Published in final edited form as:

Am J Sports Med. 2017 December ; 45(14): 3223–3232. doi:10.1177/0363546517735091.

Geometric Characteristics of the Knee Are Associated With a Noncontact ACL Injury to the Contralateral Knee After Unilateral ACL Injury in Young Female Athletes

James G. Levins, MD^{*}, Erin C. Argentieri, BS[†], Daniel R. Sturnick, MS[‡], Mack Gardner-Morse, MS^{*}, Pamela M. Vacek, PhD[§], Timothy W. Tourville, PhD, ATC^{||}, Robert J. Johnson, MD^{*}, James R. Slauterbeck, MD^{*}, and Bruce D. Beynnon, PhD^{*,||}

^{*}Department of Orthopaedics and Rehabilitation, University of Vermont, Burlington, Vermont, USA.

[†]Department of Radiology and Imaging, Hospital for Special Surgery, New York, New York, USA.

[‡]Department of Biomechanics, Hospital for Special Surgery, New York, New York, USA.

[§]Department of Medical Biostatistics, University of Vermont, Burlington, Vermont, USA.

^{||}Department of Rehabilitation and Movement Science, University of Vermont, Burlington, Vermont, USA.

Abstract

Background: Contralateral anterior cruciate ligament (CACL) injury after recovery from a first-time ACL rupture occurs at a high rate in young females; however, little is known about the risk factors associated with bilateral ACL trauma.

Hypothesis: The geometric characteristics of the contralateral knee at the time of the initial ACL injury are associated with risk of suffering a CACL injury in these female athletes.

Study Design: Case-control study; Level of evidence, 3.

Methods: Sixty-two female athletes who suffered their first noncontact ACL injury while participating in sports at the high school or college level were identified, and geometry of the femoral notch, ACL, tibial spines, tibial subchondral bone, articular cartilage surfaces, and menisci of the contralateral, uninjured, knee was characterized in 3 dimensions. We were unable to contact 7 subjects and followed the remaining 55 until either a CACL injury or an ACL graft injury occurred or, if they were not injured, until the date of last contact (mean, 34 months after their first ACL injury). Cox regression was used to identify risk factors for CACL injury.

Results: Ten (18.2%) females suffered a CACL injury. Decreases of 1 SD in femoral intercondylar notch width (measured at its outlet and anterior attachment of the ACL) were associated with increases in the risk of suffering a CACL injury (hazard ratio = 1.88 and 2.05,

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^{||}Address correspondence to Bruce D. Beynnon, PhD, McClure Musculoskeletal Research Center, Department of Orthopaedics and Rehabilitation, Robert Larner M.D. College of Medicine, University of Vermont, Burlington, VT 05405, USA (bruce.beynnon@uvm.edu).

respectively). Likewise, 1 SD decreases in medial-lateral width of the lateral tibial spine, height of the medial tibial spine, and thickness of the articular cartilage located at the posterior region of the medial tibial compartment were associated with 3.59-, 1.75-, and 2.15-fold increases in the risk of CACL injury, respectively.

Conclusion: After ACL injury, subsequent injury to the CACL is influenced by geometry of the structures that surround the ACL (the femoral notch and tibial spines). This information can be used to identify individuals at increased risk for CACL trauma, who might benefit from targeted risk-reduction interventions.

Keywords

ACL; knee; contralateral; biomechanics; injury prevention

Suffering a second anterior cruciate ligament (ACL) injury to the contralateral knee after recovery from a first-time ACL injury is devastating and represents a considerable health care concern because up to 23.7% of young females (mean age, 16.9 ± 6.28 years) who suffer a unilateral ACL injury will go on to suffer a subsequent contralateral ACL (CACL) injury within 2 years of full recovery and return to preinjury activity.^{33,52} The risk of suffering a CACL injury after ACL reconstruction (ACLR) is 30 to 40 times greater than the risk of a first-time ACL injury in an uninjured population.⁵² This is a concern because subjects who suffer bilateral ACL injuries do not return to their original sports as frequently; if they do return, a large proportion of these individuals report a significant reduction in their activity level.¹³ Perhaps even more concerning is that the long-term response to ACL injury is associated with altered knee biomechanics and the early onset of posttraumatic osteoarthritis (PTOA),^{11,25,30} and bilateral injury only adds to the burden of early-onset PTOA for the young athlete.¹² With the dearth of treatment options for PTOA in young individuals, the most effective way to reduce the incidence of this disease is to minimize the risk of suffering the inciting injury. To accomplish this, the risk factors associated with CACL injury must first be identified and understood. This information will allow us to determine who is at increased risk for CACL trauma so risk-reduction interventions and injury prevention programs can be targeted at them.

There may be different factors that contribute to or increase the baseline risk for CACL injury. For example, several groups have reported that young age and high activity level are risk factors for CACL injury.^{20,23,26,37,41,52} In addition, females younger than 18 years may be at increased risk of suffering a CACL injury compared with males of comparable age.⁴¹ These demographic risk factors explain only a portion of the overall risk associated with CACL trauma, and neuromuscular control may play a role. Paterno et al^{32,34} found kinematic differences between athletes suffering a second ACL injury (either ACL graft injury or CACL injury) compared with those who suffered only 1 ACL injury. Joint kinematics may be related to, or a product of, joint geometry.

Characterization of knee joint geometry can help elucidate the differences that exist between subjects who suffer a unilateral ACL injury and those who go on to experience CACL trauma. Indeed, several reports have indicated that a decreased width of the femoral notch is associated with increased risk of CACL injury,^{2,3,16,18,39,40,43} while 1 study refuted this

finding.³⁸ Feucht et al¹⁴ suggest that one measurement of knee geometry considered in isolation may not be sufficient to accurately characterize risk of ACL injury. There remains a significant knowledge gap in the literature regarding a comprehensive understanding of the geometric characteristics of the knee that are associated with risk of suffering a CACL injury. Previous studies^{3,18,38–40} evaluating geometric risk factors for CACL injury used combined-sex analyses, which may be a source of confounding because geometric risk factors for first-time ACL injury have been shown to differ between males and females.^{7,45–47,51} In addition, interpretation of results is difficult if the mechanism of injury is not controlled for in the statistical analyses because the relationship between geometry and biomechanics of the knee in a subject who suffers a noncontact injury may be very different than in one who suffers a contact injury. Other studies^{32,34} have chosen to combine CACL injury and ACL graft injury into a single outcome variable in an effort to analyze the total risk of “secondary” ACL trauma. Due to the different structural properties of ACL grafts,⁵ graft injuries may have different risk factors and combining them with CACL injuries may not yield results specific to contralateral injury. Finally, some groups have used subjects who have never sustained an ACL injury as a comparison group,³ prohibiting identification of factors that place a first-time ACL-injured athlete at increased risk of suffering a second CACL injury to his or her contralateral knee.

The purpose of this investigation was to prospectively follow competitive high school and college female athletes who suffered their first noncontact ACL injury to identify features of the uninjured knee that are associated with risk of suffering a subsequent noncontact CACL injury. We hypothesized that the geometric characteristics of the contralateral knee at the time of the initial injury are associated with risk of suffering a CACL injury in these female athletes.

METHODS

Human Subjects, Surveillance, and Follow-up

The investigation is an extension of a study of risk factors for a first-time, noncontact ACL injury (defined as an injury that was produced without contact to the knee joint and surrounding area) and involved female athletes from 36 different high schools and colleges who were followed prospectively over 4 years. Subjects participated in soccer, basketball, lacrosse, field hockey, or track and field. All subjects had sustained their first complete ACL rupture that was documented by clinical examination and then confirmed by arthroscopic visualization at the time of reconstruction by an orthopaedic surgeon, and they had not suffered prior trauma to either knee. After participation in the study for risk factors for a first-time ACL injury, the subjects were contacted and asked to participate in the current prospective cohort study that was designed to determine the risk factors for a CACL injury. This study was approved by our institutional review board. After reconstruction of the initial ACL injury, subjects underwent supervised rehabilitation, were cleared for return to sport by the treating orthopaedic surgeon, and then returned to participation in sport. Subjects were followed prospectively by mail, email, or telephone to determine if a CACL injury to their contralateral knee had occurred. Medical records were obtained and reviewed on all subjects who indicated that they suffered a CACL injury to confirm that a complete, grade 3,

noncontact CACL rupture had indeed occurred in the contralateral knee. In all instances, CACL injury was documented and confirmed via clinical examination, magnetic resonance imaging (MRI), and arthroscopic visualization at the time of reconstruction of the CACL injury.

MRI Data Acquisition

After the first ACL injury, but before ACLR, high-resolution MRIs of the injured and normal knees were obtained on all study participants at a mean 27 days (median, 15 days) after the initial trauma. Sagittal, 3-dimensional (3D), T1-weighted, fast-field echo (voxel size: 0.3 mm × 0.3 mm × 1.2 mm) and sagittal, 3D, proton density–weighted (voxel size: 0.4 mm × 0.4 mm × 0.7 mm) MRI sequences were acquired using the same 3-Tesla Phillips Achieva scanner (Phillips Medical Systems) for all subjects. Subject knees were scanned inside the same 8-channel SENSE knee coil. DICOM images were then viewed and manually digitized using Osirix software (Pix-meo, version 3.6.1, open source). The femoral notch, tibial plateau subchondral bone, tibial spines, tibial articular cartilage surface, menisci, and the ACL were manually segmented using a Cintiq 21 UK digitizing tablet (Wacom Tech Corp) with measurement techniques that have been described elsewhere.^{4,6,45–47,51} Segmentation of the femoral intercondylar notch width and thickness of the bony ridge at the anteromedial outlet of the femoral notch was performed in the coronal-oblique plane using the proton density–weighted image sequence, while the remaining segmentations were completed in either the sagittal or transverse planes using the T1-weighted images.

Thirty-six measurements that characterized the geometry of the articular structures of the knee and ACL were acquired. These included the medial and lateral tibial spines (12 measurements), the medial and lateral tibial plateau articular cartilage surfaces and menisci (12 measurements), the femoral intercondylar notch and ACL (8 measurements), and the tibial plateau subchondral bone in the medial and lateral compartments of the knee (4 measurements). For the medial and lateral tibial spines, the height, medial-lateral directed width, anterior-posterior depth, volume, and location of center of gravity and peaks of the spines were measured.⁴⁵ The tibial articular cartilage surface and menisci in the medial and lateral compartments were characterized by measuring the posterior-inferior directed slope of the articular cartilage surface that was covered by the posterior horn of the meniscus, the posterior-inferior directed slope of the middle portion of the articular cartilage surface that was not covered by the meniscus, the posterior articular cartilage thickness, the posterior meniscal horn height, and the angle formed between the surface of the posterior horn of the meniscus and articular cartilage surface.⁴⁷ For the tibial subchondral bone, the coronal tibial slope, the lateral and medial posterior-inferior directed slopes of medial and lateral plateaus, and the medial tibial depth were measured.⁸ The distal femur was characterized by measuring the intercondylar femoral notch width at 4 locations (the inlet of the notch, the anterior attachment of the ACL, at a point halfway between the inlet and the anterior attachment of the ACL, and at the outlet of the notch), the volume of the femoral notch, and the medial-lateral height of the ridge found on the anterior-medial outlet of the femoral notch.⁵¹ Finally, the volume and cross-sectional area of the ACL were measured.⁵¹ The methods used to obtain these before-mentioned measurements have been described, and intraclass correlation coefficient (ICC) values that were computed based on measurements

made by the same individual at 2 separate time points indicated a high level of reliability.^{4,8,45–47,51}

Three-dimensional coordinate systems located within the tibia and femur were established and used as references in an effort to standardize all measurements of knee geometry.^{4,6,45} Use of 3D coordinate systems eliminated concerns associated with positional variability of the tibia and femur within the MRI scanner at the time of data acquisition, and this allowed 3D measurements of knee geometry to be made in a reliable and reproducible manner. This is evidenced by test-retest reliability that had ICC values ranging from 0.77 to 0.91 for the significant measurements identified in the current study.^{6,45,46,51} Although measurements were made on both knees of all subjects, only data acquired from the initially uninjured knee were used. This allowed for a prospective study of a CACL injury to the contralateral knee because the knee and ACL geometry was characterized before the injury.

Statistical Methods

The statistical methods were based on survival analysis and used Cox regression, which modeled time to CACL injury with each potential risk factor considered as an independent variable to assess its univariate association with the risk of CACL injury. The primary outcome of this study was the time interval between the first and second ACL injury. This was defined as the number of months between the first ACL injury and subsequent trauma (either CACL injury for the CACL-injured subjects or reinjury to the ipsilateral knee for subjects who sustained a graft injury) or the date of final contact for the unilateral-injured females who did not suffer additional injury to either knee. Subjects who did not have a CACL injury were censored either at the end of their follow-up time interval or at the time of graft injury. Hazard ratios were determined relative to a 1 SD decrease in the variable under consideration. Significance level alpha was set at .05 a priori for all analyses. All statistical analyses were conducted using SAS version 9.2 (SAS Institute).

RESULTS

In total, 62 females who suffered their first noncontact complete ACL rupture during participation in organized sport were recruited and enrolled, and 55 (89%) of these individuals were contacted after their initial injury, ACLR, and return to sport and provided information regarding any subsequent CACL or ACL graft injury (Table 1). We were unable to make contact with 7 subjects. Of the 55 female subjects with follow-up information, 10 (18.2%) suffered a noncontact CACL injury and underwent reconstruction. In addition, 6 (10.9%) females suffered a noncontact injury to their ACL graft during the course of the study, 1 of which occurred 1 month before the CACL injury. All subjects suffering a graft injury were censored (ie, their data were included until the time of graft injury) at the time of graft injury, leaving 9 CACL injuries in the statistical analysis. For the 9 female subjects who suffered CACL injury, the mean time interval between initial ACL injury and CACL injury was 22.7 ± 11.6 months (range, 12.4–40.2 months). The mean follow-up time for unilateral ACL-injured subjects was 36.2 ± 11.6 months (range, 7.3–59.7 months); when excluding the subjects who suffered a graft injury, the minimum follow-up time was 23.9 months.

The demographic characteristics of the 55 subjects in the study cohort at the time of initial injury are shown in Table 1. Risk of CACL injury was not significantly associated with either weight ($P = .85$) or height ($P = .65$). Age at the time of initial injury was significantly associated with risk of CACL injury (hazard ratio = 0.53 per 1-year increase in age; $P = .005$) but is confounded with athletic exposure because the younger athletes generally had longer participation in competitive sport after their initial ACL injury.

Of the 36 measurements of articular geometry shown in Table 2, 5 were significantly associated with risk of CACL injury after a first-time ACL injury. For each of these, a decrease in the measurement was found to be associated with an increased risk of injury (ie, inverse relationships were found). A 1 SD (1.9-mm) decrease of the femoral notch width at the anterior attachment of the ACL (NW_AA) was associated with a 2.05-fold increase in risk of suffering a CACL injury ($P = .016$) (Figure 1 and Table 3). Likewise, a decrease in the width of the femoral notch at the anterior outlet (NW_O) of 1 SD (2.6 mm) was associated with a 1.88-fold increase in risk of experiencing a CACL injury ($P = .041$) (Figure 1 and Table 3). The unstandardized measurement of notch width was used in the analysis because a study of first-time ACL injury found that it had a stronger relationship with risk than did notch width index^{50,51}; however, we did perform analyses of notch width that included weight and height as covariates, and the results were very similar to the univariate results. A 1 SD (0.4-mm) decrease in the thickness of the articular cartilage located at the posterior region of the medial tibial compartment ($M_{ed}CBH$) was associated with a 2.15-fold increase in risk of contralateral ACL injury ($P = .014$) (Figure 2 and Table 3). Similarly, there was an inverse relationship between tibial spine geometry and CACL injury; here, a 1 SD (1.9-mm) decrease in the medial-lateral directed width of the lateral tibial spine and a 1 SD (0.9-mm) decrease in the height of the medial tibial spine were associated with 3.59- and 1.75-fold increases in the risk of CACL injury, correspondingly ($P = .039$ and $.045$, respectively) (Figure 3 and Table 3). The volume (ACL_Vol) and cross-sectional area (ACL_CSA) of the ACL itself were not associated with risk of CACL injury ($P = .88$ and $.98$, respectively). The volume of the femoral notch (N_Vol) was also not related to the risk of CACL injury ($P = .49$).

DISCUSSION

The current study of female athletes found that femoral notch width, measured at both the anterior attachment of the ACL and the outlet of the notch, is inversely associated with the risk of suffering a noncontact CACL injury. Prior work has demonstrated an inverse relationship between femoral notch width and risk of suffering an initial ACL injury,⁵¹ as well as ACL graft failure.^{22,41} Further, the current study revealed that the size of the ACL (including both volume and cross-sectional area) was not related to risk of noncontact CACL injury among female athletes, which is consistent with prior results from studies of the risk of suffering a first-time ACL injury.⁵¹ The observation that a decrease in the width of the femoral notch is associated with increased risk of injury, combined with the fact that the size of the ACL is not related to injury of this structure, is important because a decreased intercondylar femoral notch width has been associated with increased ACL strain values with the knee extended and at the extremes of tibial internal rotation, a common position of the knee at the time of noncontact ACL and CACL injury.^{15,31} This provides a

biomechanical explanation for the underlying mechanism by which a decrease of femoral notch width influences the risk of suffering unilateral and bilateral ACL injuries. It may also provide some explanation as to why females are at increased risk for suffering CACL injury in comparison to their male counterparts⁴⁷: females have been shown to exhibit a smaller femoral notch width and smaller ACLs in comparison to those of males.⁵¹

The current study also found an inverse relationship between the thickness of articular cartilage at the posterior region of the medial tibial plateau and risk of CACL injury. Although this has not been found to be associated with risk of a first-time ACL injury,⁴⁷ a decrease in the thickness of the cartilage that is located under the posterior horn of the medial meniscus may be associated with decreased conformity between the articular surfaces of the tibia and femur. This would decrease the biomechanical restraint of the tibiofemoral joint that is provided by contact between the articular surfaces and potentially expose the ACL to increased load and anterior translation of the tibia relative to the femur. This is similar to the mechanism described by Hudek et al,¹⁹ in which they proposed that a decreased height of the posterior meniscal horn would act to increase the posterior-inferior directed slope of the meniscal horns, thus allowing for increased anterior translation of the tibia relative to the femur and increased magnitude of load on the ACL. It is also similar to the possible mechanism described by Sturnick et al,⁴⁷ in which decreased height of the posterior horn of the menisci, and the corresponding decrease in the wedge-shaped profile of the menisci, was postulated to decrease the restraint to anterior translation of the tibia relative to the femur and increase the magnitude of load on the ACL.

In the current study, we identified 2 characteristics of tibial spine geometry (decreases in the height and medial-lateral directed width of the medial and lateral spines) that were associated with increased risk of CACL injury. In addition, there was evidence to suggest that a decrease in the volume of the lateral tibial spine is associated with an increased risk of CACL injury ($P = .06$). These findings may reflect the fact that the knee ligaments act in combination with the geometry of the articular surfaces of the tibia and femur to resist the intersegmental forces transmitted across the joint during normal activity and knee ligament trauma. Geometry of the tibial spines is of particular importance because the centers of contact area between the tibial and femoral articular surfaces during weightbearing activity are located along the medial and lateral tibial spines.²⁴ Further, a recent study of joint biomechanics reported by McDonald et al²⁸ determined that transection of the ACL produced a significant increase in the intersegmental load that was transmitted between the medial femoral condyle and medial tibial spine. These observations, when considered in combination with the findings from the current study, suggest that decreases in the height and medial-lateral directed width of the tibial spines may be associated with decreased conformity of the tibiofemoral articular surfaces, and this corresponds with a decreased biomechanical constraint of the joint that is provided by articular contact. In turn, this is associated with increased anterior translation and internal rotation of the tibia relative to the femur, both of which act to increase the magnitude of ACL strain values.⁵ Further, increases in both rotation and translation of the tibia relative to the femur have been observed as mechanisms associated with increased risk of suffering noncontact ACL injury.^{21,50} These before-mentioned observations point to a direct relationship between geometry of the tibial spines and contact stress transmission across this important aspect of the tibiofemoral

articular surface interface during activities that challenge the knee (eg, landing from a jump, or plant-and-cut maneuvers that involve a sudden change in direction) and the risk of CACL injury. It is unclear if this relationship has an influence on risk of CACL injury through repeated submaximal loading of the knee over time that is associated with micro tears and subsequent fatigue failure of the CACL, an isolated loading condition that exceeds the ultimate failure strength of the CACL, or some combination of both.⁵³ Except for notch width, the geometric features of the knee associated with CACL injury differed from those associated with first-time ACL injury, but they would not necessarily be expected to be the same because they pertain to 2 different populations. Risk factors for CACL injury apply to athletes who have suffered a previous ACL injury, many of whom already have the risk factors for first-time ACL injury. The latter would therefore have less variability and be less predictive in this population.

This study focused on young female athletes as they are at increased risk of suffering both their first ACL injury and CACL injury relative to males,^{7,41} and consequently our findings pertain to the individuals at greatest risk of suffering bilateral ligament trauma. It is important for us to emphasize that this work focused on a considerable health care concern, as we observed that 18.2% of the female athletes suffered a CACL tear, confirming prior reports in the literature,^{33,52} and an additional 10.9% of the female athletes tore their ACL graft during the 60 months of follow-up. CACL injury also represents a considerable health care concern for young male athletes, and we estimated that it would be necessary to enroll and follow 6 times the number of male athletes (or 360 subjects who suffered a unilateral noncontact ACL injury, underwent reconstruction and rehabilitation, and returned to activity and sport) to generate the same number of CACL-injured subjects who were enrolled in the current study. Such a prospective study of high school and college male athletes who require MRI before the CACL injury may require multiple data collection sites to execute and should be the focus of future research.

To the authors' knowledge, the current study is the first to use a truly prospective study design to characterize and evaluate a comprehensive set of MRI measurements of knee geometry in an effort to determine the factors associated with risk of noncontact CACL injury after a first-time noncontact ACL injury in young female athletes. An important strength of the prospective study design is that it allowed us to measure the geometry of the ACL and surrounding geometric characteristics of the uninjured knee and then follow the subjects over time until the CACL injury occurred. Further, the female athletes participated on sports teams that involved plant, cut, and pivot activities. It has been estimated that the noncontact CACL injuries we studied occurred over a very short time interval (between 40 and 60 milliseconds),²¹ during which fluid is unable to flow through articular cartilage and change the geometry of these structures. Therefore, we believe the measures of the ACL and geometric characteristics of the uninjured knee that were obtained at the time of MRI acquisition with the subject supine and the joint unloaded may be similar to the geometric characteristics that existed at the time of CACL injury.⁴⁷ All subjects underwent ACLR with the intent to return to sport and an active lifestyle, and they reported that they returned to sport and activity. Consequently, all study participants remained at increased risk for CACL injury.

Our study has potential limitations. The small number of CACL injuries included in the current study limited the statistical power to detect some associations with risk and precluded the use of multivariate analysis to control for any correlations between measurements that may exist. Such correlations do not alter the validity of the univariate results, but multivariate analysis would assist in the interpretation of results and provide additional information about the combinations of independent risk factors that are associated with an increased risk of suffering a CACL tear after a first-time ACL injury.⁴⁶ Another potential limitation was that the postoperative rehabilitation protocol and readiness for return to sport may have differed between study participants. In the current study, 10 different surgeons performed the ACLRs and prescribed postoperative care to the study participants. While this makes our findings more generalizable, it may have introduced variability in the return-to-sport decision making. However, this is not likely to have had a substantial effect on the results of the current study because only 1 CACL injury occurred within 12 months after initial ACL injury. Our study was not designed to study the effects of sex or age on risk of CACL injury. Prior work indicates that the risk factors for first-time ACL injury differ between males and females, and that is likely to be the case for CACL injury.^{6,45–47,50,51} As noted above, male athletes have a lower incidence of CACL injury; consequently, a larger cohort is needed to prospectively study the risk factors for CACL injury in males. Previous studies have also indicated that risk of repeated ACL injury increases with younger age.^{20,23,26,37,41,52} Although younger age at the time of initial injury was associated with increased risk of CACL injury in the current study, age was confounded with athletic exposure (younger subjects had more years to participate in high school and collegiate sports after their first injury). We did not have the detailed information needed to control for exposure and therefore could not accurately assess the risk associated with age at the time of first injury.

Although there is not a consensus on appropriate return-to-sport guidelines after an ACL injury,⁹ there are important neuromuscular and proprioceptive changes that occur bilaterally after ACL injury and reconstruction.^{10,35,49} It has been proposed that CACL injury may occur more frequently in individuals with superior rehabilitation at 6 months after ACLR, possibly due to increased activity level compared with those with relatively lesser strength and functional capacity at 6 months after ACLR.⁴⁴ Alternatively, the contralateral limb may be at increased risk of injury after ACLR because of deconditioning,⁵⁴ as observed by Chung et al,¹⁰ who noted decreased extension strength and single-legged hop performance in the contralateral limb 24 months after ACLR. Compensatory kinetic changes of the lower extremity were found by Hofbauer et al,¹⁷ with external rotation and knee flexion noted in the contralateral leg 12 months after ACLR. Similarly, hip kinetics of the uninjured limb may become similar to the injured limb 2 years after ACLR, indicating a potentially unsuccessful compensatory adaptation.³⁶ These changes in the contralateral limb may lead to an increased risk of a CACL injury independent of the geometric characteristics of the knee that were considered in this study¹⁷ and may have contributed to the higher risk of CACL injury in comparison to first-time ACL injury.

The goal of this investigation was to provide information that can be used to identify the specific aspects of knee joint geometry that place individuals at increased risk for CACL injury after sustaining a unilateral ACL injury. While geometry of the articular structures

that guide knee biomechanics is just one aspect of the many factors that play a role in ACL injury, we believe it is important and can be targeted as an identifying factor when considering the overall risk of suffering CACL trauma. With better identification of those at increased risk, clinicians may use targeted prehabilitation strategies and injury prevention programs²⁹ with the goal of attenuating the risk conferred by geometry of the articular structures of the knee. It is possible that geometry of the knee may become a modifiable risk factor. Changes in knee geometry that occur during growth and development have been observed using MRI,⁴⁸ and it may be possible to influence these changes through activity modification or specific exercises to produce knee geometry that confers less innate risk of injury. Alternatively, females who are found to have a large number of risk factors for CACL injury have the option to change the sport in which they participate or decrease their exposure to high-risk sport by reducing the amount of time spent competing in games/ scrimmages while increasing workouts that emphasize the development of strength, neuromuscular control, and skill, as well as modifying preseason workouts to include injury prevention training programs that have been shown to reduce the risk of serious knee trauma.^{1,42} Another method in which these factors may be modifiable is through surgical manipulation of joint geometry. In 1988, Souryal et al⁴³ proposed the possible use of contralateral prophylactic notchplasty for patients with stenotic femoral notches and a previous unilateral ACL rupture in an effort to reduce the risk of a CACL injury. If such a proposal were to be considered, one would need to objectively assess the increased risk of CACL injury associated with decreased intercondylar notch width, and our current study is the first to do so. In addition to the risks of surgery, the long-term effects of such a procedure are not proven, such as regrowth or further ingrowth of the femoral condyle(s). Interestingly, this topic has been studied using serial computed tomography after notchplasty performed during ACLR, and minimal bone regrowth 1 year after notch-plasty was observed.²⁷ Although this certainly requires further study, it serves as an example of how these factors may prove modifiable and how knowledge of them can aid in the risk reduction of a CACL injury.

CONCLUSION

This study of risk factors for CACL injury after a unilateral ACL injury confirmed prior reports that a decreased femoral notch width is associated with increased risk of CACL injury, while geometry of the ACL (ie, the volume and cross-sectional area of the ACL) was not associated with risk of injury to this important stabilizing structure of the knee. The current study also identified new risk factors associated with increased risk of CACL injury. These included a decreased height of the medial tibial spine, a decreased medial-lateral directed width of the lateral tibial spine, and a decreased thickness of the articular cartilage located at the posterior region of the medial tibial plateau. These lend support to the hypothesis that geometric features of the articular surfaces and femoral notch that surround the ACL are associated with increased risk of injury to this ligament, but the geometry of this important stabilizing structure of the knee (eg, the volume and cross-sectional area of the ACL) does not influence risk of injury among female athletes.

Acknowledgments

One or more of the authors has declared the following potential conflict of interest or source of funding: Support for this research was received from the following grants: National Institutes of Health - National Institute of Arthritis and Musculoskeletal and Skin Diseases 5RO1-AR050421 and DOE SC0001753.

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Figure 1.

On the left is a coronal-oblique view of the femoral intercondylar notch seen on magnetic resonance imaging (MRI). The measurements were made using the most anterior MRI slice that contained the entire anterior cruciate ligament (ACL) in a plane that was parallel to the ACL. The ACL is outlined in white. The femoral notch width measured at the anterior attachment of the ACL (NW_AA) and at the outlet of the femoral notch (NW_O) are identified on the MRI. On the right is a view of the knee that identifies the same femoral notch measurements.

Figure 2.

Lateral view of the medial tibial compartment. The height of the articular cartilage located under the posterior meniscal horn (Med_CBH) was measured at the most posterior aspect of the meniscus. The magnetic resonance imaging (MRI) data were acquired in the coordinate system of the scanner, and since the position of the knee relative to the scanner varied between knees and study participants, the measurements of joint geometry were not acquired directly from the raw MRI. Instead, a 3-dimensional coordinate system was located in the tibia with a reproducible and reliable technique, and the 3-dimensional geometry of the entire tibial subchondral bone and articular cartilage surfaces was digitized. Measurement of medial cartilage bone height was characterized 3-dimensionally in the tibial coordinate system. The white outline seen in the lower right panel indicates the profiles of the posterior horn of the meniscus, the surface of the tibial articular cartilage, and the subchondral bone/articular cartilage interface.

Figure 3.

Posterior view of the tibial plateau. The medial tibial spine height ($M_{ed}Height$) was measured from the peak of the medial tibial spine to the point of maximum concavity in the medial compartment of the tibia. The medial-lateral width of the lateral tibial spine ($L_{at}Width$) was measured as the medial-lateral distance between the peak of the lateral tibial spine and the point of maximum concavity in the lateral compartment of the tibia. The magnetic resonance imaging (MRI) data were acquired in the coordinate system of the scanner, and since the position of the knee relative to the scanner varied between knees and study participants, the measurements of joint geometry were not acquired directly from the raw MRI. Instead, a 3-dimensional coordinate system was located in the tibia with a reproducible and reliable technique, and the 3-dimensional geometry of the entire tibial subchondral bone and articular cartilage surfaces was digitized and expressed in the tibial coordinate system. Measurement of medial spine height and lateral spine width was characterized 3-dimensionally in the tibial coordinate system.

TABLE 1Subject Demographics^a

	Mean	SD	Minimum	Maximum
Height, cm	167.8	6.7	154.9	180.3
Weight, kg	65.9	9.7	50.3	90.7
Age at time of first ACL injury, y	17.45	2.15	13.20	21.89
Age at final follow-up, y	20.28	2.67	15.18	25.21
Follow-up interval, mo	33.9	12.6	7.3 ^b	59.7

^a A total of 62 subjects were enrolled, and we were unable to make contact with 7 of these individuals at follow-up. Included are the demographic characteristics for the cohort of subjects who were enrolled, followed (n = 55), and used in the data analysis. ACL, anterior cruciate ligament.

^b When excluding the subjects who suffered a graft injury, the minimum follow-up is 23.9 months.

TABLE 2

Summary Statistics for the 36 MRI-Based Measurements That Were Acquired in 3 Dimensions and Used to Characterize Geometry of the Articular Structures of the Knee and ACL^a

Knee Structures Characterized	Variable Measured	Mean	SD	Minimum	Maximum
Tibial spines (medial and lateral)	M _{ed} VOL, mm ³	261.2	100.5	27.2	550.9
	M _{ed} Height, ^b mm	9.7	0.9	7.7	11.9
	M _{ed} Width, mm	17.1	1.7	13.0	21.0
	M _{ed} Length, mm	32.6	5.2	12.0	40.0
	M _{ed} CG location, mm	0.7	2.1	-3.7	4.9
	M _{ed} Peak location, mm	-2.0	1.7	-6.0	3.0
	L _{at} VOL, mm ³	537.0	175.7	227.2	907.4
	L _{at} Height, mm	7.7	1.2	5.2	10.6
	L _{at} Width, ^b mm	16.3	1.9	13.0	22.0
	L _{at} Length, mm	27.2	5.5	19.0	44.0
Tibia articular cartilage surface and menisci (medial and lateral)	L _{at} CG location, mm	-5.9	1.5	-9.3	-2.4
	L _{at} Peak location, mm	-3.4	1.8	-7.0	0.0
	L _{at} MCS, deg	0.4	3.5	-7.2	7.5
	L _{at} PCS, deg	13.2	6.2	-1.3	26.8
	L _{at} MCA, deg	40.6	5.1	25.0	55.2
	L _{at} MBA, deg	27.9	4.2	17.5	36.6
	L _{at} MCH, mm	6.3	0.7	4.8	7.9
	L _{at} CBH, mm	2.7	0.6	1.8	4.5
	M _{ed} MCS, deg	-0.6	2.7	-6.8	4.4
	M _{ed} PCS, deg	-6.2	3.2	-12.6	1.2
	M _{ed} MCA, deg	21.7	3.2	15.9	28.8
	M _{ed} MBA, deg	24.2	2.8	17.7	29.9
	M _{ed} MCH, mm	5.1	0.8	3.6	7.1
	M _{ed} CBH, ^b mm	1.6	0.4	0.9	2.7

Knee Structures Characterized		Variable Measured	Mean	SD	Minimum	Maximum
Femoral notch and ACL		NW_AA, ^b mm	17.8	1.9	13.6	22.8
		NW_O, ^b mm	14.5	2.6	8.8	22.9
		NW_I, mm	21.7	2.2	16.3	27.0
		NW_MA, mm	19.4	2.2	14.6	25.0
		N_Vol, mm ³	6122.8	1010.7	4349.7	8468.0
Tibia plateau subchondral bone		Ridge, mm	3.7	1.1	1.2	5.9
		ACL_Vol, mm ³	998.5	217.8	551.2	1494.8
		ACL_CSA, cm ²	0.4	0.1	0.2	0.7
		MTD, mm	1.3	0.4	0.6	2.3
		MTS, deg	-3.3	2.7	-9.5	2.4
		LTS, deg	-1.3	3.0	-7.5	6.6
		CTS, deg	0.8	1.8	-3.6	4.5

^aThere were 12 measurements of the tibial spines (6 lateral [L_at] and 6 medial [M_ed]), and these included the volume (VOL), height (Height), medial-lateral width (Width), anterior-posterior length (Length), spine peak location (Peak location), and center of gravity location (CG location) relative to the origin of the tibial coordinate system. There were 12 measurements of geometry of the tibial articular cartilage surface and menisci (6 lateral and 6 medial). These included the medial and posterior cartilage slopes (MCS and PCS, respectively) of the articular cartilage surface, posterior meniscus wedge angle measured relative to the articular cartilage surface (MCA) and relative to the subchondral bone (MBA), height of the posterior meniscus measured relative to articular cartilage surface (MCH), and height of the posterior cartilage surface measured relative to subchondral bone (CBH). Eight measurements were used to characterize geometry of the femoral notch and anterior cruciate ligament (ACL). These included femoral notch volume (N_Vol); femoral notch width at 4 locations (the anterior attachment of the ACL to the lateral femoral condyle [NW_AA], at the inlet of the femoral notch [NW_I], at the middle of the ACL attachment [NW_MA], and at the outlet of the femoral notch [NW_O]); ACL volume (ACL_Vol); and ACL cross-sectional area (ACL_CSA). There were 4 measurements that characterized geometry of the tibial plateau subchondral bone, and these included the depth of the medial tibia plateau (MTD); the posterior-inferior directed slopes of the medial and lateral plateaus (MTS and LTS, respectively); and the coronal tibial slope (CTS).

^bIndicates variables that had a significant association with risk of contralateral anterior cruciate ligament (CACL) injury.

TABLE 3Significant Associations with Risk of CACL Injury From the Univariate Cox Regression Analysis^a

Variable	HR	HR 95% CI	P Value
NW_AA (1.9 mm)	2.05	1.15–3.66	.016
NW_O (2.6 mm)	1.88	1.03–3.46	.041
M _{ed} CBH (0.4 mm)	2.15	1.17–3.94	.014
L _{at} Width (1.9 mm)	3.59	1.07–12.10	.039
M _{ed} Height (0.9 mm)	1.75	1.01–3.02	.045

^aData shown are the hazard ratios (HRs) with corresponding 95% CIs, which indicate the increase in risk of contralateral anterior cruciate ligament (CACL) injury per 1 SD decrease of each variable. Significance determined as $P < .05$. The significant variables included the femoral notch width at the anterior attachment of the ACL (NW_AA); the femoral notch width at the anterior outlet of the notch (NW_O); medial tibial spine height (M_{ed}Height); lateral tibial spine width (L_{at}Width); and the medial tibial cartilage bone height (M_{ed}CBH).