



Original Article

The impact of the foot contact position and cutting angle during cutting on the risk of anterior cruciate ligament injury

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Abstract. [Purpose] This study aimed to clarify the impact of the foot contact position and cutting angle on the risk of anterior cruciate ligament injury during cutting. [Participants and Methods] Seven healthy males performed cuttings under four tasks by changing the foot contact position and cutting angle. A three-dimensional motion analysis system and force plates were used for taking measurements. The peak vertical ground reaction force and loading rate were calculated. The pelvic, hip, and knee joint angles were measured at the peak vertical ground reaction force. [Results] The loading rate was significantly higher in the lateral foot contact than in the anterior foot contact when the cutting angle was large. The knee flexion angle at the peak vertical ground reaction force was significantly smaller in the lateral foot contact than in the anterior foot contact when the cutting angle was large, similar to the pelvic forward inclination angle, regardless of the foot contact position. [Conclusion] As the cutting angle increased, the knee flexion and pelvic forward inclination angles decreased, resulting in an increase in the loading rate during cutting with the lateral foot contact. Therefore, an increase in the cutting angle can increase the risk of anterior cruciate ligament injury.

Key words: Cutting, Ground reaction force, Foot contact position

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INTRODUCTION

Anterior cruciate ligament (ACL) injuries are common knee joint injuries among athletes, and approximately 70% of them suffer from sudden deceleration and direction changes¹⁾. Various factors have been proposed as risk factors of ACL injuries, one of which is the increase in vertical ground reaction force (VGRF) during landing. Meyer et al.²⁾ observed knee joint displacement when a compressive force was applied to the tibiofemoral joint until the ACL ruptured in cadaver models. As a result, the anterior shear force and internal rotation of the tibia increased with increasing compressive force. In an *in vivo* study, Cerulli et al.³⁾ demonstrated that the peak VGRF (pVGRF) and the maximum value of ACL distortion appeared at the same time during the single-leg landing. In addition, Hewett et al.⁴⁾ reported in a prospective cohort study that ACL-injured female athletes had a kinematic characteristic that the VGRF during jump landing was large. In addition, Paterno et al.⁵⁾ evaluated the loading rate as an impact absorption capacity from VGRF data and associated a high loading rate with a high ACL injury rate after returning to sports. These results suggest that increased pVGRF and decreased impact absorption capacity during landing may increase the risk of ACL injury.

On the other hand, during cutting, the load on the ligaments of the knee joint, including the ACL, increased owing to the ground reaction force (GRF) compared to straight running⁶⁾. It is considered that the kinematic characteristics during cutting are significantly different from straight running or jump landing because it is necessary to increase the normal vector of the

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GRF by inclining the body inward⁷). Side cutting, in which the direction is changed by stepping in the opposite direction, is the most common cutting technique⁸). While the propulsive force in the direction of cutting is obtained by increasing the hip abduction angle (or lateral foot contact) in the side cutting⁹), increasing the hip abduction angle has been associated with ACL injuries in video analysis^{10, 11}). Dempsey et al.¹²) analyzed the effect of technique changes on the knee loads during side cutting and stated that the knee valgus and internal rotation moments increased when the foot was placed away from the body.

As described above, there is no definite view on the usefulness of the lateral foot position (increasing hip abduction angle) in cutting, and no report about changes in the VGRF and the impact absorption capacity due to the foot contact position.

Therefore, this study focused on cutting, which is a common motion for ACL injuries. The purpose of this study was to examine the impact of foot contact position and cutting angle on ACL injury risk from the viewpoints of the VGRF parameters and kinematic data.

PARTICIPANTS AND METHODS

Seven healthy adult males who had experiences of playing soccer in their twenties (age, 24.3 ± 1.7 years; height, 172.0 ± 6.1 cm; weight, 61.6 ± 5.6 kg; competitive experience, 9.9 ± 1.6 years) participated in this study. Furthermore, they had no history of operation or fracture of the lower limb, neurological disease, or orthopedic disease within the last 6 months. Ethical approval for this study was obtained from the ethics review committee of Gunma University (approval code: 2019-063). This study was conducted in accordance with the Declaration of Helsinki. Written informed consent was obtained from all the participants.

Each participant was asked to perform repeated trials of four cutting tasks with barefoot and athletic shorts. The participants stood with their feet placed on the start line, initiated a two-legged jump, landed on a single foot with the dominant leg, and immediately executed a cutting away from the landing leg. The dominant leg was defined as the leg used to kick a

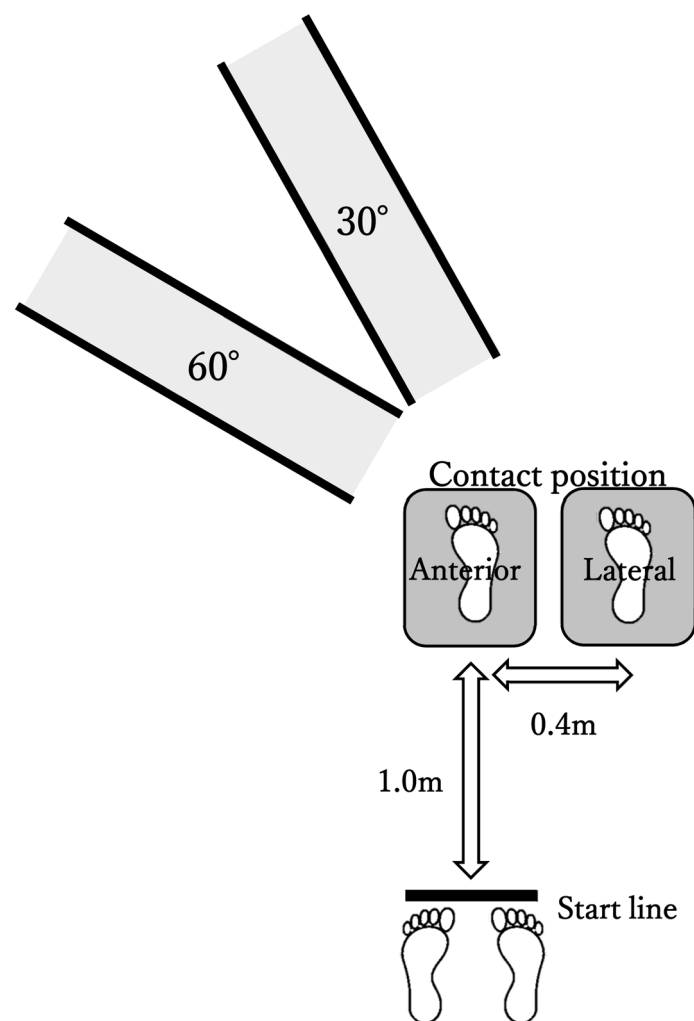


Fig. 1. Overhead view of experimental set-up.

ball, and all the participants were right-leg dominant. The cutting tasks included two foot contact positions (anterior point: 1 m forward from the start line, lateral point: 0.4 m outside from the anterior point) and two cutting angles (30°, 60°), and a total of four tasks (A30, anterior point and 30° cutting; A60, anterior point and 60° cutting; L30, lateral point and 30° cutting; L60, lateral point and 60° cutting) (Fig. 1). For each trial, a colored tape placed on the floor and at 30° and 60° angles from the force plates were used to provide visual feedback to the participants, enabling the foot contact position and reproducible cutting angles near these angles. After adequate practice, they performed the cutting in a random order to account for fatigue, and 1-min intervals were also given between each trial to reduce the influence of fatigue. A trial was deemed unacceptable if it was in contact with outside the contact position, the foot moved or slid after the landing, or if the opposite foot touched the force plate or floor. The trial was repeated three times under each task.

The VGRF parameters were collected using 2 force plates (AMTI Corp.) at a sampling frequency of 1,000 Hz. Initial contact (IC) and toe-off (TO) were defined as VGRF greater and lower than 10 N, respectively. In cutting, the VGRF consists of a bimodal curve. Based on previous studies, the weight acceptance (WA) phase was determined by the force plate recording and was defined as the period from IC to the first curve of the VGRF⁶. Three-dimensional kinematic data were recorded using a Vicon 10-video camera analysis system (Vicon Motion System Ltd.) at a sampling frequency of 250 Hz. A total of 15 reflective markers (9.5 mm in diameter) that were placed on the anatomical landmarks according to the Vicon plug-in-gait lower body marker set were as follows: bilateral anterior superior iliac spine, lateral epicondyle of femur, lateral of thigh, lateral of tibia, lateral malleolus, second metatarsal head, and calcaneus, and between the posterior superior iliac spine.

Plug-in-gait Model software of Vicon Nexus (version 1.7.1) was used to quantify the VGRF parameters and three-dimensional kinematic data. The VGRF parameters including pVGRF, time to pVGRF, and loading rate^{13, 14}, were calculated from the VGRF data. The pVGRF was the peak point of the VGRF at the WA phase and normalized by the body mass (%). The time to pVGRF was defined as the interval between IC and the instance of the pVGRF. The loading rate was obtained by dividing the pVGRF by the time to pVGRF. In addition to the cutting time, the time during WA phase (WA time) and the total landing phase time (total time) were calculated from the VGRF data. The kinematic data included pelvic forward inclination/backward inclination and lateral inclination, hip flexion/extension and adduction/abduction, and knee flexion/extension angles. The positive direction of each angle was defined as a pelvic forward inclination, pelvic lateral inclination on the contralateral side for the landing of the leg, hip flexion, hip abduction, and knee flexion angles, respectively. These angles were analyzed at the pVGRF. The GRF and kinematic data were low-pass filtered using a fourth-order Butterworth filter (cutoff frequency of 18 Hz).

The values of all the variables were averaged over three cutting tasks. One-way repeated-measures analysis of variance (ANOVA) tests was conducted on all the variables. When a significant difference between tasks was apparent, a post-hoc test was performed using the Friedman test. All the statistical analyses were performed using IBM SPSS Statistics version 25.0 for Windows, with a significance level of 5%.

RESULTS

The VGRF parameters are listed in Table 1. The loading rate was significantly higher in L60 than in A30. The total time was significantly longer in L60 than in A30 and A60. The kinematic data are shown in Table 2. The pelvic forward inclination angle was significantly smaller in A60 and L60 than in A30 and L30. The pelvic lateral inclination angle was significantly larger in A60 than in L30 and L60. The hip abduction angle was significantly larger in L30 and L60 than in A30, and larger in L60 than in A60. The knee flexion angle was significantly smaller in L60 than in A30 and A60.

DISCUSSION

In this study, we focused on cutting, which is a common motion that causes ACL injuries, and investigated the impact of changes in foot contact position and cutting angle on ACL injury risk, using VGRF parameters and kinematic data. Regarding the VGRF parameters, which could explain the mechanism of ACL injury, although there was a tendency for the pVGRF to increase at the lateral foot contact than at the anterior foot contact, and as the cutting angle increased, there was no significant difference. In a previous study, pVGRF was larger in 110° cutting than in 45° cutting¹⁵. The cutting in this study was considered to have a slower approach speed because of the lack of run-up as compared with the previous study. In addition, the change in the cutting angle between the tasks was as small as 30° and 60°. Havens et al.¹⁶ demonstrated that the larger deceleration and redirection demands of the over 90° cutting may not be evenly distributed across all joints, with a greater reliance on the knee in the sagittal plane. These may be why no significant difference in pVGRF was found between the tasks in this study. On the other hand, the loading rate tended to be higher at the lateral foot contact than at the anterior foot contact, and as the cutting angle increased, there was a significant difference between A30 and L60. The loading rate represents the impact absorption capacity at landing during the jump and cutting motions. In a previous study comparing the impact absorption capacity during jump landing between the ACL reconstructed (ACLr) knees and the uninjured knees found that the ACLr group delayed the time to pVGRF and had a significantly lower loading rate than the uninjured group¹³. It was considered that this is an intentional strategy to reduce the impact at landing. Paterno et al.⁵ stated that the non-operated side of ACL injury had a higher loading rate than the operated side, suggesting a high ACL injury rate on the non-operated side

Table 1. Average value of VGRF parameters in each task during cutting

	A30	A60	L30	L60
pVGRF (%BW)	131.5 ± 19.8	167.9 ± 37.0	137.3 ± 23.2	183.1 ± 43.4
Time to pVGRF (ms)	44.6 ± 9.4	41.7 ± 12.6	36.6 ± 16.5	34.7 ± 12.2
Loading rate (%BW/ms)	3.0 ± 0.5	4.2 ± 0.6	4.7 ± 2.7	5.9 ± 2.8
	(*A30 vs. L60)			
WA time (ms)	63.4 ± 7.4	59.0 ± 10.8	54.9 ± 10.2	57.5 ± 8.3
Total time (ms)	269.4 ± 25.3	280.4 ± 30.1	296.4 ± 39.2	322.5 ± 44.8
	(*A30 vs. L60)	(*A60 vs. L60)		

All data are presented as mean ± SD. Significant differences among conditions are indicated in parentheses (p<0.05). pVGRF: peak vertical ground reaction force; loading rate: pVGRF/time to pVGRF; WA time: the time during weight acceptance phase; total time: the time during landing phase. A30: anterior point and 30° cutting; A60: anterior point and 60° cutting; L30: lateral point and 30° cutting; L60: lateral point and 60° cutting.

Table 2. Average value of kinematic data at pVGRF in each task during cutting (°)

		A30	A60	L30	L60
Pelvic	Forward inclination	24.7 ± 2.9	18.9 ± 4.3	24.6 ± 4.5	18.7 ± 5.1
		(*A30 vs. A60, L60)		(*L30 vs. A60, L60)	
	Lateral inclination	15.8 ± 3.8	20.9 ± 3.9	14.5 ± 2.8	15.3 ± 4.3
			(*A60 vs. L30, L60)		
Hip	Flexion	51.6 ± 5.3	50.3 ± 5.6	52.9 ± 6.0	49.4 ± 3.7
	Abduction	3.0 ± 6.7	5.0 ± 2.3	11.6 ± 4.6	19.1 ± 1.6
		(*A30 vs. L30, L60)	(*A60 vs. L60)		
Knee	Flexion	50.2 ± 5.4	44.7 ± 6.1	41.7 ± 6.2	36.2 ± 6.9
		(*A30 vs. L60)	(*A60 vs. L60)		

All data are presented as mean ± SD. Significant differences among conditions are indicated in parentheses (p<0.05). A30: anterior point and 30° cutting; A60: anterior point and 60° cutting; L30: lateral point and 30° cutting; L60: lateral point and 60° cutting.

after returning to sports. These results suggest that when the cutting angle becomes large, the strategy contacting the foot lateral increases the loading rate, which may increase the risk of ACL injury.

Regarding the kinematic data in this study, the knee flexion angle tended to be smaller at the lateral foot contact than at the anterior foot contact, and as the cutting angle increased, there were significant differences between A30, A60, and L60. The knee joint is the major impact absorber during landing¹⁴⁾, and it was reported in the video analysis of ACL injury scenes where many injuries occurred at a small knee flexion angle¹⁾. In addition, in the analysis of jump landing, the relationship between the decrease in the knee flexion angle and the increase in pVGRF was reported¹⁷⁻¹⁹⁾. These results were also supported in this study, and it was considered that lateral foot contact and an increase in the cutting angle caused a decrease in the knee flexion angle. As a result, the loading rate increased significantly as the pVGRF increased. In the lateral foot contact, the decrease in the knee flexion angle was considered to be due to the distance between the COG and the foot contact position being extended by abducting the hip joint to extend and reach the lower limb outside. In addition, the hip abduction angle tended to increase as the cutting angle increased. If the radius of curvature at the turn is small, it is necessary to incline the body inward more⁷⁾. In addition, in cutting, it was considered that the normal vector of the GRF was increased by increasing the hip abduction angle when the cutting angle was large, and with it, the decrease in the knee flexion angle increased. On the other hand, the pelvic lateral inclination angle increased as the cutting angle increased in the anterior foot contact; therefore, it was considered that the propulsive force was obtained by inclining the whole body in the direction of cutting. In summary, in cutting with a large cutting angle, it was necessary to incline the body inward to obtain the normal vector of the GRF. Therefore, it was suggested that the two different strategies could be used: inclining the whole body in the direction of cutting or contacting the foot lateral (abducting the hip joint) and leaning the lower limb inward.

Similarly, the pelvic forward inclination angle was reported to be related to pVGRF¹⁷⁾. There were significant differences between A30, L30, A60, and L60, and the pelvic forward inclination angle decreased as the cutting angle increased, regardless of the foot contact position. When the cutting angle was increased, a larger deceleration was required to redirect the propulsion force to the new direction of the cutting, and it is considered that the postural control strategy to shift the COG posterior was adopted. Sheehan et al.²⁰⁾ performed video analysis of ACL injury scenes on one-leg landing. They reported that the trunk forward inclination angle was smaller than that in similar uninjured scenes and speculated that this postural control strategy caused a shift in the COG posterior from the foot contact position, and ACL rupture occurred because of

inefficient impact absorption.

From the above results, when the cutting angle was large, the postural control strategy with lateral foot contact increased the loading rate by decreasing the knee flexion and the pelvic forward inclination angles. Therefore, it is considered that by inclining the whole body in the direction of cutting, it is possible to perform a large direction change in the cutting with the anterior foot contact, which will decrease the ACL injury risk.

The consideration of performance is also important when considering postural control strategies in sports movements. Dos'Santos et al. conducted a comprehensive review examining the influence of angle and velocity on cutting biomechanics and stated that increased hip abduction (lateral foot contact) is necessary to execute sharper cuttings. However, this position can lead to smaller knee flexion angle and larger GRF, this may create a 'performance-injury conflict' from a technique perspective²¹). From the results of cutting time in this study, the time to pVGRF and the WA time tended to be shortened at the lateral foot contact regardless of the cutting angle. In contrast, the total time was prolonged, and a significant difference was observed between A60 and L60. Soft landing, which flexes the knee joint deeply, prolongs the WA time, so it may be an inefficient strategy in situations when the demands imposed upon the performer is to quickly execute another movement²²). On the other hand, soft landing was also reported to improve jumping height immediately after it²³). In the present study, the time to pVGRF and the WA time were shortened at the lateral foot contact, and the knee flexion angle was reduced. However, as a result, the extension torque of the lower limb became inefficient, and the total time was prolonged to compensate for it. From the above, it is considered that the postural control strategy with lateral foot contact during cutting does not contribute to performance improvement in terms of cutting time. Meanwhile, it is also important how the cutting can be performed without deceleration. The approach and exit speeds were not measured in this study, and further study is required.

The limitation of this study was that the relationship between the VGRF parameters and kinematic data was mainly examined in the sagittal plane. A previous study reported that knee valgus and rotational moments are associated with ACL injury risk²⁴). Future studies could assess how the foot position and the cutting angle change the frontal and horizontal plane kinematics and the strain on the ACL. In addition, regarding the relationship between the VGRF parameters and the strain on the ACL, the positional relationship between the COG and the GRF direction is important²³). Therefore, it is necessary to consider the effect on the risk of ACL injury.

In conclusion, the results of this study suggest that as the cutting angle increases, the knee flexion and pelvic forward inclination angles decrease, resulting in an increase in the loading rate during cutting with the lateral foot contact. The increase in the loading rate indicates a decrease in the impact absorption capacity at the landing. It is considered that lateral foot contact during cutting may increase the risk of ACL injury. Therefore, by inclining the whole body in the direction of cutting, it is possible to perform a large direction change of the cutting with anterior foot contact, which will decrease the risk of ACL injury. In the future, the differences in characteristics between ACL-injured or ACLr athletes and healthy athletes should be compared.

Funding and Conflict of interest

There are none.

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