Title	Knee rotation associated with dynamic knee valgus and toe direction
Author(s)	Ishida, Tomoya; Yamanaka, Masanori; Takeda, Naoki; Aoki, Yoshimitsu
Citation	The Knee, 21(2), 563-566 https://doi.org/10.1016/j.knee.2012.12.002
Issue Date	2014-03
Doc URL	http://hdl.handle.net/2115/58953
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Rights(URL)	http://creativecommons.org/licenses/by-nc-nd/4.0/
Type	article (author version)
File Information	Knee_21(2)_563-566.pdf

Knee Rotation Associated with Dynamic Knee Valgus and Toe Direction

Tomoya Ishida, PT, MS[1,2]
Masanori Yamanaka, PT, PhD[3]
Naoki Takeda, MD, PhD[3]
Yoshimitsu Aoki, MD, PhD[4]

[1]Graduate School of Health Sciences, Hokkaido University, Sapporo, Hokkaido, Japan
[2]Dept. of Rehabilitation, Hokushin Orthopaedic Hospital, Sapporo, Hokkaido, Japan
[3]Faculty of Health Sciences, Hokkaido University, Sapporo, Hokkaido, Japan
[4]Dept. of Orhopaedic Surgery, Hokushin Orthopaedic Hospital, Sapporo, Hokkaido, Japan

Address correspondence to Masanori Yamanaka. Faculty of Health Science, Hokkaido University, West 5, North 12, Kitaku, Sapporo, 060-0812, Japan. Tel. and Fax: +81 11 706 3383; E-mail: yamanaka@hs.hokudai.ac.jp

***Key words*:** Anterior Cruciate Ligament, knee rotation, dynamic knee valgus, toe direction

1. Introduction

Anterior cruciate ligament (ACL) injury is one of the most common sports injuries, with about 100,000 such injuries occurring each year in the United States (US) [1]. Approximately 50,000 ACL reconstructions are performed each year in the US [2], and if an ACL reconstruction costs $17,000 [3], the economic cost is almost $850,000,000 per year in the US. However, ACL injury causes not only economic loss, but also results in time lost from sports activity and work in the short term. In the long term, it causes osteoarthritic changes with or without ACL reconstruction [4]. These reports indicate that prevention of ACL injury is very important.

Various programs for the prevention of ACL injury have been suggested, and their efficacies have been validated [5-7]. Nevertheless, the rate of ACL injury remains constant over the decades [8]. The reason for this appears to be that prevention programs are not popular, and they are not provided in cooperation with athletes and therapists. If ACL injury prevention programs were to become effective and easy to implement, they may become widespread. To prepare simple programs, however, understanding the mechanisms and risk factors for ACL injury is important.

It has been reported that 70% of ACL injuries occur in noncontact situations, including cutting, landing, pivoting, and deceleration without contact with opponents [9]. Based on the reports of video analyses of ACL injuries, the knee is in slight flexion and abduction at the moment of ACL injury [10, 11]. Bone bruises appear after ACL injury in the lateral knee compartment [12-14]. These studies suggest that knee abduction motion occurs at the time of ACL injuries. Hewett et al. [15], in their prospective report, examined the relationships among ACL injury, the knee abduction angle, and the external knee abduction moment during the landing maneuver. They noted that the subjects who demonstrate the dynamic posture called dynamic knee valgus had greater risk for ACL injury. Poor neuromuscular control may induce greater knee abduction, which is thought to be a risk factor for ACL injury.

The prevention programs have focused on dynamic posture, such as preventing knee abduction motion during athletic tasks [5-7, 16]. Many researchers have reported that knee rotation is significantly related to ACL injury [17-22]. However, knee rotation has not been sufficiently investigated *in vivo*. Internal rotation of the knee combined with knee abduction significantly increases ACL strain, compared with knee abduction alone [18, 21, 22]. Furthermore, knee external rotation combined with knee abduction increases the risk of ACL injury, because the ACL impinges on the femoral condyle [17, 19, 20]. Therefore, it is very important to examine how the knee rotates during dynamic knee valgus.

Dynamic knee valgus is regarded not only as frontal plane motion (hip adduction, knee abduction, and ankle eversion), but also as horizontal plane motion (femoral internal rotation and tibial internal or external rotation) [15, 23]. There is no consensus about the direction of tibial rotation during dynamic knee valgus. Tibial rotation should be significantly affected by ankle and foot kinematics. Ankle eversion causes tibial internal rotation [24, 25], and foot internal and external rotation also theoretically cause tibial internal and external rotation through the ankle joint.

The purposes of this study were to reveal how the knee rotates during dynamic knee valgus and to determine whether knee rotation is affected by toe direction, including foot internal and external rotation. We hypothesized that the knee rotates externally during dynamic knee valgus and that knee rotation is affected by toe direction.

2. MATERIALS and METHODS

2.1. Subject

Sixteen women (mean ± SD: age 21.5 ± 1.6 years; height 158.5 ± 5.8 cm; weight 53.1 ± 7.6 kg) participated in this study. Women were chosen as subjects because they have a greater risk of ACL injury [8]. Subjects were excluded if they reported any previous history of musculoskeletal injury (e.g., sprain, fracture, low back pain) or neurological or systemic disease. All subjects read and signed an informed consent form approved by the Institutional Review Board of Hokkaido University.

2.2. Procedures and instrumentations

The experimental trials were conducted in the laboratory of Hokkaido University. Forty retroreflective markers were placed on the sacrum, right iliac crest, and bilateral shoulders, anterior superior iliac spines, greater trochanters, hips, medial and lateral knees, medial and lateral ankles, heels, 2nd and 5th metatarsal heads, and right thigh and shank cluster markers (Figure 1). In all subjects, the dominant leg (the side for kicking a ball) was the right leg. Throughout the experiment, the subjects were barefoot. First, the data of the static standing trial were collected for each subject. Then, the data for the dynamic knee valgus trials, in which the subjects stepped forward 40% of their height with their dominant leg and maintained the trunk upright were collected for each subject (Figure 2). During the dynamic knee valgus trials, the subjects maintained the knee flexion angle at 30°, and the investigator checked the knee flexion angle with a traditional goniometer. The toe directions (from the heel to the 2nd metatarsal head) of the right foot were set in three directions, including 0° (neutral), 10° (toe-out), and -10° (toe-in) relative to the sagittal plane on the horizontal plane (Figure 3). The toe direction of the left foot was always set at 0° (neutral). The subjects were asked to maintain the knee directed forward in the start position. The subjects performed maximum dynamic knee valgus for 5 seconds in each toe direction (Figure 2). During the dynamic knee valgus position, the subjects maintained neutral rotation of their pelvis as much as possible, and the investigator checked their pelvic rotation. All data were collected with EVaRT 4.3.57 (Motion Analysis Corporation, Santa Rosa, CA) using a motion analysis system with 7 digital cameras (Hawk cameras, Motion Analysis Corporation). The sampling rate was set at 100 Hz.

2.3. Data Analysis

The trajectories of markers were filtered at a cutoff frequency of 6 Hz with a low-pass fourth-order Butterworth filter. The knee angles (flexion/extension, abduction/adduction, internal/external rotation) were calculated with SIMM 4.0 (MusculoGraphics, Inc., Santa Rosa, CA). All knee angles were expressed for the tibial motion relative to the femur and relative to the static standing trial (knee joint angles in the static standing trial were 0°). Positive values indicate knee flexion, abduction and internal rotation. The data of the dynamic knee valgus trials were averaged for the middle 3 seconds of the total 5 seconds. SIMM uses the Global Optimization Method [26] to reduce the effects of artifact due to skin movement relative to actual bone movement.

2.4. Statistical Analysis

To analyze the effect of dynamic knee valgus and toe direction on knee angles, repeated measures two-way ANOVA was conducted. The dependent variables were knee flexion, abduction, and internal rotation angles. The independent variables were position (start and dynamic knee valgus) and toe direction (neutral, toe-in, and toe-out) as repeated measures. The Bonferroni post hoc test was used. All statistical analyses were performed with the level of significance set at $p<0.05$ using IBM SPSS Statistics 19 (SPSS, an IBM company, Chicago, Illinois).

3. RESULTS

There were significant main effects of toe direction (*F*=127.88, *p*<0.001) and position (*F*=19.97, *p*<0.001) on the knee rotation angle. There was also an interaction (*F*=10.13, *p*<0.001) between toe direction and position on the knee rotation angle.

For neutral and toe-out, the knee significantly rotated externally during dynamic knee valgus from the start position (*p*<0.001), and there was a similar trend for toe-in (*p*=0.090, Figure 3). During both the start and the dynamic knee valgus positions, the knee for toe-in and toe-out showed significantly greater internal and external rotation compared with the neutral position, respectively (*p*<0.001, Figure 3).

The knee abduction and flexion angles are shown in Table 1. There were significant main effects of toe direction (*F*=39.25, *p*<0.001) and position (*F*=85.82, *p*<0.001) on the knee abduction angle. There was also an interaction (*F*=3.57, *p*=0.041) between toe direction and position on the knee abduction angle. The knee abduction angles during the dynamic knee valgus position were significantly greater than during the start position in all three toe directions (p<0.001). During the start position, the knee abduction angles were significantly greater and less for toe-in and toe-out, respectively, than for neutral (*p*<0.001). During the dynamic knee valgus position, the knee abduction angle was greater for toe-in than for the other toe directions (*p*<0.001).

A significant main effect of toe direction on the knee flexion angle was observed (*F*=3.98, *p*=0.029), but a main effect and interaction of position were not observed. The knee flexion angle was significantly greater for toe-in than for toe-out during the start position (*p*=0.040) on the post hoc test.

4. DISCUSSION

The purposes of this study were to reveal how the knee rotates during dynamic knee valgus and to determine whether toe direction affects knee rotation. The results of this study showed that the knee rotates externally during dynamic knee valgus and that knee rotation is affected by toe direction.

Dynamic knee valgus is considered to be associated with poor neuromuscular control and ACL injury [15]. This dynamic alignment consists of hip adduction, hip internal rotation, knee abduction, and ankle eversion [15, 23]. However, the direction of knee rotation has been unclear. The results of this study showed that the knee rotates externally during dynamic knee valgus compared to the start position. This finding is similar to that of previous report that rotation of the knee shifts externally during dynamic knee valgus position at the time of ACL injury [11]. However, current experimental trial was conducted in a specific setting, including a fixed knee flexion angle and maintaining the trunk upright position. On the actual athletic field, the knee may rotate internally because of the knee flexion movement (known as the “screw-home movement”). In this study, the knee rotated internally at the start position (knee flexed 30°) compared to that in the static standing trial.

Nagano et al. [27] reported the knee kinematics during one leg landing. They suggested that the knee rotates internally immediately after initial contact, and that female subjects demonstrated greater internal rotation than males. Considering an *in vitro* ACL strain study [18, 21] and the finding of bone bruises after ACL injury, [12-14] they noted that greater internal rotation immediately after landing is a risk factor for ACL injury. Kiriyama et al. [28] also reported that female subjects demonstrated greater knee internal rotation during landing than males, and that this knee internal rotation may be the one of the risk factors for ACL injury. However, because the knee flexion occurs with the landing task, these internal rotations of the knee may contain a component of the “screw-home movement” during weight bearing [29].

Olsen et al. [11] suggested that the mechanism of ACL injury was knee abduction combined with external rotation of the knee. This combination causes impingement of the ACL on the femoral condyle and increases the risk of ACL injury [17, 19, 20]. Which direction of knee rotation causes ACL injury remains controversial. The results of this study showed that the knee rotates externally during dynamic knee valgus. Considering this finding, the knee may rotate externally at the time of ACL injury. Further analysis of knee kinematics during a dynamic task should include examination of whether the knee rotation deviates from the normal “screw-home movement”.

Knee rotation was also affected by toe direction. Toe-out and toe-in cause external and internal knee rotation, respectively, compared with neutral. These findings would appear because of the lower extremity kinetic chain. Toe-out and toe-in would induce foot external and internal rotation, respectively, and this foot rotation affects tibial external and internal rotation through the ankle joint. When evaluating dynamic alignment, it is important to note not only dynamic knee valgus but also toe direction to estimate knee rotational stress. Noyes et al. [16] instructed athletes to direct the knee and toe forward. This instruction may be beneficial for the prevention of ACL injury.

The knee abduction angle during dynamic knee valgus was also affected by toe direction. Because knee rotation in the start position was significantly different among the three toe directions, the tension of the collateral ligaments (i.e., medial and lateral collateral ligaments) would differ among the three toe directions. The tension of the medial collateral ligament, which is known to be the primary restraint of knee abduction, increases during knee external rotation, but decreases during knee internal rotation [30, 31]. Therefore, the knee abduction angle would increase with toe-in. Because the toe direction also affects the knee abduction angle, this study indicates that it is very important to instruct athletes on toe direction to prevent ACL injury.

There were a few limitations to this study. First, the experimental trials were performed in a specific quasi-static situation. If dynamic knee valgus is performed on the actual athletic field, the multiple joint motions, ground reaction force, inertial force, and various muscle activities should be considered for knee rotation. Another limitation is that the dynamic knee valgus position was affected by each subject's balance ability and strength, as well as other related factors. In this study, each subject performed dynamic knee valgus at maximum effort, but toe direction may also be affected by balance ability.

5. Conclusion

The present study showed that the knee rotates externally during dynamic knee valgus and that the knee rotation is affected by toe direction (foot rotation). Because of knee abduction and external rotation, the ACL may impinge on the femoral condyle in dynamic valgus, especially in the toe-out position. Finally, taking care to rotate the foot may help athletes prevent ACL injuries.

6. Conflict of interest

No author of this manuscript has any conflict of interest.

Acknowledgements

The authors would like to thank Prof. Junko Fukushima for her suggestions in the preparation of this article.

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Captions

FIGURE 1. Marker placement.

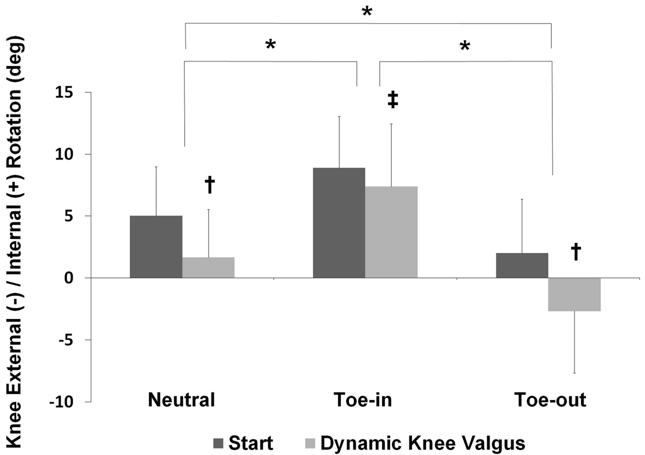
FIGURE 2. Upper and lower panels demonstrate start position and dynamic knee valgus position respectively. Also, left, center and right panels show neutral, toe-in and toe-out toe directions. Neutral toe direction was set at 0°relative to the sagital plane on the horizontal plane, and toe-in and toe-out was set -10° and 10°, respectively. During trials, the subjects were asked to step forward 40% of their height with dominant leg, and also maintain the trunk upright and the knee flexion angle at 30 degree. The subjects performed maximum dynamic knee valgus for 5 seconds on each toe directions (lower three panels).

FIGURE 3. Mean and standard deviations of the knee rotation angle during start position and dynamic knee valgus position.

† Indicates significantly differences between start and dynamic knee valgus position each foot direction ($p<0.05$).

‡ Indicates statistical trend between start and dynamic knee valgus position each foot direction ($p<0.10$).

* Indicates significantly differences between foot directions ($p<0.05$). There were significantly differences between all foot direction pairs during start position and dynamic knee valgus position respectively.


*
*
*
‡
†
†
15
10
5
0
-5
-10
Knee External (-) / Internal (+) Rotation (deg)
Neutral
Toe-in
Toe-out
Start
Dynamic Knee Valgus

TABLES

TABLE 1. Mean (SD) of knee flexion and abduction angles.

Knee angle	Position	Neutral	Toe-in	Toe-out
Flexion	Start	36.4 (5.7)	34.3 (4.6)	36.2 (5.0) [‡]
	Valgus	36.6 (5.8)	34.5 (5.4)	36.8 (5.9)
Abduction	Start	-0.3 (4.6)	2.9 (4.0) [†]	-1.8 (4.0) [†, ‡]
	Valgus	9.9 (6.9) [*]	12.8 (6.4) [*, †]	9.7 (5.8) [*,‡]

Start: Start position, Valgus: dynamic knee valgus position.

For knee flexion, positive value indicates flexion. For knee abduction, positive value indicates abduction.

[*] Indicates significant differences from start position each foot directions ($p<0.05$).

[†] Indicates significant differences from Neutral ($p<0.05$).

[‡] Indicates significant differences from Toe-in ($p<0.05$).