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Effect of foot strike patterns and cutting angles on knee kinematics and kinetics during side-cutting maneuvers

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Abstract

Purpose: Cutting maneuvers are important actions in multidirectional sports but associated with noncontact anterior cruciate ligament (ACL) injuries. This study aimed to investigate the effect of different foot strike patterns and cutting angles on knee kinematics and kinetics. *Methods:* Twenty healthy male team sports athletes performed cuts with maximum speed at three angles (45°, 90°, and 135°) with different foot strike patterns (rearfoot strike [RFS] and forefoot strike [FFS]). A three-dimensional motion capture system combined with a force plate was used to collect makers trajectory and ground reaction force (GRF). Vertical GRF, and knee joint angles and moments were compared among these cutting tasks. *Results:* Regardless of foot strike patterns, increased knee flexion angle, knee valgus moment, and knee internal rotation moment were observed during cutting to sharper angles ($p < 0.001$). At 90° and 135°, the FFS condition remained in a varus position and showed lower knee flexion moment than the RFS condition ($p \leq 0.004$). However, no significant differences in knee kinematic and kinetic variables were found between foot strike patterns during cutting to 45°. *Conclusions:* These findings suggest that sharper cutting angles potentially increase the risk of ACL injury. Compared with the RFS pattern, the FFS pattern induces a slight knee varus angle and a lower knee flexion moment at sharper angles, which might further reduce the load placed on the knee.

Keywords: Cutting movement, rearfoot strike pattern, forefoot strike pattern, anterior cruciate ligament

1. Introduction

Cutting maneuvers are key abilities during fast change directions in multidirectional sports and can be used in evaluating performance [3]. The maneuvers occur more than 100 times during a football or basketball game [1]. An athlete who participates in team sports is required to perform cutting maneuvers at a wide range of angles in response to a defender or to pursue the ball.

However, cutting maneuvers have been identified as a potential risk factor causing noncontact anterior cruciate ligament (ACL) injury [26]. In team sports athletes, noncontact ACL injuries are responsible for 20% of knee injuries [17]. To perform a cutting maneuver, athletes have to decelerate in the original direction, then reorient their body into the new direction, and finally accelerate into the new direction [12]. During the deceleration phase, greater knee valgus angle [23], knee valgus moment [26], and knee internal rotation moment [28] increase the risk of ACL rupture.

Different foot strike patterns (rearfoot strike [RFS] and forefoot strike [FFS]) were performed during cutting maneuvers and may affect knee biomechanics. Rearfoot strikers were found to land with a shallow knee flexion angle compared with FFS during performing 45° cutting [32]. Peak knee flexion and valgus moments were greater in RFS than in FFS during 45° cutting movement [4, 8]. David et al. [6] demonstrated increase in vertical ground reaction force (GRF), knee flexion angle, and knee valgus and internal rotation moments when rearfoot strikers were instructed to perform 90° cutting movement. Furthermore, combined knee valgus and tibial internal rotation moments occur more frequently in RFS than in FFS during 60° cutting movement [25]. The changes in frontal and transversal plane kinematics may produce greater leg stiffness during FFS cutting than during RFS cutting, which is more beneficial to team athletes [6, 31]. However, most of these studies used a single cutting angle to investigate the effect of foot strike patterns on knee biomechanics. Less is known regarding foot strike patterns on knee biomechanics when athletes have to change direction to different angles.

As mention above, technique selection is angle dependent when changing direction. Therefore, different cutting angles are used during movement. Athletes have greater knee flexion angle at initial contact and knee valgus moment during a 90° cutting movement than in a 45° cutting movement [13, 15]. Cortes et al. [5] reported no differences in maximum knee flexion angle between the angles of 45° and 180°. Schreurs et al. [27] found that knee flexion moment and vertical GRF decreased and knee valgus moment increased during cutting towards sharper angles. However, these studies did not distinguish foot strike patterns when examining the effects of cutting angles on knee biomechanics.

To the best of our knowledge, whether the same differences in foot strike patterns in knee loading can be observed when athletes perform cutting movements at a diverse range of angles. Understanding the postures that contribute to knee loading during cutting to different angles with proper foot strike patterns should provide valuable information to inform ACL prevention strategies.

This study aimed to investigate knee joint kinematics and kinetics of different cutting angles with RFS and FFS patterns. We hypothesized that RFS patterns will decrease knee flexion angle, with a concomitant increase in knee valgus angle, knee valgus moment, and vertical GRF, compared with FFS patterns during among three tasks. Additionally, we hypothesized that cutting to sharper angles will lead to increased knee joint load regardless of foot strike patterns.

2. Materials and Methods

2.1 Participants

Twenty healthy male team sports athletes (22.4 ± 2.5 years, 1.74 ± 0.1 meters, and 75.2 ± 10.5 kg) participated in this study. The sample size was estimated based on a priori power calculations to achieve a 80% statistical power with an alpha level of 0.05 [22].

The inclusion criteria were: (1) participating in basketball or soccer sports with regular practice (≥ 3 times/week) for at least one year; (2) right leg dominant, which was determined by ball kicking test; and (3) free of lower-limb injuries and pains during the past 12 months. The participant reporting history of ACL injury was excluded. All the participants provided written informed consent before their participation. The study protocol was reviewed and approved by the university ethical committee (102772020RT002).

2.2 Data collection

All participants wore a black shorts and pants. The effect of footwear was minimized by requiring the participants to wear assigned non-studded indoor soccer shoes (Adidas SAMBA 019000). A total of forty markers were used for tracking the side-cutting maneuvers. Twenty-four reflective markers (14 mm) were firmly attached to each participant's bilateral lower limbs (the superior border of the iliac crests, anterior and posterior superior iliac spines, greater trochanters, medial and lateral epicondyles of the femurs, medial and lateral malleoli, the first and fifth metatarsal heads, and the end of the second toes and heels). Tracking marker clusters mounted on semirigid plastic plates were placed on the participants' bilateral thighs, shanks, and shoes. Participants were instructed to run on the 7.5-meter run up track, plant their right dominant foot and subsequently made a 45°, 90°, or 135° cut to the contralateral side. Cutting angles were marked on the floor with tape and controlled using a 1-meter marked runway.

The three side-cutting maneuvers (45°, 90°, and 135°) were performed under two different landing techniques (RFS and FFS). The RFS pattern was defined as when the heel first made contact with the force plate followed by the forefoot. For the FFS pattern, initial contact was performed with the toes followed by the rearfoot [4, 8]. Participants performed side-cutting maneuvers with maximum effort to simulate a real movement scenario. They were encouraged to sprint at full speed from start to finish by a experimenter. A Brower timing system (Brower Timing Systems, Draper, UT, USA) with two photocell sensors were placed three meters apart before the force plate for monitoring the approaching speed.

Before the tests, participants were given five minutes to familiarize the experimental settings and a five-minute warm-up at a self-selected pace on a treadmill. During the data collection, participants performed the side-cutting maneuvers of 45°, 90°, and 135° in random order using the RFS pattern, followed by the FFS pattern. At least three trials were performed. Marker trajectories and synchronized kinetic data were collected using a motion capture system with eight cameras (Vicon Nexus, Oxford, UK) at 200 HZ and a force plate (90 cm×60 cm; Kistler 9287 C, Winterthur, Switzerland) at 1000 HZ.

All participants were required to complete three successful trails for each condition. The successful trial was defined as when the entire right foot stroke on the force plate and the correct maneuver (e.g., foot strike patterns, cutting angles) was performed with maximum effort. To minimize fatigue, participants were allowed to rest for five minutes between trials.

2.3 Data processing

The three successful trials for each side-cutting maneuver condition were used for analysis. Marker trajectories were initially processed using Vicon Nexus software (version 1.7), then exported together with GRF data and processed using Visual 3D software (C-Motion Inc., Rockville, MD, USA). Raw marker trajectory and GRF data were filtered with a recursive fourth-order low-pass filter at 10 Hz and 50 Hz, respectively. GRF data were normalized to body mass. Initial contact events were identified using a threshold of 50 N. All the kinematic and kinetic variables of the right side were analyzed using a customized MATLAB program (The MathWorks, Natick, MA). The kinematic variables referred to knee flexion and varus/valgus angles. The kinetic variables were the vertical GRF and knee joint moments (knee flexion, knee valgus, and knee internal rotation moments).

All variables were analyzed for the deceleration phase, which is from the right foot initially contacting the force plate to maximal knee flexion. The deceleration phase was selected, as the knee injuries occurs generally in this period and it has been associated with noncontact ACL injuries [2, 18].

2.4 Statistical analysis

All statistical analyses were conducted using a statistical software (SPSS version 20, IBM Inc., Chicago, USA). Results were presented as mean ± standard deviation. Two-way repeated measure ANOVA (2 foot strike patterns × 3 side-cutting angles) were used to determine differences of all dependent variables between foot strike patterns (RFS and FFS) or side-cutting angles (45°, 90°, and 135°). When indicated, post-hoc pairwise comparisons with Bonferroni correction ($p < 0.0056$) were performed. The significance level was set at $p = 0.05$. Effect sizes were quantified using partial eta squared (η_p^2).

3. Results

3.1 Approach speed

The approach speed for RFS patterns was 4.51 ± 0.23, 3.92 ± 0.19, and 3.75 ± 0.16 m/s, respectively. For FFS patterns these averages were 4.53 ± 0.24, 4.04 ± 0.19, and 3.81 ± 0.17 m/s. No significant differences were found in approach speed between foot strike patterns at the same angle ($p > 0.05$). However, both foot strike patterns performed increasing approach speed with increasing cutting angle ($p < 0.001$).

3.2 Kinematic variables

A significant foot strike patterns × cutting angles interaction was found in the knee varus/valgus angle ($p = 0.003$, $\eta_p^2 = 0.16$; Figure 1B; Table 1). In RFS patterns, post-hoc test showed that the knee valgus angle was not significant among the three cutting angles ($p > 0.0056$). Forefoot strikers adopted a slight varus position when cutting to 90° and 135°. At 45°, they showed a valgus angle. In general, the RFS pattern had increased knee valgus angle over the FFS pattern at 90° ($p < 0.001$, 95% confidence interval [CI]: 1.94 to 4.27°) and 135° ($p < 0.001$, 95% CI: 2.73 to 6.27°). However, post-hoc test revealed no statistical differences in knee varus/valgus angle during 45° cutting movements between two foot strike patterns ($p > 0.0056$).

A significant main effect of cutting angles was observed in knee flexion angle ($p < 0.001$, $\eta_p^2 = 0.43$; Figure 1A; Table 1). Both foot strike patterns had a greater knee flexion angle during cutting to 90° ($p < 0.001$, 95% CI: −5.89 to 0.84°) and 135°

(p < 0.001, 95% CI: −10.83 to 1.48°) compared to the 45° cutting angle and during cutting to 135° compared with 90° (p = 0.001, 95% CI: −4.93 to 1.23°). Regarding foot strike patterns, no significant difference was found for knee flexion angle (p = 0.78).

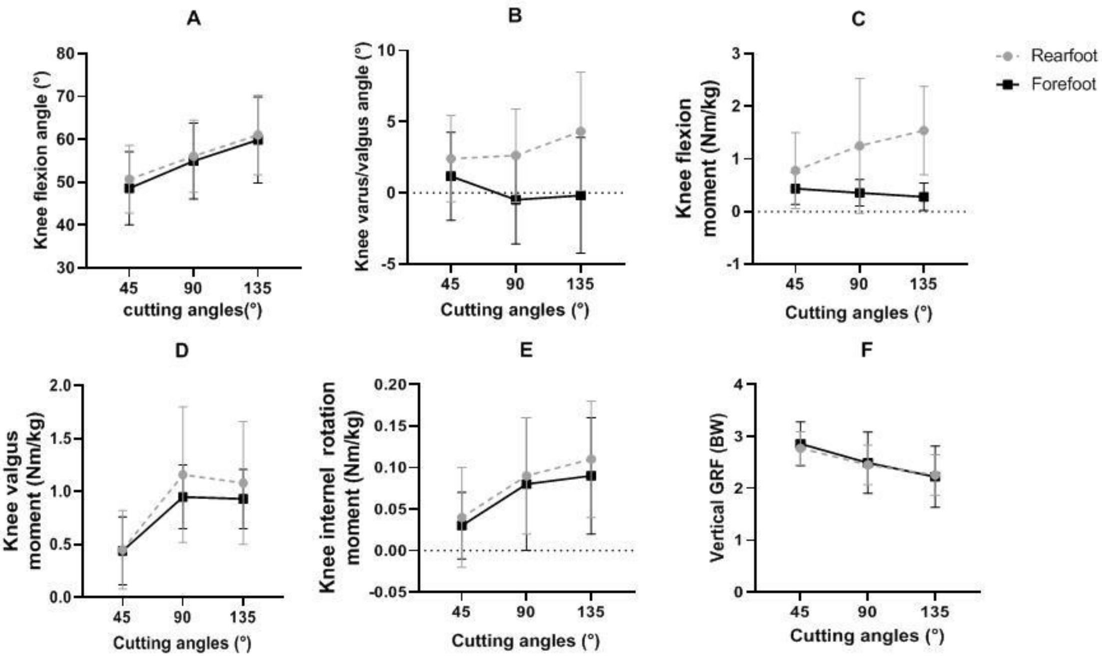

Figure 1. knee flexion angle, knee varus/valgus angle, and knee flexion moment (top row, A–C), and knee valgus moment, knee internal rotation moment, vertical GRF (bottom row, D–F). Gray diamonds rearfoot strike patterns; black squares represent forefoot strike patterns. Statistically significant differences are reported in Table 1.

3.3 Kinetic variables

Knee joint moments

A significant foot strike patterns × cutting angles interaction was found in knee flexion moment (p < 0.001, η_p^2 = 0.47; Figure 1C; Table 1). In the RFS condition, the knee flexion moment at 135° cutting angle was smaller than that at 45° cutting angle (p < 0.001, 95% CI: 0.36 to 1.16 Nm/kg). No differences in knee flexion moment were found for FFS patterns when the participants made cutting movements at the three angles (p ≥ 0.01). RFS patterns exhibited a greater knee flexion moment than FFS patterns at cutting angles of 90° (p = 0.004, 95% CI: −1.46 to −0.33 Nm/kg) and 135° (p < 0.001, 95% CI: −1.69 to −0.84 Nm/kg). However, post-hoc test showed no significant difference in knee flexion moment between foot strike patterns at 45° task ($p > 0.0056$).

Significant differences in knee valgus moment ($p < 0.001$, $\eta_p^2 = 0.54$; Figure 1D; Table 1) and internal rotation moment ($p < 0.001$, $\eta_p^2 = 0.26$; Figure 1E; Table 1) were observed among cutting angles. Knee valgus and internal rotation moments at 90° cutting angle (knee valgus moment, $p < 0.001$, 95% CI: 0.45 to 0.79 Nm/kg; knee internal rotation moment, $p < 0.001$, 95% CI: 0.04 to 0.01 Nm/kg) and 135° cutting angle (knee valgus moment, $p < 0.001$, 95% CI: 0.56 to 0.07 Nm/kg; knee internal rotation moment, $p < 0.001$, 95% CI: 0.06 to 0.01 Nm/kg) were greater than those at 45° cutting angle for both foot strike patterns. However, no significant foot strike pattern effects were determined on the knee valgus ($p = 0.26$) and internal rotation moments ($p = 0.39$).

Vertical ground reaction force

A significant difference in vertical GRF ($p < 0.001$, $\eta_p^2 = 0.44$; Figure 1F; Table 1) was observed among cutting angles. Both foot strike patterns had lower vertical GRF when cutting to 90° ($p < 0.001$, 95% CI: −0.35 to 0.08 BW) and 135° ($p < 0.001$, 95% CI: −0.58 to 0.08 BW) than when cutting to 45°. No differences in vertical GRF were found between the RFS and FFS conditions ($p = 0.77$).

4. Discussion

This study aimed to determine the influences of different cutting angles and foot strike patterns on knee biomechanics. In line with our initial hypothesis, RFS patterns induced greater knee valgus angle at 90° and 135° cutting angles. However, this change was inconsistent at 45° cutting angle. No significant differences were found in knee flexion angle, knee valgus moment, and verticial GRF between two foot strike patterns during cutting tasks. In addition, differences were observed in all variables at sharper cutting angles. For instance, knee valgus and internal rotation moments increased.

Table 1. Comparison of the knee joint angles (mean ± standard deviation) during the foot strike patterns and cutting angles tasks.

Variables	Foot strike patterns	45°	90°	135°	Interaction effects		Cutting angle effects		Foot strike pattern effects	
					p	η_p^2	p	η_p^2	p	η_p^2
Knee flexion angle (°)	Rearfoot	50.69±7.87	56.08±8.38	61.04±9.25	0.53	0.01	**<0.001**	0.43	0.78	0.002
	Forefoot	48.59±8.52	54.94±8.84	59.84±10.01			abc			
Knee varus/valgus angle (°)	Rearfoot	2.41±3.03	2.63±3.27	4.32±4.17	**0.003**	0.16	0.08	0.07	**0.005**	0.19
	Forefoot	1.17±3.09	-0.48±3.11 &	-0.18±4.07 &						
Knee flexion moment (Nm/kg)	Rearfoot	0.78±0.72	1.25±1.28	1.54±0.84 *	**<0.001**	0.47	**0.03**	0.27	**<0.001**	0.36
	Forefoot	0.44±0.30	0.36±0.25 &	0.28±0.26 &						
Knee valgus moment (Nm/kg)	Rearfoot	0.45±0.37	1.16±0.64	1.08±0.58	0.39	0.024	**<0.001**	0.54	0.26	0.03
	Forefoot	0.44±0.32	0.95±0.30	0.93±0.28			ab			
Knee internal rotation moment (Nm/kg)	Rearfoot	0.04±0.06	0.09±0.07	0.11±0.07	0.85	0.004	**<0.001**	0.26	0.39	0.02
	Forefoot	0.03±0.04	0.08±0.08	0.09±0.07			ab			
Vertical GRF (BW)	Rearfoot	2.77±0.32	2.45±0.38	2.26±0.39	0.69	0.01	**<0.001**	0.44	0.77	0.002
	Forefoot	2.86±0.42	2.49±0.59	2.22±0.59			abc			

a = significant difference between 45° and 90°; b = significant difference between 45° and 135°; c = significant difference between 90° and 135°.

When significant interaction effect was found, simple main effect was applied to identify the significant differences between foot strike patterns and between cutting angles:

* Significant difference from the 45° cutting angle ($p < 0.0056$).

Significant difference from the 90° cutting angle ($p < 0.0056$).

& Significant difference from the rearfoot strike pattern ($p < 0.0056$).

One key finding was that forefoot strikers adopted a slight varus position when cutting to 90° and 135°. This finding was consistent to the reports of David et al. [6], who found that forefoot strikers always stabilized their knee joints in the varus position when performing 90° cutting movement. However, at 45° cutting angle, we obseved a valgus angle in the FFS condition. This phenomenon may be because of different preparatory actions during the braking phase prior to transition. Individuals would pre-rotate their limbs according to the demand of plan cutting maneuvers [30]. More body preorientation toward a new movement direction is demonstrated when cutting to 90° or larger [14, 29]. Furthermore, RFS patterns presented an increased valgus angle during both tasks. Consistent to our findings, Yoshida et al. [33] showed that knee valgus angles tended to be greater during 60° cuts performed with an RFS pattern. Previous studies have found through video analysis that participants were in a valgus position at the time of injury [19]. The position of the knee valgus may increase risk of ACL injury compared with neutral to varus aligned position. Accordingly, the use of FFS patterns would decrease the risk of injury, especially when cutting to 90° or 135° angles.

Regardless of cutting angles, no differences in maximum knee flexion angle were found between foot strike patterns. Meanwhile, both foot strike patterns showed a greater maximum knee flexion angle when comparing 90° and 135° to the 45° condition. Uno et al. [32] found that rearfoot strikers were in a more extended knee position in the early phase compared with forefoot strikers but presented similar angles between foot strike patterns at peak flexion angle. As participants completed the tasks at maximum effort in our study, similar maximum knee flexion angle helped them maintain performance in different foot landing techniques. However, inconsistent to our finding, Cortes et al. [4] observed greater knee flexion angle at peak stance during 45° cuts performed with an RFS pattern. Additionally, Schreurs et al. [27] reported a reduction in knee flexion angle for females cutting to an angle of 90° or larger. This discrepancy may be because males were recruited in the current study, whereas females participated in their study. Compared with females, males used a greater knee flexion regardless of cutting angles [21, 27], therby greatly absording landing impact. A cut with a greater knee flexion angle requires more strength from the quadriceps muscles, which was better handled by our participants at sharper cutting angles. In addition, greater muscle activities of the vastus lateralis and biceps femoris were observed when cutting to sharper angles [11]. Accordingly, our participants subconsciously adjusted the recruitment of muscles around the knee joint in response to change in direction during the deceleration phase. This adjustment resulted in a greater knee flexion angle. Another explanation is that the finding of the knee flexion angle is related with the finding of approach speed. The sagittal plane angle increased with sharper angles, where participants decreased their approach speed. Athletes would sacrifice performance to reduce the load placed on the knee. In addition, a previous study reported that the changes of the approach speed may be mediated by the leg stiffness [20]. Accordingly, to minimize the loss of approach speed when cutting to sharper angels, exercises should be designed to improve leg stiffness..

The results of the current study demonstrated that the knee valgus and internal rotation moments increased during cutting to sharper angles. Similarly, previous studies found that knee valgus moment increased with cutting angle [13, 29]. As greater knee valgus and internal rotation moments have been identified as key factors to increase ACL injury risk [16, 28], the strain of ACL may be high during cutting towards sharper angles.

In the study, no changes in knee valgus and internal rotation moments were found between foot strike patterns during cutting to different angles. Consistent to our findings, Corters et al. [4] reported athletes with an enforced FFS pattern displayed similar knee valgus moment at peak stance during cutting to 45° or 180°. However, the knee valgus and internal moments were high when all participants were habitual rearfoot strikers [6, 8]. In the current study, the participants were instructed to perform two foot strike patterns. Difference in task demands, regardless of the foot strike pattern utilized, may explain the lack of change in knee valgus and internal rotation moments. The notion was supported by Cortes et al. [5], suggesting that multiple biomechanical risk factors vary with task constraints.

Interestingly, RFS patterns produced a greater knee flexion moment when comparing 135° to 45° condition, whereas the knee flexion moment tended to be smaller during cutting to sharper angles performed with FFS patterns. In addition, we observed that the knee flexion moment in RFS was 1.7, 3.4, and 5.5 times that in FFS when cutting to 45°, 90°, or 135°. Simulation research has shown that the combination of a knee valgus position with a flexion moment may increase ACL injury risk [24]. Load placed on the knee joint increases when landing in heel. However, the use of FFS patterns could alleviate impact through foot structures, such as foot arch and plantar fat pad of forefoot, at increased cutting angles. The phenomenon may increase ankle stiffness, which may help an FFS pattern shifted from a knee-absorption strategy to ankle absorption strategy [7]. Further evidence is required to support our interpolation because the joint stiffnesses were not investigated in the current study.

With regard to vertical GRF, we found that the value was lower when cutting to 135° compared with cutting to 45°. This finding may be because of greater shock attenuation by knee flexion when cutting to sharper angles. In addition, the large redirection requirements increased distance between the center of pressure and center of mass when cutting angles increased, thus making the vertical GRF less perpendicular to the ground. Regarding foot strike patterns, no differences in vertical GRF were found. These finding were unexpected when compared with the results of other studies [4, 6], which reported that RFS patterns produced a lower maximum vertical GRF than FFS patterns at cutting angles of 45° or 90°. The discrepancy may be due to gender differences. Our findings demonstrated that males may distribute vertical forces to maintain the similar approach speed in two foot strike patterns.

Three limitations should be highlighted. First, gender-specific responses on knee biomechanics were found when cutting to different angles [27]. However, this study only recruited male athletes. Second, the cutting maneuver was performed in a planned condition, which also occurred frequently during a match due to practiced moves. However, unlike unplanned cutting maneuvers, planned cutting maneuvers may affect athletes' lower limbs in a certain way [10]. Thus, the main findings of the present study should be applied with caution to unplanned cutting tasks. Lastly, this study only investigated the dominant leg when performing cutting maneuvers, as it can be better controlled. In addition, whether limb dominance is related to noncontact ACL biomechanical risk factors remain unclear [9]. Therefore, caution should be taken when explaining knee biomechanics with the nondominant leg.

5. Conclusion

This study demonstrated that different cutting angles and foot strike patterns demand different knee biomechanics. Cutting tasks with sharper angles might potentially increase the risk of ACL injury due to the results of knee valgus and internal rotation moments. However, the knee biomechanics presented inconsistent trends when participants performing cutting tasks with FFS patterns. In the FFS condition, participants remained in a varus position and showed lower knee flexion moment during cutting to sharper angles, whereas the knee kinematics and kinetics presented similar values between foot strike patterns during cutting to 45°. Therefore, the use of FFS patterns can further reduce the load placed on the knee compared with the RFS patterns at increased cutting angles.

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References

1. BLOOMFIELD J., POLMAN R., O'DONOGHUE P., *Physical demands of different positions in FA Premier League soccer*, J. Sports. Sci. Med., 2007, 6 (1), 63.
2. BODEN B., DEAN G., FEAGIN J., GARRETT W., *Mechanisms of anterior*

cruciate ligament injury, Orthopedics., 2000, 23 (6), 573-578, DOI: 10.3928/ 0147-7447-20000601-15

3. BRUGHELLI M., CRONIN J., LEVIN G., CHAOUACHI A., *Understanding change of direction ability in sport: a review of resistance training studies*, Sports. Med., 2008, 38 (12), 1045-1063, DOI: 10.2165/00007256-200838120-00007
4. CORTES N., MORRISON S., VAN LUNEN B., ONATE J., *Landing technique affects knee loading and position during athletic tasks*, J. Sci. Med. Sport., 2012, 15 (2), 175-181, DOI: 10.1016/j.jsams.2011.09.005
5. CORTES N., ONATE J., VAN LUNEN B., *Pivot task increases knee frontal plane loading compared with sidestep and drop-jump*, J. Sports Sci., 2011, 29 (1), 83-92, DOI: 10.1080/02640414.2010.523087
6. DAVID S., KOMNIK I., PETERS M., FUNKEN J., POTTHAST W., *Identification and risk estimation of movement strategies during cutting maneuvers,* J. Sci. Med. Sport., 2017, 20 (12), DOI: 1075-1080.10.1016/j.jsams. 2017.05.011
7. DAVID S., MUNDT M., KOMNIK I., POTTHAST W., *Understanding cutting maneuvers - The mechanical consequence of preparatory strategies and foot strike pattern*, Hum. Movement. Sci., 2018, 62, 202-210, DOI:10.1016/j.humov. 2018.10.005
8. DONNELLY C., CHINNASEE C., WEIR G., SASIMONTONKUL S., ALDERSON J., J*oint dynamics of rear- and fore-foot unplanned sidestepping.* J. Sci. Med. Sport., 2017, 20 (1), 32-37, DOI: 10.1016/j.jsams.2016.06.002
9. DOS'SANTOS T., BISHOP C., THOMAS C., COMFORT P., JONES P. A., *The effect of limb dominance on change of direction biomechanics: a systematic review of its importance for injury risk*, Phys. Ther. Sport., 2019, 37, 179-189, DOI: 10.1016/j.ptsp.2019.04.005
10. DUTAILLIS B., OPAR D. A., PATAKY T., TIMMINS R. G., HICKEY J. T., MANIAR N., *Trunk, pelvis and lower limb coordination between anticipated and unanticipated sidestep cutting in females*, Gait. Posture., 2021, 85, 131-137,

DOI: 10.1016/j.gaitpost.2020.12.011

11. HADER K., MENDEZ-VILLANUEVA A., PALAZZI D., AHMAIDI S., BUCHHEIT M., *Metabolic power requirement of change of direction speed in young soccer players: not all is what it seems*, PloS. One., 2016, 11 (3), DOI: 10. 1371/journal.pone.0149839
12. HASE K., STEIN R., *Turning strategies during human walking. Journal of neurophysiology*, 1999, 81 (6), 2914-2922, DOI: 10.1152/jn.1999.81.6.2914
13. HAVENS K., SIGWARD S., *Cutting mechanics: relation to performance and anterior cruciate ligament injury risk*, Med. Sci. Sport. Exer., 2015, 47 (4), 818-824, DOI: 10.1249/MSS.0000000000000470
14. HAVENS K., SIGWARD S., *Joint and segmental mechanics differ between cutting maneuvers in skilled athletes*, Gait. Posture., 2015, 41 (1), 33-38, DOI: 10. 1016/j.gaitpost.2014.08.005
15. HAVENS K., SIGWARD S., *Whole body mechanics differ among running and cutting maneuvers in skilled athletes*, Gait. Posture., 2015, 42 (3), 240-245, DOI: 10.1016/j.gaitpost.2014.07.022
16. HEWETT T., MYER G., FORD K., HEIDT R., COLOSIMO A., MCLEAN, S., VAN DEN BOGERT A. J., Paterno M.V., SUCCOP P., *Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes: a prospective study*, Am. J. Sport. Med., 2005, 33 (4), 492-501, DOI: 10.1177/0363546504269591
17. HOOTMAN J. M., DICK R., AGEL J., *Epidemiology of collegiate injuries for 15 sports: summary and recommendations for injury prevention initiatives*, J. Athl. Training., 2007, 42 (2), 311.
18. JAMISON S. T., PAN X., CHAUDHARI A. M., *Knee moments during run-to-cut maneuvers are associated with lateral trunk positioning*, J. Biomech., 2012, 45 (11), 1881–1885, DOI: 10.1016/j.jbiomech.2012.05.031
19. KROSSHAUG T., NAKAMAE A., BODEN B., ENGEBRETSEN L., SMITH G., SLAUTERBECK J., Hewett T. E., BAHR R., *Mechanisms of anterior cruciate ligament injury in basketball: video analysis of 39 cases*, Am. J. Sport.

Med., 2007, 35 (3), 359-367, DOI: 10.1177/0363546506293899

20. LIEW B. X. W., SULLIVAN L., MORRIS S., NETTO K., *Lower-limb stiffness mediates speed but not turning angle during unplanned side-step cutting.* J. Biomechanics., 2021, 115, 110132, DOI: 10.1016/j.jbiomech.2020. 110132.
21. MALINZAK R., COLBY S., KIRKENDALL D., YU B., GARRETT W., *A comparison of knee joint motion patterns between men and women in selected athletic tasks*, Clin. Biomech., 2001, 16 (5), 438-445, DOI: 10.1016/s0268-0033 (01)00019-5
22. MCLEAN S., HUANG X., VAN DEN BOGERT A., *Association between lower extremity posture at contact and peak knee valgus moment during sidestepping: implications for ACL injury*, Clin. Biomech., 2005, 20 (8), 863-870, DOI: 10. 1016/j.clinbiomech.2005.05.007
23. MCLEAN S. G., LIPFERT S. W., VAN DEN BOGERT A. J., *Effect of gender and defensive opponent on the biomechanics of sidestep cutting*, Med. Sci. Sport Exer., 2004, 36 (6), 1008–1016, DOI: 10.1249/01.mss.0000128180.51443.83
24. MCLEAN S., HUANG X., VAN DEN BOGERT A., *Investigating isolated neuromuscular control contributions to non-contact anterior cruciate ligament injury risk via computer simulation methods*, Clin. Biomech., 2008, 23 (7): 926-936. DOI: 10.1016/j.clinbiomech.2008.03.072
25. OGASAWARA I., SHIMOKOCHI Y., MAE T., NAKATA K., *Rearfoot strikes more frequently apply combined knee valgus and tibial internal rotation moments than forefoot strikes in females during the early phase of cutting maneuvers*, Gait. Posture., 2020, 76, 364-371, DOI: 10.1016/j.gaitpost.2019.11. 014
26. OLSEN O., MYKLEBUST G., ENGEBRETSEN L., BAHR R., *Injury mechanisms for anterior cruciate ligament injuries in team handball: a systematic video analysis*, Am. J. Sport. Med., 2004, 32 (4), 1002-1012, DOI: 10.1177/0363546503261724
27. SCHREURS M., BENJAMINSE A., LEMMINK K., *Sharper angle, higher risk? The effect of cutting angle on knee mechanics in invasion sport athletes*, J.

Biomech., 2017, 63, 144-150, DOI: 10.1016/j.jbiomech. 2017.08.019

28. SHIN C. S., CHAUDHARI A. M., ANDRIACCHI T. P., *Valgus plus internal rotation moments increase anterior cruciate ligament strain more than either alone*, Med. Sci. Sport. Exer., 2011, 43 (8), 1484-1491, DOI: 10.1249/MSS. 0b013e31820f8395
29. SIGWARD S., CESAR G., HAVENS K. L., *Predictors of frontal plane knee moments during side-step cutting to 45 and 110 degrees in men and women: Implications for anterior cruciate ligament injury*, Clin. J. Sport. Med., 2015, 25 (6), 529-534, DOI: 10.1097/JSM.0000000000000155
30. SIGWARD S., POWERS C. M., *Loading characteristics of females exhibiting excessive valgus moments during cutting*, Clin. Biomech., 2007, 22 (7), 827-833, DOI: 10.1016/j.clinbiomech.2007.04.003
31. STRUZIK A., KARAMANIDIS K., LORIMER A., KEOGH J. W., GAJEWSKI J., *Application of leg, vertical, and joint stiffness in running performance: a literature overview*, Appl. Bionics. Biomech., 2021, DOI: 10.1155/2021/ 9914278.
32. UNO Y., OGASAWARA I., KONDA S., WAKABAYASHI K., MIYAKAWA M., NAMBO M., UMEGAKI K., CHENG H., HASHIZUME K., NAKATA K., *Effect of the foot-strike pattern on the sagittal plane knee kinetics and kinematics during the early phase of cutting movements*, J. Biomech., 2022, 136, DOI: 10.1016/j.jbiomech.2022. 111056
33. YOSHIDA N., KUNUGI S., MASHIMO S., OKUMA Y., MASUNARI A., MIYAZAKI S., HISAJIMA T., MIYAKAWA S., *Effect of forefoot strike on lower extremity muscle activity and knee joint angle during cutting in female team handball players*, Sports. Med. Open., 2016, 2 (1), 1-6, DOI: 10.1186/s40798- 016-0056-x