CrossMark

Two-dimensional motion analysis of dynamic knee valgus identifies female high school athletes at risk of non-contact anterior cruciate ligament injury

Hitoaki Numata[1] · Junsuke Nakase[1] · Katsuhiko Kitaoka[2] · Yosuke Shima[3] ·
Takeshi Oshima[1] · Yasushi Takata[1] · Kengo Shimozaki[1] · Hiroyuki Tsuchiya[1]

Abstract

Purpose Female athletes are at greater risk of non-contact ACL injury. Three-dimensional kinematic analyses have shown that at-risk female athletes have a greater knee valgus angle during drop jumping. The purpose of this study was to evaluate the relationship between knee valgus angle and non-contact ACL injury in young female athletes using coronal-plane two-dimensional (2D) kinematic analyses of single-leg landing.

Methods Two hundred ninety-one female high school athletes newly enrolled in basketball and handball clubs were assessed. Dynamic knee valgus was analysed during single-leg drop jumps using 2D coronal images at hallux–ground contact and at maximal knee valgus. All subjects were followed up for 3 years for ACL injury. Twenty-eight (9.6%) of 291 athletes had ACL rupture, including 27 non-contact ACL injuries. The injured group of 27 knees with non-contact ACL injury was compared with a control group of 27 randomly selected uninjured knees. The relationship between initial 2D movement analysis results and subsequent ACL injury was investigated.

Results Dynamic knee valgus was significantly greater in the injured group compared to the control group at hallux–ground contact (2.1 ± 2.4 vs. 0.4 ± 2.2 cm, $P = 0.006$)

and at maximal knee valgus (8.3 ± 4.3 vs. 5.1 ± 4.1 cm, $P = 0.007$).

Conclusion The results of this study confirm that dynamic knee valgus is a potential risk factor for non-contact ACL injury in female high school athletes. Fully understanding the risk factors that increase dynamic knee valgus will help in designing more appropriate training and interventional strategies to prevent injuries in at-risk athletes.

Level of evidence Prognostic studies, Level II.

Introduction

Anterior cruciate ligament (ACL) injury is a serious and increasingly common sports injury affecting young athletes. ACL injuries frequently require ligament reconstruction, with prolonged rehabilitation delaying the athletes' return to sports. Furthermore, ACL reconstruction is often complicated by knee joint degeneration and osteoarthritis over the long term. Therefore, adequate prevention and prophylaxis for ACL injury, particularly non-contact injuries, are crucial in athletes at risk of such injuries [2, 3, 28, 31].

Adequate prevention requires an in-depth understanding of the aetiological factors, risk factors, and mechanisms underlying sports injuries [2, 3, 28, 31]. Preventive measures are then introduced to reduce the risk and/or severity of the sports injuries, and their efficacy evaluated in subjects. Following this paradigm, ACL injury prevention has focused on identifying risk factors. Besides race [30] and family history [8], female sex has been identified as one of the most significant risk factors

✉ Junsuke Nakase
nakase1007@yahoo.co.jp

1 Department of Orthopaedic Surgery, Graduate School of Medicine, Kanazawa University, 13-1 Takara-machi, Kanazawa, Ishikawa 920-8641, Japan

2 Department of Orthopaedic Surgery, Kijima Hospital, Kanazawa, Ishikawa 920-0011, Japan

3 Department of Orthopaedic Surgery, KKR Hokuriku Hospital, Kanazawa, Ishikawa 921-8035, Japan

for ACL injury [1, 10, 14, 18, 19, 21, 24–26, 32]. Women have a 3.8-fold greater risk of ACL injury than similarly trained men [4, 9, 22, 24]. ACL injury is particularly prevalent among female athletes in sports such as basketball and handball, which require cutting and landing motions [1, 19].

Besides non-modifiable anatomical and hormonal risk factors [10, 15, 18], various modifiable neuromuscular risk factors such as decreased neurocognitive function [27] and increased trunk displacement after sudden force release [34] have been shown to be associated with an increased risk of ACL injury in female athletes. Additionally, neuromuscular control of the core and hip muscles, which play important roles in lower extremity mechanics, likely influences ACL and lower extremity injury risk [2, 10, 24]. Although static malalignment of the lower limbs such as excessive knock-knee [23] and hyperpronation of the foot [5] also increases ACL injury risk, dynamic alignment of the lower limbs during the two-leg drop jump [18] and single-leg drop jump is known to significantly differ in knees at risk of ACL injury [20, 33]. However, two-dimensional (2D) movement analysis of single-leg landing in the context of ACL injury risk has not been adequately studied to date [7, 17]. Based on the hypothesis that dynamic knee valgus will help identify female high school athletes at risk of non-contact ACL injury, this study aimed to evaluate the relationship between the extent of knee valgus and the development of non-contact ACL injury by measuring knee valgus with coronal-plane 2D imaging of single-leg landing in young female athletes.

Materials and methods

Two hundred ninety-one female high school athletes newly enrolled in basketball and handball clubs at 15 high schools between 2009 and 2011 were assessed. Subjects with a previous knee injury were excluded. The purpose and potential risks of this study were explained to the subjects, and written informed consent was obtained from all the participants and their parents or guardians. The study design was approved by the ethics committees of our university. Subjects were asked to perform a single-leg drop jump at the time of high school admission, which was recorded with a video camera. Video acquisition and 2D motion analysis were successfully performed in all subjects at enrolment. All subjects were followed up for 3 years for ACL injury, and the relationship between initial 2D motion analysis results and subsequent ACL injury, including the nature and mechanism of injury, was investigated.

Two-dimensional motion analysis

Two-dimensional motion analysis was performed using a previously validated methodology [12]. Surface markers (diameter: 9.0 mm) were attached over the bilateral anterior superior iliac spine and medial and lateral femoral condyles. Subjects were instructed to jump with a single leg from a 30-cm-high box and land 60 cm in front of the starting point on the single leg and then jump straight up to the maximal height. Each subject performed the jump three times using each leg (total of six jumps). Since all 2D motion analyses were performed shortly after enrolment, prior to any of the subjects experiencing ACL injury, the investigators were inherently blinded to the study groups.

Dynamic knee valgus was analysed during single-leg drop jumps using 2D coronal-plane images acquired using a video camera (IVIS HFS10, Canon). Videos of the jump were divided into 30 frames per second, and all markers were identified in the still images. The images from the three jumps on each side were analysed for rotation and postural sway. The most stable jump with the minimum rotation and postural sway (balance maintained for more than 1 s) was selected for further analysis using ImageJ software (National Institutes of Health). The midpoint between the medial and lateral femoral condyles was defined as the centre of the patella. Dynamic knee valgus was measured by the distance from the tip of the hallux to the point where the line connecting the centre of the patella and anterior superior iliac spine intersected the floor (Fig. 1) [12]. This index was chosen because it has previously been shown to be significantly correlated with and a reliable alternative for three-dimensional (3D) valgus [12]. Calculations were done at two time points: first, when the hallux contacted the ground, and then, when the knee was at the most valgus position (Fig. 2). The distance was graded as positive if the point was located inward from the hallux.

ACL injury

During the 3-year follow-up period, 28 athletes (9.6%) had a confirmed ACL rupture. Within the injured group, three subjects had a contact ACL injury and 25 had a non-contact ACL injury (two athletes had bilateral injury). Among these 27 non-contact ACL injuries, 15 occurred in basketball players and 12 in handball players. In terms of mechanism of injury, 15 knees were injured during a feint, six during landing, and six during other movements. The results of the 2D movement analysis in the injured group of 27 knees with non-contact ACL injury were compared with those of a control group consisting of 27 knees that were randomly selected from the uninjured knees.

The study was approved by the Ethical Committee of Graduate School of Medical Sciences, Kanazawa University
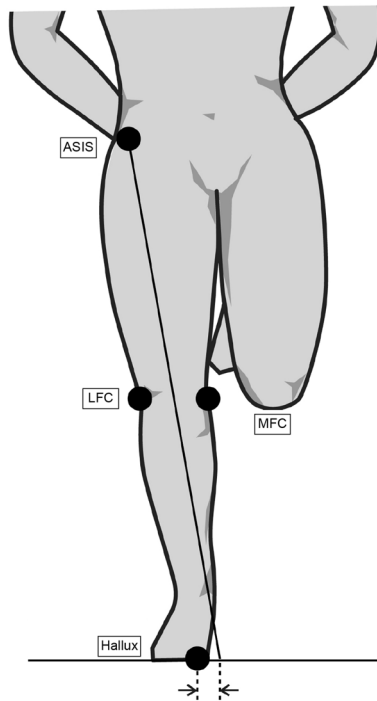
Fig. 1 Dynamic knee valgus distance was measured as the distance from the hallux to the point where the line connecting the centre of the patella and anterior superior iliac spine intersected with the floor. The midpoint between the medial and lateral femoral condyles was defined as the centre of the patella. *ASIS* anterior superior iliac spine, *MFC* medial femoral condyle, *LFC* lateral femoral condyle

(approval #1050). Written informed consent was obtained from all the participants and their parents or guardians for publication of images and other identifying information included in this article.

Statistical analysis

All data are presented as mean ± standard deviation. Unpaired *t* tests were used to evaluate differences between the injured and uninjured groups. SPSS for Windows, version 19.0 (SPSS Inc., Chicago, IL, USA), was used to perform the statistical analyses. The threshold for statistical significance was set at $P < 0.05$. Based on the enrolment rate of 100 students in one academic year and 3-year observation period to detect ACL injuries in the subjects, the study was estimated to include 300 subjects.

Results

The subjects had a mean age of 15 years at enrolment, and the height, weight, and body mass index were similar between the two groups (Table 1).

At contact of the hallux with the ground, the dynamic knee valgus distance was significantly greater in the injured group than in the control group (2.1 ± 2.4 vs. 0.4 ± 2.2 cm, $P = 0.006$; effect size: 0.74, power: 0.76). Similarly, at maximum knee valgus, the dynamic knee valgus distance was significantly greater in the injured group than in the control group (8.3 ± 4.3 vs. 5.1 ± 4.1 cm, $P = 0.007$; effect size: 0.76, power: 0.78; Table 2).
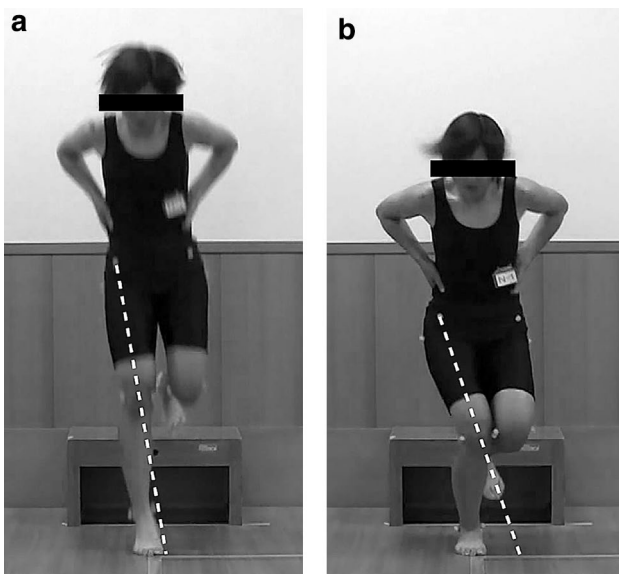
Discussion

The most important finding of the present study was that dynamic knee valgus was significantly greater in young female athletes with subsequent non-contact ACL injury. Twenty-eight (9.6%) of the 291 subjects in the study experienced an ACL injury during the 3-year observation period.

Fig. 2 Frontal 2D images, **a** at contact of the hallux with the ground and **b** at maximum knee valgus

Table 1 Physical characteristics of the subjects in the injured and control groups

	Injured group ($n = 27$)	Control group ($n = 27$)	*P* value
Age (years)	15.0 ± 0	15.0 ± 0	–
Height (cm)	161.2 ± 7.1	159.2 ± 5.8	ns
Weight (kg)	57.4 ± 7.2	54.3 ± 5.4	ns
BMI (kg/m²)	22.1 ± 1.5	21.4 ± 1.9	ns

BMI body mass index, *ns* not significant ($P \geq 0.05$)

Data are shown as mean ± standard deviation

Table 2 Dynamic knee valgus distance (cm) in the injured and control groups

Dynamic knee valgus distance	Injured group (n = 27)	Control group (n = 27)	P value
At contact of the hallux with the ground	2.1 ± 2.4	0.4 ± 2.2	0.006
At maximum knee valgus	8.3 ± 4.3	5.1 ± 4.1	0.007

Data are shown as mean ± standard deviation

Twenty-five of these 28 subjects had non-contact ACL injuries. The incidence and mechanisms of ACL injury observed in this cohort are similar to those reported in previous studies [16, 28, 32]. For example, 76 (15%) of 506 female professional basketball players reported an ACL injury during an 8-year retrospective study [16]. ACL injury rates in female athletes are generally higher in collegiate and high school athletes compared to professional and elite athletes [16]. This difference is likely due to attrition, selection bias, and better training at the professional level.

In a prospective study of 205 female athletes, dynamic 3D movement analysis revealed a significantly greater knee valgus angle during exercise in athletes with ACL injury compared to athletes without ACL injury [10]. Although the analysis of dynamic knee valgus appears to be very useful in assessing risk of ACL injury, the complexity of 3D movement analysis in terms of the infrastructure and technique makes it inaccessible in general sports settings. The camera, motion capture systems, and data collection instruments necessary for 3D movement analysis are expensive. Additionally, 3D kinematic analysis requires complex data processing and programming skills that may not be available at most sports settings. Two-dimensional movement analysis can potentially overcome these limitations of 3D analysis. Our motivation in this study was therefore to simplify the test and analysis methods using a simple 2D kinematic analysis and a previously validated simple dynamic knee valgus distance measurement [12] to make them suitable for on-field use in low-resource sports settings.

The study showed that dynamic knee valgus was significantly greater in the injured group compared to the control group, suggesting that dynamic knee valgus may be a risk factor for non-contact ACL injury. Previous studies using motion analysis have used the two-leg drop jump to calculate normalized knee separation distance and hip separation distance as a measure of dynamic knee valgus [18]. Studies comparing bilateral and unilateral leg drop jumps have shown that the dynamic change in lower limb alignment is greater in the single-leg drop jump compared to bilateral-leg drop jump [20]. Specifically, single-leg drop jump was associated with increased knee valgus, decreased knee flexion at initial contact, decreased peak knee flexion, and decreased relative hip adduction, and female subjects landed with increased knee valgus compared to male subjects [20]. A comparison of coronal- and sagittal-plane biomechanics during drop landings demonstrated that landing kinematics and kinetics differ between male and female athletes in the coronal plane but not in the sagittal plane [13]. Thus, through single-leg drop jumping and coronal 2D motion analysis, we were able to conduct motion analysis under the conditions best suited to detect kinematic differences in the study group.

The results of this study are also consistent with previous studies that used 3D motion analysis to investigate knee joint kinematics in non-contact ACL injuries [10, 14]. However, compared to technically complex and expensive 3D motion analysis setups, 2D motion analysis as performed in our study offers a more feasible and affordable alternative for dynamic motion analysis of athletes in general settings [7, 17]. Indeed, knee valgus distance calculated from 2D motion analysis using a video camera was previously shown to be a reliable alternative to that determined by 3D motion analysis using VICON® systems [12].

Taken together, these results indicate that greater knee valgus angle is a risk factor for non-contact ACL injury in female athletes. Further studies are required to understand fully the risk factors that increase dynamic knee valgus. For example, lower hip abductor peak torque [6, 11], but not hip muscle strength [29], has been shown to increase knee valgus. A more thorough understanding of these mechanisms will aid in the development of appropriate training and clinical interventional strategies to prevent injuries in at-risk athletes, improve outcomes, and lower costs [28].

This study has several limitations and scope for future work. First, a relatively low-resolution and low-speed video camera (30 frames per second) was used in the study. As a result, afterimages of the markers were observed in the extracted still images, making their localization difficult. Using a higher-resolution and high-speed video camera could increase the quality and number of still images and potentially allow for more accurate motion analysis. Second, the mechanism of ACL injury (contact/non-contact) was recorded based on reporting by patients or other players, which could be a potential source of bias in this study. Finally, we did not compare the contralateral healthy leg in ACL-deficient subjects. There is the possibility of different kinematics in the unaffected legs of healthy individuals versus the pre-injured affected knee in ACL-deficient subjects, which may specifically predispose one knee to non-contact ACL injury. However, understanding such risk factors will

require a more controlled study in which the injury mechanism is accurately characterized in all subjects.

Conclusion

This study shows that 2D motion analysis is a feasible and affordable modality for dynamic motion analysis of athletes. Dynamic knee valgus measured using 2D motion analysis was shown to be a potential risk factor for non-contact ACL injury in young female athletes. The results of this study will help in fully understanding the risk factors that increase dynamic knee valgus and help design more appropriate training and interventional strategies to prevent injuries in at-risk athletes.

References

1. Agel J, Olson DE, Dick R, Arendt EA, Marshall SW, Sikka RS (2007) Descriptive epidemiology of collegiate women's basketball injuries: national collegiate athletic association injury surveillance system, 1988–1989 through 2003–2004. J Athl Train 42:202–210
2. Alentorn-Geli E, Myer GD, Silvers HJ, Samitier G, Romero D, Lazaro-Haro C, Cugat R (2009) Prevention of non-contact anterior cruciate ligament injuries in soccer players. Part 1: mechanisms of injury and underlying risk factors. Knee Surg Sports Traumatol Arthrosc 17:705–729
3. Alentorn-Geli E, Myer GD, Silvers HJ, Samitier G, Romero D, Lazaro-Haro C, Cugat R (2009) Prevention of non-contact anterior cruciate ligament injuries in soccer players. Part 2: a review of prevention programs aimed to modify risk factors and to reduce injury rates. Knee Surg Sports Traumatol Arthrosc 17:859–879
4. Arendt E, Dick R (1995) Knee injury patterns among men and women in collegiate basketball and soccer. NCAA data and review of literature. Am J Sports Med 23(6):694–701
5. Beckett ME, Massie DL, Bowers KD, Stoll DA (1992) Incidence of hyperpronation in the ACL injured knee: a clinical perspective. J Athl Train 27:58–62
6. Claiborne TL, Armstrong CW, Gandhi V, Pincivero DM (2006) Relationship between hip and knee strength and knee valgus during a single leg squat. J Appl Biomech 22:41–50
7. Dingenen B, Malfait B, Nijs S, Peers KH, Vereecken S, Verschueren SM, Staes FF (2015) Can two-dimensional video analysis during single-leg drop vertical jumps help identify non-contact knee injury risk? A one-year prospective study. Clin Biomech 30:781–787
8. Flynn RK, Pedersen CL, Birmingham TB, Kirkley A, Jackowski D, Fowler PJ (2005) The familial predisposition toward tearing the anterior cruciate ligament: a case control study. Am J Sports Med 33:23–28
9. Griffin LY, Agel J, Albohm MJ, Arendt EA, Dick RW, Garrett WE, Garrick JG, Hewett TE, Huston L, Ireland ML, Johnson RJ, Kibler WB, Lephart S, Lewis JL, Lindenfeld TN, Mandelbaum BR, Marchak P, Teitz CC, Wojtys EM (2000) Noncontact anterior cruciate ligament injuries: risk factors and prevention strategies. J Am Acad Orthop Surg 8(3):141–150
10. Hewett TE, Myer GD, Ford KR, Heidt RS Jr, Colosimo AJ, McLean SG, van den Bogert AJ, Paterno MV, Succop P (2005) Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes: a prospective study. Am J Sports Med 33:492–501
11. Jacobs CA, Uhl TL, Mattacola CG, Shapiro R, Rayens WS (2007) Hip abductor function and lower extremity landing kinematics: sex differences. J Athl Train 42:76–83
12. Kagaya Y, Kawasaki W, Fujii Y, Nishizono H (2010) Validation of a two-dimensional motion analysis technique for quantifying dynamic knee valgus during a drop landing by comparisons to data from three-dimensional analysis. Jpn J Phys Fit Sports 59:407–414
13. Kernozek TW, Torry MR, Van Hoof H, Cowley H, Tanner S (2005) Gender differences in frontal and sagittal plane biomechanics during drop landings. Med Sci Sports Exerc 37:1003–1012
14. Koga H, Nakamae A, Shima Y, Iwasa J, Myklebust G, Engebretsen L, Bahr R, Krosshaug T (2010) Mechanisms for noncontact anterior cruciate ligament injuries: knee joint kinematics in 10 injury situations from female team handball and basketball. Am J Sports Med 38:2218–2225
15. Leetun DT, Ireland ML, Willson JD, Ballantyne BT, Davis IM (2004) Core stability measures as risk factors for lower extremity injury in athletes. Med Sci Sports Exerc 36:926–934
16. McCarthy MM, Voos JE, Nguyen JT, Callahan L, Hannafin JA (2013) Injury profile in elite female basketball athletes at the Women's National Basketball Association Combine. Am J Sports Med 41:645–651
17. McLean SG, Walker K, Ford KR, Myer GD, Hewett TE, van den Bogert AJ (2005) Evaluation of a two dimensional analysis method as a screening and evaluation tool for anterior cruciate ligament injury. Br J Sports Med 39:355–362
18. Noyes FR, Barber-Westin SD, Fleckenstein C, Walsh C, West J (2005) The drop-jump screening test: difference in lower limb

control by gender and effect of neuromuscular training in female athletes. Am J Sports Med 33:197–207

19. Olsen OE, Myklebust G, Engebretsen L, Bahr R (2004) Injury mechanisms for anterior cruciate ligament injuries in team handball: a systematic video analysis. Am J Sports Med 32:1002–1012

20. Pappas E, Hagins M, Sheikhzadeh A, Nordin M, Rose D (2007) Biomechanical differences between unilateral and bilateral landings from a jump: gender differences. Clin J Sport Med 17:263–268

21. Ramesh R, Von Arx O, Azzopardi T, Schranz PJ (2005) The risk of anterior cruciate ligament rupture with generalised joint laxity. J Bone Joint Surg Br 87:800–803

22. Sallis RE, Jones K, Sunshine S, Smith G, Simon L (2001) Comparing sports injuries in men and women. Int J Sports Med 22(6):420–423

23. Shambaugh JP, Klein A, Herbert JH (1991) Structural measures as predictors of injury basketball players. Med Sci Sports Exerc 23:522–527

24. Smith HC, Vacek P, Johnson RJ, Slauterbeck JR, Hashemi J, Shultz S, Beynnon BD (2012) Risk factors for anterior cruciate ligament injury: a review of the literature-part 1: neuromuscular and anatomic risk. Sports Health 4:69–78

25. Smith HC, Vacek P, Johnson RJ, Slauterbeck JR, Hashemi J, Shultz S, Beynnon BD (2012) Risk factors for anterior cruciate ligament injury: a review of the literature-part 2: hormonal, genetic, cognitive function, previous injury, and extrinsic risk factors. Sports Health 4:155–161

26. Sueyoshi T, Emoto G, Yuasa T (2016) Generalized joint laxity and ligament injuries in high school-aged female volleyball players in Japan. Orthop J Sports Med 4:2325967116667690

27. Swanik CB, Covassin T, Stearne DJ, Schatz P (2007) The relationship between neurocognitive function and noncontact anterior cruciate ligament injuries. Am J Sports Med 35:943–948

28. Swart E, Redler L, Fabricant PD, Mandelbaum BR, Ahmad CS, Wang YC (2014) Prevention and screening programs for anterior cruciate ligament injuries in young athletes: a cost-effectiveness analysis. J Bone Joint Surg Am 96:705–711

29. Thijs Y, Van Tiggelen D, Willems T, De Clercq D, Witvrouw E (2007) Relationship between hip strength and frontal plane posture of the knee during a forward lunge. Br J Sports Med 41:723–727 **discussion 7**

30. Trojian TH, Collins S (2006) The anterior cruciate ligament tear rate varies by race in professional women's basketball. Am J Sports Med 34:895–898

31. Van Mechelen W, Hlobil H, Kemper HC (1992) Incidence, severity, aetiology and prevention of sports injuries a review of concepts. Sports Med 14:82–99

32. Walden M, Hagglund M, Magnusson H, Ekstrand J (2011) Anterior cruciate ligament injury in elite football: a prospective three-cohort study. Knee Surg Sports Traumatol Arthrosc 19:11–19

33. Yeow CH, Lee PV, Goh JC (2010) Sagittal knee joint kinematics and energetics in response to different landing heights and techniques. Knee 17:127–131

34. Zazulak BT, Hewett TE, Reeves NP, Goldberg B, Cholewicki J (2007) Deficits in neuromuscular control of the trunk predict knee injury risk: a prospective biomechanical-epidemiologic study. Am J Sports Med 35:1123–1130