The effect of changing toe direction on knee kinematics during drop vertical jump: a possible risk factor of anterior cruciate ligament injury

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Purpose: The purpose of this study was to examine the effect of changing toe direction on knee kinetics and kinematics associated with anterior cruciate ligament injury during drop vertical jumps

Methods: Fourteen females performed drop vertical jumps under three toe conditions (natural, toe-in, toe-out). The knee kinetics and kinematics during landing were evaluated using a motion analysis system. Results under three toe conditions were compared using a one-way repeated-measures analysis of variance and a post-hoc Bonferroni test.

Results: Toe-in landing was associated with a significantly greater knee abduction angle, tibial internal rotation angle, and knee abduction moment than the natural and toe-out conditions. Toe-out landing was associated with significantly greater tibial internal rotational angular velocity.

Conclusions: Changing toe direction significantly affects knee kinetics and kinematics during landing. It is important to avoid changing toe direction excessively inward or outward during landing to prevent the increases of knee abduction and tibial internal rotation which might increase the risk of ACL injury.

Level of Evidence: Prognosis, level 4

Key words: Anterior cruciate ligament injury • Injury prevention • Knee biomechanics • Landing • Motion analysis

Introduction

Approximately 70% of anterior cruciate ligament (ACL) injuries are caused by noncontact injury mechanisms [3, 16, 21]. Female athletes are two to eight times more likely to sustain noncontact ACL injuries than male athletes [1, 2]. Although there are several successful prevention programs for ACL injuries [8, 12, 14, 17, 23], the exact mechanism of preventative effects of these programs has not been shown. Understanding the mechanisms and risk factors for ACL injury is necessary to develop ACL injury prevention strategies [6]. Greater knee abduction and tibial internal rotation during landing have been thought as the biomechanical risk factors for ACL injury [9, 11, 22]. In addition, such biomechanical characteristics were observed in females than males [5, 15]. Understanding appropriate landing patterns and providing effective instructions are important for establishing ACL injury prevention strategies.

One of the most useful check points evaluating the landing posture is toe direction during landing [18]. A previous study reported that toe direction affects knee kinematics in the quasi-static lunge position [10]. However, there is no study examining the specific effect of toe direction on knee kinematics and kinetics in the dynamic condition, such as landing. It is important to determine the effects of toe direction on knee kinematics and kinetics during landing for establishing the foundation of ACL injury prevention strategies. The purpose of this in-vivo study was to examine the effect of changing toe direction on knee kinetics and kinematics at landing. Our hypothesis was that changing toe direction during landing affect knee kinetics and kinematics, including the knee abduction moment and angle and the internal tibial rotation angle.

Materials and methods

Fourteen females (mean ± SD: age 21.0 ± 1.6 years; height 157.0 ± 5.4 cm; weight 48.4 ± 4.7 kg) participated in this study. Female were selected because they have a greater risk of ACL injury than males [1, 2]. Hence, it was important to examine the risk factors for females at high risk of ACL injury [13, 20]. All subjects had experience with regular sports activities (e.g., basketball, handball, lacrosse). No subjects had excessive knee valgus/varus alignment. The distance between the medial malleoli or between the femoral medial epicondyles was <3.0 cm for all subjects. Subjects were excluded from this study if they reported any history of musculoskeletal injury (e.g., sprain, low back pain) within the previous 6 months, knee injury, surgery, fracture of the lower extremities or trunk, or previous participation in jump landing training or ACL prevention programs. All subjects read and signed informed consent forms prior to their inclusion in this study.

Procedures and data collection

A total of 39 retroreflective markers were placed on the sacrum, right iliac crest, medial knee, bilateral shoulders, anterosuperior iliac spine (ASIS), greater trochanter, hips, lateral knees, medial and lateral ankles, heels, second and fifth metatarsal heads, and right thigh and shank clusters. The subjects were barefoot during all phases of data collection. All data were collected with the EVaRT 4.3.57 (Motion Analysis Corporation, Santa Rosa, CA, USA) using a motion analysis system with six digital cameras (Hawk cameras; Motion Analysis Corporation). The sampling rate was set at 1000 Hz for force data and at 200 Hz for camera data.

First, the static standing trial data were collected for each subject. Then, data for the three landing task conditions were recorded. Drop vertical jump (DVJ) tasks were used to collect the landing data. The subjects stood on a box (height 30 cm) with their feet shoulder-width apart. The subjects then dropped off the box and landed on two force plates (Type 9286, Kistler AG, Winterthur, Switzerland), one for each foot. The two force plates were positioned 5.5 cm apart so each foot would contact a different platform during the landing. All subjects were asked to perform a maximum vertical jump immediately after landing. The subjects elevated their hands to ear level and looked forward throughout the DVJ tasks.

The DVJs were recorded during each of three conditions to examine the effects of changing toe direction on knee kinetics and kinematics during landing (Fig. 1): (1) natural landing: a DVJ without any specific instructions about toe direction (Fig. 1a); (2) toe-in landing: subjects were asked to point their toes inward at a maximum but still comfortable position during the landing from the box (Fig. 1b); (3) toe-out landing: subjects were asked to point their toes outward at a maximum but still comfortable position during the landing from the box (Fig. 1c). In the present study, the subjects landed with a toe angle of 8.9 ± 6.4° (range –2.7º to 20.3º). Thus, no one met the criterion of the Landing Error Scoring System (LESS) that used a toe angle cutoff of >30° for either toe-in or toe-out [18]. The toe-in and toe-out landing tasks were recorded randomly following the natural landing task after the subjects felt familiar with the tasks following several practices. The subjects were allowed to practice each landing condition until they felt familiar with the task. Three successive trials for each landing task were recorded.

Data processing and reduction

The knee kinematics and kinetics (external movements) were calculated with SIMM 4.0 software (MusculoGraphics, Santa Rosa, CA, USA) [7]. The knee kinematics were represented as the tibial motion relative to the femur. Zero references were set at the knee angles during the static standing trial (the knee joint angles in the static standing trial were 0°). The inter-observer reliability of the knee kinematics and kinetics were calculated using intraclass correlation coefficient ($ICC_{3,3}$) and 95% confidence interval (CI) of the differences between observers (mean ± 95%CI) for the following variables: peak knee flexion angle (ICC = 0.99; 3.4 ± 1.4º), peak knee abduction angle (ICC = 0.72; 0.6 ± 3.6º), peak tibial internal rotation (ICC = 0.94; 3.8 ± 2.1º) and peak knee abduction moment (ICC = 0.90; 0.02 ± 0.11 Nm/kg). The classifications of ICC for these variables were good to excellent [4].

The initial ground contact (IC) was defined as the time when the vertical ground reaction force (VGRF) exceeded 10 N. The peak of VGRF after landing was calculated and normalized by each subject's body weight. To confirm compliance with the toe conditions, the toe direction angle was calculated. The toe direction was defined as the line through the second metatarsal head and heel markers. All variables used the average of three successful trials for each toe condition.

This study was approved by the institutional review board of the Faculty of Health Sciences, Hokkaido university (ID: 09-56).

Statistical Analysis

The results of pilot study using 7 subjects showed large differences in the peak knee abduction angle and moment during landing between the three toe conditions. If an α level, statistical power (1-β), and effect size were respectively set 0.40, 0.05 and 0.80 in a one-way repeated-measures analysis of variance (ANOVA) model, 12 subjects were needed for this study. Assuming possible defective data, 14 subjects were included.

A one-way repeated-measures ANOVA and a post-hoc Bonferroni test were conducted to examine the effects of toe direction on knee kinetics and kinematics during landing. All statistical analyses were performed with the level of significance set at P <

0.05 using the IBM SPSS Statistics 19 software program (IBM, Chicago, IL, USA).

Results

The toe direction angle was significantly different among the three toe conditions ($P < 0.001$) (Table 1). Toe-in landing was associated with significantly greater knee abduction angle (IC, peak) (Fig. 2b) and tibial internal rotation (IC, peak) (Fig. 2c) than natural and toe-out conditions, whereas toe-out landing was associated with significantly smaller knee abduction angle (IC, peak) (Fig. 2b), tibial internal rotation (IC) (Fig. 2c) than natural condition. No significant differences in the knee flexion angle were found between the natural landing condition and toe-in or toe-out landing conditions (Fig. 2a).

Toe-in landing was also associated with significantly greater angular velocity of knee abduction during 50ms after IC and peak knee abduction moment than natural and toe-out landing conditions (Table 2). Toe-out landing was associated with smaller peak knee abduction moment than natural condition (Table 2), although toe-out landing was associated with significantly greater angular velocity of tibial internal rotation during 50ms after IC than natural and toe-in landing conditions (Table 2).

Discussion

The most important finding of the present study was that the changing toe directions significantly affected the frontal and horizontal plane knee biomechanics including the knee abduction moment and angle and the tibial internal rotation angle during landing. These findings support our hypothesis that changing toe direction during landing affects knee kinetics and kinematics. The results of this study, however, showed that there were no differences in peak VGRF among the toe conditions. These results indicated that the impact of landing were similar among three toe conditions in the present study. ,

A previous cadaver study simulating landing has shown that knee abduction combined with tibial internal rotation increases the ACL strain more than either alone [22]. In addition, video analysis of ACL injury situations indicated that knee abduction and tibial internal rotation were thought to be key risk factors for ACL injury [11]. Previous studies on ACL injury mechanism also suggested that the noncontact ACL injury mechanism occurs attributable to quadriceps loading with the knee in slight flexion, with abduction and internal rotation of the tibia [24]. Considering these findings, the greater knee abduction angle and tibial internal rotation observed during toe-in landing are supposed to increase the risk of ACL injury. Therefore, toe-in landing should be avoided to prevent ACL injuries.

A recent video analysis of ACL injuries using a model-based image-matching technique suggested that rapid tibial internal rotation occurred in most cases with ACL injuries [11]. The present study showed that the rapid and large range of tibial internal rotational motion immediately after landing was observed during toe-out landing. The strain rate significantly affects mechanical properties of the ACL [19]. A greater tibial internal angular velocity is considered to increase the ACL strain rate. Therefore, toe-out landing is also considered to provide at greater risk of ACL injury than natural landing and should also be avoided.

Concerning clinical relevance, the findings of the present study suggest that clinicians should note the toe direction during landing and instruct female athletes to avoid changing toe direction excessively inward or outward to prevent the increases of knee abduction and tibial internal rotation. Since previous studies showed that excessive knee abduction and tibial internal rotation increase the risk of the ACL injury in female athletes [5, 9, 11, 15, 22].

This study has some limitations. Although changing toe direction significantly altered knee kinetics and kinematics during landing, it is unclear whether changing the in situ force of the ACL. Future studies using a sophisticated model are needed to predict the ACL in situ force and/or length during landing and to examine the effects of toe direction. Second, it has remained unknown whether the results of this study can apply to other situations, such as single leg landing or a cutting maneuver. Therefore, further studies examining the effects of toe direction on knee kinetics and kinematics during other tasks are needed.

Conclusion

The present study shows that changing toe direction significantly affects knee kinetics and kinematics during landing (i.e., increased knee abduction and tibial internal rotation). Clinicians should note the toe direction during landing, and then instruct female athletes to avoid changing toe direction excessively inward or outward to prevent the increases of knee abduction and tibial internal rotation which might increase the risk of ACL injury.

Conflict of interest

All authors have no conflicts of interest to declare.

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Table 1. Comparison of the toe angle among the three toe conditions

	Natural*	Toe-in*	Toe-out*	*P* value†
Toe angle (°)				
IC	-8.9 ± 6.4	12.3 ± 7.1‡	-23.8 ± 8.3‡§	<0.001
Peak knee flexion	-11.0 ± 5.6	7.0 ± 6.4‡	-24.3 ± 7.3‡§	<0.001

Abbreviations: IC, Initial Contact

**Values are presented as the mean ± SD.*

†Repeated measures analysis of variance

‡Indicates significant differences from Natural ($P < 0.05$).

§Indicates significant differences from Toe-in ($P < 0.05$).

Table 2. Comparison of the kinetic data among the three toe conditions

	Natural*	Toe-in*	Toe-out*	*P* value[†]
Peak VGRF (N/kg)	22.1 ± 3.5	22.0 ± 3.1[‡]	20.9 ± 4.1[‡§]	n.s.
Angular velocity[a] (°/sec)				
Knee Abduction	-57.8 ± 56.5	-90.3 ± 62.2[‡]	-21.7 ± 68.7[‡§]	<0.001
Tibial Internal Rotation	-17.8 ± 66.4	57.3 ± 88.4[‡]	172.9 ± 88.4[‡§]	<0.001
Peak Moment (Nm/kg)				
Knee Abduction	0.8 ± 0.2	1.1 ± 0.3[‡]	0.6 ± 0.2[‡§]	<0.001

Abbreviations: VGRF, vertical ground reaction force

[a]*Angular velocity during 50ms after initial contact*

**Values are presented as the mean ± SD.*

[†]*Repeated measures analysis of variance*

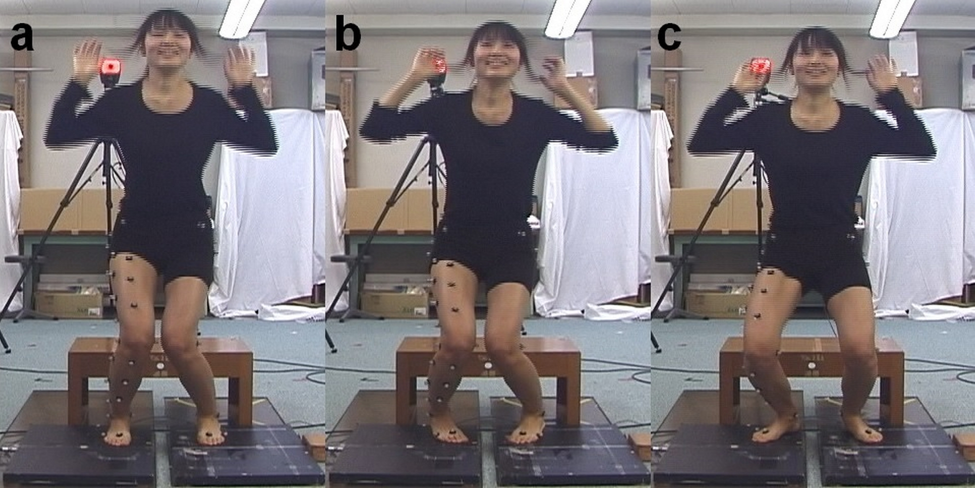
[‡]*Indicates significant differences from Natural ($P < 0.05$).*

[§]*Indicates significant differences from Toe-in ($P < 0.05$).*

Captions

Fig. 1 Three toe conditions during landing. a) Natural landing: without specific instructions about toe direction; b) Toe-in landing: the subjects were asked to point their toes inward during landing after drop off the box; c) Toe-out landing: the subjects were asked to point their toes outward during landing after drop off the box.

Fig. 2 Average knee joint motion curves throughout the normalized landing phase. The landing phase (from initial contact to peak knee flexion) was normalized to 101 data points.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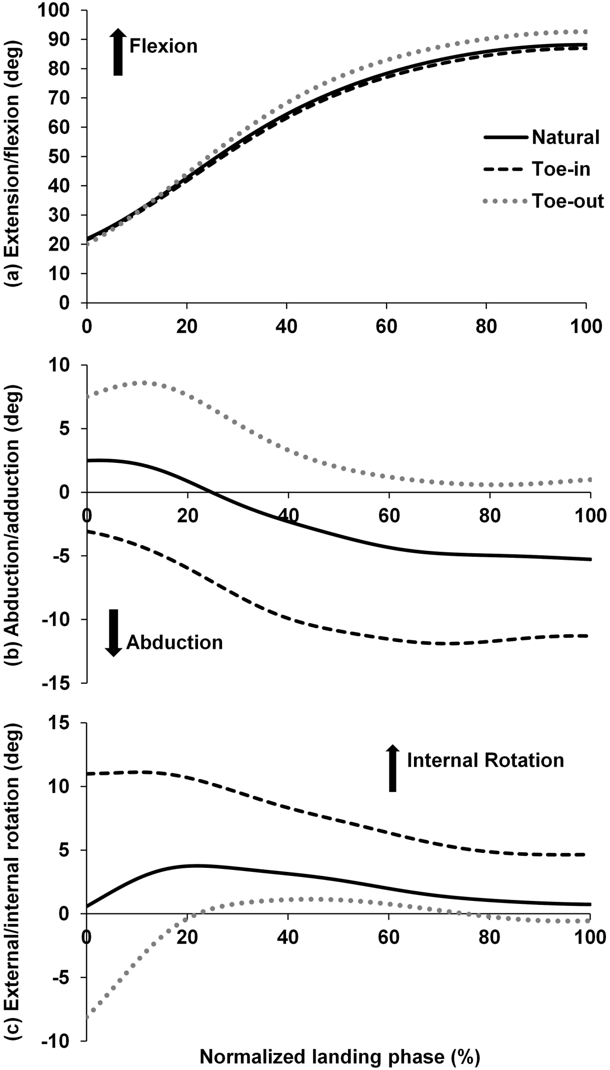

(a) Extension/flexion (deg)
Flexion
Natural
Toe-in
Toe-out
(b) Abduction/adduction (deg)
Abduction
(c) External/internal rotation (deg)
Internal Rotation
Normalized landing phase (%)