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Research article

Mechanisms of the anterior cruciate ligament injury in sports activities: A twenty-year clinical research of 1,700 athletes

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Abstract
The mechanisms of anterior cruciate ligament (ACL) injuries are still inconclusive from an epidemiological standpoint. An epidemiological approach in a large sample group over an appropriate period of years will be necessary to enhance the current knowledge of the ACL injury mechanism. The objective of the study was to investigate the ACL injury occurrence in a large sample over twenty years and demonstrate the relationships between the ACL injury occurrence and the dynamic knee alignment at the time of the injury. We investigated the activity, the injury mechanism, and the dynamic knee alignment at the time of the injury in 1,718 patients diagnosed as having the ACL injuries. Regarding the activity at the time of the injury, "competition" was the most common, accounting for about half of all the injuries. The current result also showed that the noncontact injury was the most common, which was observed especially in many female athletes. Finally, the dynamic alignment of "Knee-in & Toe-out" (i.e. dynamic knee valgus) was the most common, accounting for about half. These results enhance our understanding of the ACL injury mechanism and may be used to guide future injury prevention strategies.

Key words: Anterior cruciate ligament, injury mechanism, dynamic alignment, prevention.

Introduction

The injury of the anterior cruciate ligament (ACL) is a typical injury of the knee joint that occurs during sports activities (Arendt and Dick, 1995; Bjordal et al, 1997; Gray et al., 1985). For the past twenty years, surgical techniques for ACL reconstruction and rehabilitation have been highly developed, which has enabled the patients to resume sports activities at the same level as they had before the injury. However, it still takes them a long period of time to fully recover and get back to their previous level. The recovery period causes heavy mental, physical and economic burdens on the patients. Thus, the importance of injury prevention has been suggested in the past years.

The risk factors for an ACL injury have been reported from the standpoints of the environment, anatomical structure, hormones, and biomechanics (Anderson et al., 1987; Arendt and Dick, 1995; Boden et al., 2009; Chaudhari et al., 2007;Davis et al., 2007; Deie et al., 2002; Griffin et al., 2000; Griffin et al., 2006; Gray et al., 1985; Hewett et al., 2006a; Huston et al., 2000; Kobayashi, 1994; LaPrade and Burnett, 1994; Masujima et al.,1986; Myer et al., 2008, 2009; Olsen et al., 2004; Renstrom et al., 2008; Shelbourne et al., 1998; Souryal and Freeman, 1993; Uhorchak et al., 2003). Previous studies indicate that gender and anatomical structures such as the width of the intercondylar notch are associated with an ACL injury occurrence (Shelbourne et al., 1998; Souryal and Freeman, 1993). However, it is impossible to change the gender and is difficult to modify the anatomical structure for injury prevention. Furthermore, studies of video observational analysis reported that most of the ACL injuries were caused by a noncontact mechanism and suggested that the dynamic knee valgus was one of the highest-risk actions against the injury (Olsen et al., 2004). Other biomechanical studies also suggested the valgus knee has an injury risk due to the torque applied to the knee joint (Hewett et al., 2005). However, we have found few epidemiologic researches using a large sample group supporting the findings of the biomechanical studies.

Therefore, in this study we analyzed the data of more than 1,700 athletes with an ACL injury with the aim of confirming the relationship between the ACL injury occurrence and the dynamic alignment of the lower extremity at the time of the injury. The results of this investigation may enhance our understanding of the mechanism which causes an ACL injury and help guide current preventive measures especially against a noncontact ACL injury occurrence.

Methods

The subjects were 1,718 athletes (838 males and 880 females) who visited the orthopedic clinic in the Institute of Sports Medicine and Science, Aichi, Japan over a period of twenty years from June 1988 to June 2008. All the subjects were diagnosed as having an ACL injury confirmed by magnetic resonance imaging and/or an arthroscopic procedure. Approximately seventy percent of the subjects visited the clinic within one month, and 46 percent of the subjects visited the clinic within one week after an ACL injury incident. Table 1-a shows the characteristics, and Table 1-b shows the participation of the subjects in sports. In this study, we included subjects who had other knee injuries (meniscus lesion, medial collateral ligament injury, etc.) along with the ACL injury. The study protocol was approved by the Ethics Committee of the Institute of Sports Medicine and Science.

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Table 1-b. Sports participation of the male (n = 838) and the female (n = 880) subjects (n =1,718).

Male Sports	n	Rate (%)	Female Sports	n	Rate (%)
Soccer	154	18.3	Basketball	333	37.8
Ski	118	14.1	Ski	134	15.2
Basketball	113	13.5	Handball	106	12.0
Rugby	109	13.0	Volleyball	81	9.2
Handball	57	6.8	Track&Field	27	3.1
Baseball	50	6.0	Judo	26	3.0
Judo	47	5.6	Gymnastics	21	2.4
American football	30	3.6	Badminton	20	2.3
Volleyball	17	2.0	Softball	19	2.2
Sumo	16	1.9	Tennis	14	1.6
Other	127	15.1	Other	99	11.3

Table 1-a. Mean and standard divisions of height, body weight and age (n =1,718). Data Are means (±SD).

	Male (n =838)	Female (n = 880)
Height (m)	1.72 (.07)	1.61 (.07)
Body weight (kg)	71.3 (16.3)	56.6 (7.9)
Age (yrs)	22.6 (7.0)	20.5 (7.4)

We used the medical records of the orthopedic surgery and the physical therapy of the subjects as the database. When the subjects visited the Institute, skilled physical therapists themselves interviewed the subjects and prepared and kept their medical records. They interviewed the subjects about the situations at the time of the injury in detail using a standardized questionnaire. In addition, the therapists confirmed the injury mechanism and the dynamic alignment by having the subjects reproduce the scene of the injury occurrence with the use of the unaffected leg (Figure 1). We investigated the following items:

1. Activity at the time of the injury: We classified the activity of the subject at the time of the ACL injury into categories such as competitions, practice, leisure activities, other, and unknown.

2. Injury mechanism: We classified the injury mechanism into the following five categories according to the type of contact with the body at the time of the injury:

(1) Noncontact: No contact with another person at the time of the injury
(2) Contact: Physical contact with another person on body parts other than the lower extremity at the time of the injury including the case where the subject was not sure about the type of contact with the lower extremity at the time of the injury
(3) Collision: Direct physical contact with another person on the affected lower extremity
(4) Accident: Particular situations during sports activities such as motocross or a dangerous fall in skiing
(5) Unknown: The injury mechanism data missing in medical records

3. Dynamic alignment at the time of the injury (Figure 2): We classified the dynamic alignment at the time of the injury into six categories (Kawano, 1998).
(1) Knee-in & Toe-out: Knee valgus and foot abduction position
(2) Knee-out & Toe-in: Knee varus and foot adduction position
(3) Hyperextension: Hyper-extended knee position
(4) Unclear: Injury mechanism that was not expressed clearly by the patients
(5) Unknown: The injury mechanism data missing in medical records
(6) Other

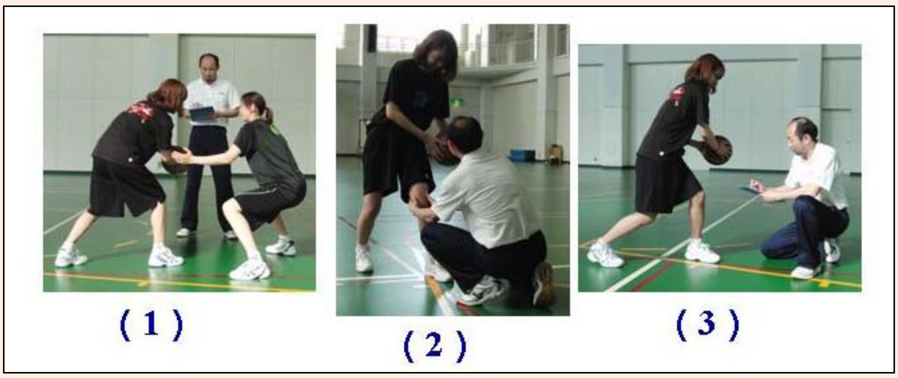

Figure 1. Confirmation of situations at the time of an ACL injury by physical therapists (photo by Hirokazu Kobayashi, the first author): The data of "injury mechanism," "dynamic alignment," etc. from the interviews and observation of the subjects were kept in medical records: (1) Skilled physical therapists listened to the subjects mention situations at the time of the injury and requested them to reproduce the situations at the time of the injury as accurately as possible. (2) & (3) The skilled physical therapists also requested them to reproduce the scene by using the unaffected leg to confirm the injury mechanism and the dynamic alignment at the time of the injury.

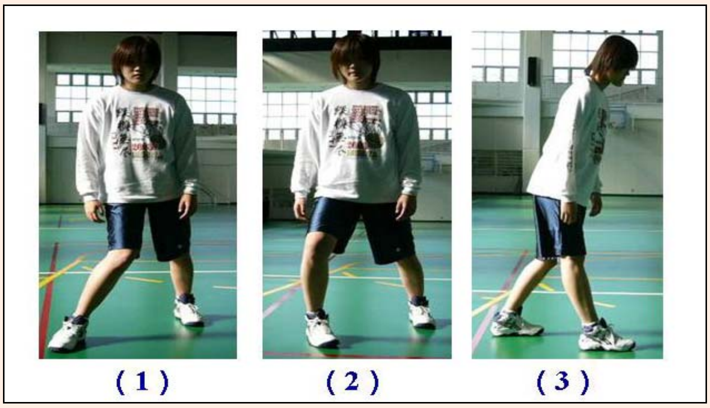

Figure 2. Classification of the dynamic alignment at the time of the injury: We classified the dynamic alignment into six categories: (1) Knee-in & Toe-out: Dynamic alignment with the valgus position of the knee and the abduction position of the foot during the loading phase, (2) Knee-out & Toe-in: Dynamic alignment with the varus position of the knee and the abduction position of the foot during the loading phase, (3) Hyperextension: Dynamic alignment with the hyper-extended position of the knee during the loading phase, (4) Unclear, (5) Unknown, and (6) Other.

Statistical analysis

We carried out a chi-square test to demonstrate the relationships in each category. When we analyzed the relationships between injury mechanism and gender, we divided the subjects into two groups according to the injury mechanisms; the noncontact injury group and the group of injuries other than noncontact injuries. We used the SPSS Ver.17J for Windows (SPSS Japan Inc., Shibuya, Tokyo, Japan) for statistics. The significant level was set at 5% in this study.

Results

1. Activity at the time of the injury (Table 2)

Regarding the activity at the time of the injury, the number of subjects who had the injury during "Competitions" was the largest (846/1718), accounting for 49.2% of all the subjects. The number of subjects who had the injury during "Practice" and "Leisure activities" accounted for 34.8 % and 8.5%, respectively. No significant difference was found between the male and the female subjects.

2. Injury mechanism (Table 3a, b)

We were able to obtain the information of the injury mechanism from 1,661 (809 males and 852 females) out of 1,718 subjects. The number of "Noncontact" cases was 1,010, followed by "Accident" cases (266/1661). We observed differences in the distribution of the injury mechanism between the male and the female subjects. As for the male subjects, the number of "Noncontact" cases was the largest (417/809), and the number of "Collision" cases was 127, which accounted for 15.7%. On the other hand, the number of the female subjects with "Noncontact" cases was 593, which accounted for 69.7%, and "Contact" and "Collision" cases turned out to be less, compared with those of the male subjects.

Regarding the ratios of "Noncontact" and "Contact" cases, there was a significant difference observed between the male and the female subjects. The ratio of "Noncontact" cases in the female subjects was higher than that in the male subjects (p = 0.026).

3. Dynamic alignment at the time of the injury (Table 4)

We investigated the dynamic alignment at the time of the injury in 1,603 (781 males and 822 females) out of 1,718 subjects. Among all the subjects, the number of the subjects with the alignment of "Knee-in & Toe-out" was the largest (793/1,603), followed by "Unclear," "Knee-out & Toe-in" and "Hyperextension" in this order. We found no significant difference in the dynamic alignment at the time of the injury between the male and the female subjects.

4. Relationship between the injury mechanism and the dynamic alignment (Table 5a to c)

We analyzed the relationship between the injury mechanism and the dynamic alignment in 1,563 (764 males and 799 females) out of 1,718 subjects. The results of all the subjects were shown in Table 5a. Among all the items except for "Accident," "Knee-in & Toe-out" was the most common, which tendency was also observed in the classification of the male and the female subjects as shown in Table 5b and 5c. "Knee-in & Toe-out" was the most common especially in the "Noncontact" cases in the female subjects, that is, 304 out of 551 subjects (55.2%). The three hundred and four accounted for 72.9% out of the 417 female subjects who tore the ACL through "Knee-in & Toe-out".

Table 2. Activity at the time of the injury (n =1,718).

	Total (n = 1 718)	Rate (%)	Male (n = 838)	Rate (%)	Female (n = 880)	Rate (%)
Competitions	846	49.2	421	50.2	425	48.3
Practice	598	34.8	278	33.2	320	36.4
Leisure activities	146	8.5	71	8.5	75	8.5
Other	128	7.5	68	8.1	60	6.8

$\chi^2 = 2.55$, p = 0.47

Table 3-a. Injury mechanism at the time of the injury (n = 1,661), unknown (n = 57) excluded.

	Total (n = 1 661)	Rate (%)	Male (n = 809)	Rate (%)	Female (n = 852)	Rate (%)
Noncontact	1010	60.8	417	51.5	593	69.6
Contact	227	13.7	130	16.0	97	11.4
Collision	158	9.5	127	15.7	31	3.6
Accident	266	16.0	135	16.7	131	15.4

$\chi^2 = 92.80$, $p = 0.001$

Table 3-b. Injury mechanism at the time of the injury (n = 1,661), unknown (n = 57) excluded.

	Total (n = 1 661)	Rate (%)	Male (n = 809)	Rate (%)	Female (n = 852)	Rate (%)
Noncontact	1010	60.8	417	51.5	593	69.6
Other than Noncontact	651	39.2	392	48.5	259	30.4

$\chi^2 = 56.77$, $p = 0.001$

Discussion

Our result showed an ACL injury occurred more often during a competition than during a practice. The situations during a competition and a practice are different in many respects. Athletes usually spend a much longer time in practice than in competition. Along with longer commitment, athletes usually challenge new team formation and technique during a practice rather than during a competition, which might increase the risk of injury. However, a more stressful situation might be imposed on the athletes during a competition than during a practice both physically and mentally. The current result might reflect the increased physical and mental stress during competitions

The current result also showed that noncontact cases were the most common in both the male and the female subjects. The ratio of the noncontact injuries in the female subjects was about 70%, which was significantly higher than that of the noncontact injuries in the male subjects and that of the injuries other than the noncontact injuries in the female subjects. Previous studies also reported a relatively high ratio of the noncotact ACL injury in female athletes, ranging from 64% to 80% (Arendt and Dick et al., 1995; Boden, 2000; Gray et al., 1985; Kobayashi, 1994). The current result is in good agreement with the previous findings. However, the interpretation of the data may warrant careful consideration. The injury mechanism might be associated with the sports they participated in. In our sample group it seemed that female athletes were involved more noncontact sports (e.g. basketball, team handball, and volleyball) than male athletes were. Therefore, we may need to conduct further analysis to elucidate the gender difference in the ACL injury mechanism.

The investigation on the dynamic alignment at the time of the injury revealed that the knee-in & toe-out alignments were most often reported. In retrospective interviewing studies, the subjects often encounter difficulty in recalling the dynamic alignment at the time of the injury, which may be related to the passage of time between the injury and the interview. The interview was usually held long after the injury occurred; for example, Boden et al. (2000) reported that the interview was held 3.4 years after the injury on average. In addition, whether the information obtained is accurate or not may depend on how the subject described the dynamic alignment at the time of the injury. Therefore, there might be questions about the accuracy of the information obtained in the retrospective interviewing study (Krosshaug et al., 2005; Shimokochi and Shultz, 2008). In this study, we asked the subjects not only to describe the injury mechanism and the dynamic alignment but also to reproduce the situation by using the unaffected leg so that we could confirm the description by the subjects and gain information of the injury mechanism as accurately as possible. Then, we confirmed that the data from both sources exactly matched each other. If the data was unmatched, we regarded the description of the ACL injury mechanism as an “unclear” dynamic alignment. In addition, 70% of our subjects visited our institution and had an interview within one month after the injury, which was a much shorter period between the interview and the ACL injury incident compared to previous studies (Boden et al., 2000; Koshida et al., 2010). Although we still might need to take the inherent limitation of the retrospective interviewing study in to consideration on the data interpretation, we believe that the current data is appropriately accurate and that the dynamic alignment of “Knee-in & Toe-out” is strongly related to the occurrence of an ACL injury.

There are many reports on the mechanism of the ACL injury, that is, what kind of mechanical stress an action pattern of “Knee-in & Toe-out” applies to the ACL. Most researchers agreed that an ACL injury occurs at the weight loading phase. However, there are diverse opinions about joint movement forced at the time of the injury. Regarding knee biomechanics at the time of the injury, according to the information obtained from the

Table 4. Dynamic alignment at the time of the injury (n = 1,603), unknown (n = 115) excluded.

	Total (n = 1 603)	Rate (%)	Male (n = 781)	Rate (%)	Female (n = 822)	Rate (%)
Knee-in&Toe-out	793	49.5	373	47.8	420	51.0
Knee-out&Toe-in	142	8.9	70	9.0	72	8.8
Hyper Extension	97	6.1	59	7.6	38	4.6
Other	23	1.4	15	1.9	8	0.9
Unclear	548	34.2	264	33.8	284	34.5

$\chi^2 = 9.18$, $p = 0.057$

Table 5-a. Cross tabulation analysis between injury mechanism and dynamic alignment in all the subjects (n = 1,563) unknown (n=155) excluded. Data are number (%).

	Noncontact (n = 945)	Contact (n = 218)	Collision (n = 154)	Accident (n = 246)
Knee-in&Toe-out	490 (51.9)	122 (56.0)	99 (64.3)	76 (30.9)
Knee-out&Toe-in	102 (10.8)	16 (7.3)	10 (6.5)	12 (4.9)
Hyper Extension	59 (6.2)	9 (4.1)	11 (7.1)	18 (7.3)
Other	12 (1.3)	3 (1.4)	1 (0.6)	5 (2.0)
Unclear	282 (29.8)	68 (31.2)	33 (21.4)	135 (54.9)

$\chi^2 = 84.52$, $p = 0.001$

Table 5-b. Cross tabulation analysis between injury mechanism and dynamic alignment in the male subjects (n=764). Data are number (%).

	Noncontact (n = 394)	Contact (n = 124)	Collision (n = 124)	Accident (n = 122)
Knee-in&Toe-out	186 (47.2)	68 (54.8)	79 (63.7)	37 (30.3)
Knee-out&Toe-in	46 (11.7)	13 (10.5)	6 (4.8)	3 (2.5)
Hyper Extension	28 (7.1)	6 (4.8)	11 (8.8)	14 (11.5)
Other	5 (1.3)	3 (2.4)	1 (0.8)	4 (3.3)
Unclear	129 (32.7)	34 (27.4)	27 (21.8)	64 (52.4)

$\chi^2 = 54.04$, $p = 0.001$

Table 5-c. Cross tabulation analysis between injury mechanism and dynamic alignment in the female subjects (n=799). Data are number (%).

	Noncontact (n = 551)	Contact (n = 94)	Collision (n = 30)	Accident (n = 124)
Knee-in&Toe-out	304 (55.1)	54 (57.4)	20 (66.7)	39 (31.4)
Knee-out&Toe-in	56 (10.2)	3 (3.2)	4 (13.3)	9 (7.3)
Hyper Extension	31 (5.6)	3 (3.2)	0	4 (3.2)
Other	7 (1.3)	0	0	1 (0.8)
Unclear	153 (27.8)	34 (36.2)	6 (20.0)	71 (57.3)

$\chi^2 = 51.80$, $p = 0.001$

patients, some reports suggested that the injury would occur when the ACL was overstretched due to forced valgus/external rotation movement (Annoura et al., 1996; Noyes et al., 1980). Other researchers discussed the mechanical stress imposed on the knee joint on the basis of the MR images after an ACL injury (Fayad et al., 2003; Viskontas et al., 2008). Viskontas et al. (2008) stated that the noncontact mechanism of an ACL injury occurs by the internal rotation through bone bruise site on the articular surface after an ACL injury. In addition, the results of a dynamic load test suggest that the ACL injury is caused by forced valgus/internal rotation movement (Kanamori, 2002). On the other hand, the video analysis of the actual occurrence of the noncontact injury in female handball players demonstrated the valgus movement in all the ACL injury occurrences, but that both the external and the internal tibial rotations were observed at the time of the ACL injury (Olsen et al., 2004). Finally, some previous studies demonstrated that the large valgus movement of the knee was to be observed in action patterns of female athletes at the loading phase, and that this movement might add stress to the ACL (Barber-Westin et al., 2005; 2006; Boden et al., 2000; 2009; Hewett et al., 2009; Krosshaug and Bahr, 2003; Krosshaug et al., 2007; McLean et al., 2005; Myer et al., 2006; Noyes et al., 2005; Quatman and Hewett, 2009). Due to these previous findings and our current finding we speculated that the "valgus knee" observed in an action with "Knee-in & Toe-out" is related to the occurrence of a noncontact injury and that both internal and external rotations of the tibia may occur at the time of an ACL injury. In any case, for prevention of an ACL injury we think it important to avoid the dynamic alignment of "Knee-in & Toe-out" during sports activities.

As for the limitation of this study we did not directly analyze the actions at the time of the injury from a quantitative standpoint, and thus we were not able to confirm that the stress was added to the ACL due to the alignment of "Knee-in & Toe-out." In the future we will need to quantify sports actions at the time of the injury and discuss the results along with other information to clarify the specific dynamic stress and the injury mechanism.

In addition, because we focused on the injury mechanism and the dynamic alignment of injured athletes with an ACL of any sports at the time of their injury, we did not take the playing surface into consideration. The difference of playing surfaces (e.g. wooden floor vs. turf) might affect the injury mechanism and the dynamic alignment, and we need to demonstrate the injury mechanism on different playing surfaces in future studies. However, we believe that the Knee-in & Toe-out alignment at the time of the injury may be the most risky alignment against a noncontact ACL injury occurrence on any playing surface.

Conclusion

In this study through the investigation of a large number of subjects we demonstrated that "Knee-in & Toe-out" alignment at the time of the injury is related to the ACL injury occurrence and is a dynamic alignment to be carefully examined. In future studies we intend to investigate not only the dynamic stress to the ACL added by "Knee-in & Toe-out" but also the physical characteristics including the static alignment, the range of motion, and the muscle strength of the lower extremity which are likely to be related to this action pattern. We also intend to clarify the factors related directly and indirectly to the ACL injury occurrence and obtain useful findings for prevention of the ACL injury.

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Key points

- We investigated the situation of ACL injury occurrence, especially dynamic alignments at the time of injury, in 1,718 patients who had visited our institution for surgery and physical therapy for twenty years.
- Our epidemiological study of the large patient group revealed that "knee-in & toe-out" alignment was the most frequently seen at the time of the ACL injury.
- From an epidemiological standpoint, we need to pay much attention to avoiding "Knee-in & Toe-out" alignment during sports activities.

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