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1 Knee Rotation Associated with Dynamic Knee Valgus and Toe Direction

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

19 direction

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1 **1. Introduction**

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

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

17 It has been reported that 70% of ACL injuries occur in noncontact situations,
18 including cutting, landing, pivoting, and deceleration without contact with opponents [9].
19 Based on the reports of video analyses of ACL injuries, the knee is in slight flexion and
20 abduction at the moment of ACL injury [10, 11]. Bone bruises appear after ACL injury in
21 the lateral knee compartment [12-14]. These studies suggest that knee abduction
22 motion occurs at the time of ACL injuries. Hewett et al. [15], in their prospective report,
23 examined the relationships among ACL injury, the knee abduction angle, and the
24 external knee abduction moment during the landing maneuver. They noted that the
25 subjects who demonstrate the dynamic posture called dynamic knee valgus had

26 greater risk for ACL injury. Poor neuromuscular control may induce greater knee
27 abduction, which is thought to be a risk factor for ACL injury.

28 The prevention programs have focused on dynamic posture, such as preventing
29 knee abduction motion during athletic tasks [5-7, 16]. Many researchers have reported
30 that knee rotation is significantly related to ACL injury [17-22]. However, knee rotation
31 has not been sufficiently investigated *in vivo*. Internal rotation of the knee combined
32 with knee abduction significantly increases ACL strain, compared with knee abduction
33 alone [18, 21, 22]. Furthermore, knee external rotation combined with knee abduction
34 increases the risk of ACL injury, because the ACL impinges on the femoral condyle [17,
35 19, 20]. Therefore, it is very important to examine how the knee rotates during dynamic
36 knee valgus.

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

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

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51 **2. MATERIALS and METHODS**

52 **2.1. Subject**

53 Sixteen women (mean \pm SD: age 21.5 ± 1.6 years; height 158.5 ± 5.8 cm; weight
54 53.1 ± 7.6 kg) participated in this study. Women were chosen as subjects because
55 they have a greater risk of ACL injury [8]. Subjects were excluded if they reported any
56 previous history of musculoskeletal injury (e.g., sprain, fracture, low back pain) or
57 neurological or systemic disease. All subjects read and signed an informed consent
58 form approved by the Institutional Review Board of Hokkaido University.

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60 **2.2. Procedures and instrumentations**

61 The experimental trials were conducted in the laboratory of Hokkaido University.
62 Forty retroreflective markers were placed on the sacrum, right iliac crest, and bilateral
63 shoulders, anterior superior iliac spines, greater trochanters, hips, medial and lateral
64 knees, medial and lateral ankles, heels, 2nd and 5th metatarsal heads, and right thigh
65 and shank cluster markers (Figure 1). In all subjects, the dominant leg (the side for
66 kicking a ball) was the right leg. Throughout the experiment, the subjects were
67 barefoot. First, the data of the static standing trial were collected for each subject.
68 Then, the data for the dynamic knee valgus trials, in which the subjects stepped
69 forward 40% of their height with their dominant leg and maintained the trunk upright
70 were collected for each subject (Figure 2). During the dynamic knee valgus trials, the
71 subjects maintained the knee flexion angle at 30° , and the investigator checked the
72 knee flexion angle with a traditional goniometer. The toe directions (from the heel to
73 the 2nd metatarsal head) of the right foot were set in three directions, including 0°
74 (neutral), 10° (toe-out), and -10° (toe-in) relative to the sagittal plane on the horizontal
75 plane (Figure 3). The toe direction of the left foot was always set at 0° (neutral). The

76 subjects were asked to maintain the knee directed forward in the start position. The
77 subjects performed maximum dynamic knee valgus for 5 seconds in each toe direction
78 (Figure 2). During the dynamic knee valgus position, the subjects maintained neutral
79 rotation of their pelvis as much as possible, and the investigator checked their pelvic
80 rotation. All data were collected with EVaRT 4.3.57 (Motion Analysis Corporation,
81 Santa Rosa, CA) using a motion analysis system with 7 digital cameras (Hawk
82 cameras, Motion Analysis Corporation). The sampling rate was set at 100 Hz.

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84 **2.3. Data Analysis**

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

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96 **2.4. Statistical Analysis**

97 To analyze the effect of dynamic knee valgus and toe direction on knee angles,
98 repeated measures two-way ANOVA was conducted. The dependent variables were
99 knee flexion, abduction, and internal rotation angles. The independent variables were
100 position (start and dynamic knee valgus) and toe direction (neutral, toe-in, and toe-out)

101 as repeated measures. The Bonferroni post hoc test was used. All statistical analyses
102 were performed with the level of significance set at $p < 0.05$ using IBM SPSS Statistics
103 19 (SPSS, an IBM company, Chicago, Illinois).

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126 **3. RESULTS**

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

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

135 The knee abduction and flexion angles are shown in Table 1. There were
136 significant main effects of toe direction ($F=39.25$, $p<0.001$) and position ($F=85.82$,
137 $p<0.001$) on the knee abduction angle. There was also an interaction ($F=3.57$,
138 $p=0.041$) between toe direction and position on the knee abduction angle. The knee
139 abduction angles during the dynamic knee valgus position were significantly greater
140 than during the start position in all three toe directions ($p<0.001$). During the start
141 position, the knee abduction angles were significantly greater and less for toe-in and
142 toe-out, respectively, than for neutral ($p<0.001$). During the dynamic knee valgus
143 position, the knee abduction angle was greater for toe-in than for the other toe
144 directions ($p<0.001$).

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

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151 **4. DISCUSSION**

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

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

168 Nagano et al. [27] reported the knee kinematics during one leg landing. They
169 suggested that the knee rotates internally immediately after initial contact, and that
170 female subjects demonstrated greater internal rotation than males. Considering an *in*
171 *vitro* ACL strain study [18, 21] and the finding of bone bruises after ACL injury, [12-14]
172 they noted that greater internal rotation immediately after landing is a risk factor for
173 ACL injury. Kiriya et al. [28] also reported that female subjects demonstrated
174 greater knee internal rotation during landing than males, and that this knee internal
175 rotation may be the one of the risk factors for ACL injury. However, because the knee

176 flexion occurs with the landing task, these internal rotations of the knee may contain a
177 component of the “screw-home movement” during weight bearing [29].

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

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

195 The knee abduction angle during dynamic knee valgus was also affected by toe
196 direction. Because knee rotation in the start position was significantly different among
197 the three toe directions, the tension of the collateral ligaments (i.e., medial and lateral
198 collateral ligaments) would differ among the three toe directions. The tension of the
199 medial collateral ligament, which is known to be the primary restraint of knee
200 abduction, increases during knee external rotation, but decreases during knee internal

201 rotation [30, 31]. Therefore, the knee abduction angle would increase with toe-in.
202 Because the toe direction also affects the knee abduction angle, this study indicates
203 that it is very important to instruct athletes on toe direction to prevent ACL injury.

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

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226 **5. Conclusion**

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

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251 **6. Conflict of interest**

252 No author of this manuscript has any conflict of interest.

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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 sagittal 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 ($p < 0.05$).

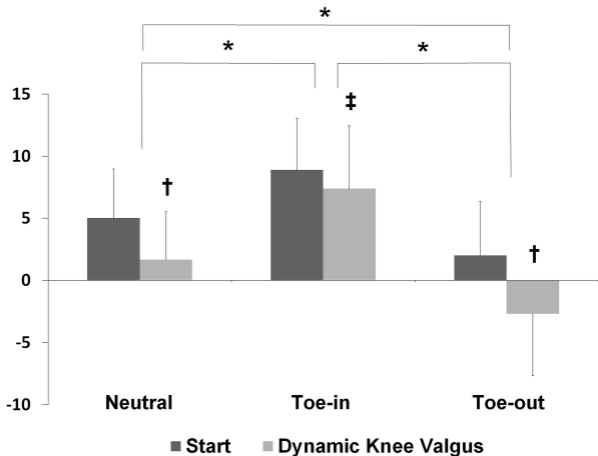
‡ Indicates statistical trend between start and dynamic knee valgus position each foot direction ($p < 0.10$).

* 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.





Knee External (-) / Internal (+) Rotation (deg)



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 ($p < 0.05$).