of lateral sprains during shuttle run defensive forehand stroke (SRDF) while it was not the case during jab run offensive forehand stroke (JROF).

From a practical relevance point of view, adapting shoe torsional stiffness to the population of interest might be beneficial for limiting tennis ankle sprains. This study leads to encouraging defensive or baseliner tennis players, who like to play long rallies with shuttle run defensive strokes behind the baseline, to wear shoes with low torsional stiffness to limit ankle inversion and consequently lateral ankle sprain risks. One may hypothesise that this advice could also be provided to players with chronic ankle instability. Further complementary studies combining biomechanical analyses of the lower limbs during specific tennis motions and prospective epidemiological follow-up of the foot and ankle injuries sustained by the players according to the stiffness of their shoes could help to approximate a threshold value for the maximal shoe torsional stiffness for tennis use.

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