Stenotic Intercondylar Notch as a Risk Factor for Physeal-Sparing ACL Reconstruction Failure: A Case-Control Study

ABSTRACT

Introduction: Identifying risk factors is crucial for developing strategies that minimize reinjury after anterior cruciate ligament reconstruction (ACLR). This study aims to determine whether certain features of intercondylar notch geometry are associated with failure of physeal-sparing ACLRs in skeletally immature athletes.

Methods: Nine failed physeal-sparing ACLRs were compared with a control subject group of 15 age- and sex-matched intact physeal-sparing ACLRs. Notch width index (NWI), notch angle (NA), and intercondylar notch roof inclination angle (RA) were measured on preoperative MRIs.

Results: Median NWI was smaller in the failed ACLR versus control subject group in coronal (0.23 versus 0.27; \( P < 0.05 \)) and axial planes (0.25 versus 0.27; \( P = 0.055 \)). Median NA was smaller in the failed ACLR versus control subject group in coronal (49.6 versus 61.0°; \( P < 0.05 \)) and axial planes (48.6° versus 54.9°; \( P < 0.05 \)). Median RA was steeper in the failed ACLR versus control subject group (132.0° versus 125.7°; \( P < 0.05 \)).

Conclusion: NWI, NA, and RA were associated with ACLR failure in skeletally immature patients undergoing physeal-sparing reconstruction. A smaller, narrower, and steeper notch may predispose these patients to reinjury.

A nterior cruciate ligament (ACL) injuries are increasingly common in children and adolescents, likely because of an increase in participation in athletic activities coupled with increased recognition of these injuries.\(^1,2\) According to the Danish Knee Ligament Reconstruction Registry, 6% of all ACL reconstructions are performed in patients younger than 15 years of age.\(^3\) ACL tears are notable injuries for skeletally immature athletes because they increase the risk of subsequent chondral and meniscal injury.\(^3-6\)
As a result, the treatment strategy is to perform early ACL reconstruction (ACLR).

Several studies have reported satisfactory objective and subjective outcomes after ACLR in children and adolescents, yet alarmingly, the risk for revision has been estimated as 2.5 to 13× higher in patients younger than 20 years old versus their adult counterparts.6–9 Interestingly, there may be a specific range of pediatric ages that are at greatest risk. In a study investigating the rates of ACLR failure in a pediatric cohort, patients with a median age of 14.3 had a 20% failure rate, whereas similar groups with median ages of 12 and 16.2 experienced failure rates of only 6%.10 Despite efforts to optimize surgical treatment, failure of ACL grafts after a successful surgery remains a concern because of the high health and financial burdens. Because revision ACLRs produce inferior results compared with primary ACLRs,10–12 prevention is the most effective strategy to avoid reinjury. A thorough understanding of the modifiable (extrinsic) and nonmodifiable (intrinsic) risk factors is crucial to developing strategies to minimize reinjury.

Intrinsic and extrinsic risk factors for tearing a native ACL have been studied extensively. Nonmodifiable or intrinsic risk factors include female sex, increased posterior tibial slope, recurvatum, Beighton score >4, grade 3 pivot, anterior translation >7 mm, ACL size, alignment (fixed valgus), and age (eighth and ninth graders are a particularly high risk group).10 Modifiable or extrinsic risk factors include neuromuscular factors (dynamic valgus, quad/hamstring ratios, and gluteus weakness) and the shoe-surface interface.13–16 Several studies have attempted to determine the contribution of intercondylar bony anatomy to the risk of ACL tears, with conflicting results. In 1938, Palmer et al17 were the first to suggest that a narrow intercondylar notch may increase the risk of ACL injury because the anatomy causes the ACL to contact the top of the intercondylar notch in full extension and to stretch over the inner margin of the lateral femoral condyle in flexion. In the pediatric population, where growth plates have not yet fused, notch morphology may be an especially important risk factor for ACL tears.18

Literature regarding notch geometry has focused predominantly on notch width and notch width index (NWI). Multiple studies support the relationship between narrow intercondylar notch and ACL tears; some reports suggest cutoff values for NWI that indicate increased risk,18–22 whereas others have shown no notable correlation between NWI and tear risk.21,23–25 The influence of notch geometry on the risk of ACL tears has also been assessed in pediatric populations, where studies suggest that narrow notch sizes are associated with higher risk of ACL rupture.18,24,26,27 Importantly, other novel radiographic parameters, such as the intercondylar notch roof inclination angle (RA) and notch angle (NA), have been reported as possible nonmodifiable factors for ACL injuries, with conflicting reports.28–30

The aim of this study is to determine whether certain elements of the intercondylar notch geometry are associated with failure of physeal-sparing ACLRs in skeletally immature athletes. Our hypothesis is that a stenotic and steeper notch increases the risk for failure. This is the first study to evaluate notch dimensions as risk factors for physeal-sparing ACLR failure in skeletally immature athletes.

**Methods**

Nine failed physeal-sparing ACLRs were identified among a cohort of skeletally immature patients treated consecutively by the same surgical team between 2011 and 2014 (Figure 1). For all cases, the team used a retrograde tunnel drilling approach to create an all-epiphyseal femoral socket. All grafts were fixed with cortical buttons in the femur and tibia. All individuals in the cohort followed instructions to abstain from playing sports until at least 12 months after surgery. ACLR reinjury was identified clinically by an attending surgeon and confirmed using MRI. All patients were reconstructed using hamstring autografts, with a median diameter of 9.4 mm for the failed ACLR group (range = 7.5 to 11) and 9.0 mm for the control subject group (range = 7 to 11).

Failures were compared with an age- and sex-matched control subject group of 15 intact physeal-sparing ACLRs from the same initial cohort who had returned to athletics with a minimum of 2 years clinical and radiological follow-up (Figure 1). NWI and NA were measured in coronal and axial proton density-weighted MRI studies using a previously reported method.31,32 The intercondylar notch width was measured on the coronal and axial MRI slices that best showed the popliteus groove. NWI is the ratio of the notch width to the bicondylar width on the same image slice (Figure 2, A and D). NA was also measured on the same coronal and axial images (Figure 2, B and E). RA was measured on a midsagittal proton density-weighted MRI images and defined as the obtuse angle between a line parallel to the long axis of the knee and a line parallel to the...
intercondylar roof or Blumensaat line (Figure 2C). Measurements were made by a single physician researcher. Chi-squared and Wilcoxon tests with an alpha level of 0.05 were used for statistical analysis (STATA software, version 14, StataCorp LP).

Results

Both study groups had comparable distributions of age and sex (Table 1). Median coronal NWI in the failed ACLR group (0.23; range \(= 0.16 \text{ to } 0.27\)) was markedly

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**Figure 1**

A flow chart showing how failed anterior cruciate ligament reconstruction and control subject groups were selected from the initial cohort.

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**Figure 2**

Radiographs showing that the notch width index is the ratio of the intercondylar notch width to the bicondylar width of the distal femur at the level of the popliteus groove in coronal (A) and axial (D) views. The notch angle is measured at the level of the popliteus groove, tracing the opening of the intercondylar notch in coronal (B) and axial (E) views. Roof inclination angle is the obtuse angle formed by the intersection of a line over the Blumensaat line and a line parallel to the long axis of the knee in the midsagittal view (C).
smaller than in the control subject group (0.27; range = 0.20 to 0.31). In the axial plane, although the failed ACLR group NWI (0.25; range = 0.20 to 0.29) was also smaller than in the control subject group (0.27; range = 0.21 to 0.33), the association was not statistically significant (P value = 0.055). Median NA in the failed ACLR group was markedly smaller than in the control subject group in both the coronal (49.6°; range = 35.3° to 57.9° versus 61.0°; range = 43.8° to 71.9°) and axial planes (48.6°; range = 37.4° to 55.3° versus 54.9°; range = 41.9° to 71.9°). Median inclination of the RA was markedly steeper in the failed ACLR group (132.0°; range 147.1° to 123.4°) compared with the control subject group (125.7°; 146.8° to 113.9°) (Table 2).

**Discussion**

All three measurements used to assess intercondylar notch morphology (NWI, NA, RA) were markedly associated with ACLR failure, suggesting that in patients undergoing a physeal-sparing ACLR and a narrow and steeper notch predisposes to reinjury. Most of the literature studying notch geometry and ACL tears has focused on native ACL injuries in adult populations. This is the first study that evaluates intercondylar notch morphology as a risk factor for ACLR failure in a pediatric cohort that underwent physeal-sparing surgery.

Reinjury after ACLR in pediatric patients is associated with high morbidity, inferior long-term outcomes, and a long and costly rehabilitation. Importantly, patients younger than 20 years old are far more likely to experience ACLR failure than their adult counterparts, and eighth and ninth graders are at particularly high risk. As a result, the identification of risk factors in this population and subsequent application of preventive measures is critical. A common theory regarding the high rate of reinjury in teenagers was that young athletes were encouraged to return to contact sports prematurely, but according to the Danish Knee Ligament Reconstruction Registry, a large proportion of failures occurred after the first year of recovery, which is the recommended time for abstaining from athletics after ACLR surgery.

Most evidence indicates that a narrow notch may put the ACL at a greater risk of initial injury. A meta-analysis by Zeng et al concluded that a lower NWI or notch width stenosis predisposes an individual to ACL injury. This association has also been reported in pediatric populations, concordant with the findings of this study. Domzalski et al reviewed 46 MRIs of children and adolescents with torn ACLs and compared them with 44 healthy control subjects. Similar to this study, they found that the NWI was markedly larger in intact knees (0.27) versus joints with torn ACLs (0.24). Swami et al compared three-dimensional notch volumes in 50 MRI studies of pediatric patients with torn ACLs versus healthy control subjects and showed that three-dimensional notch volume was markedly smaller in knees with ACL tears than in intact knees.

**Table 1. Demographic Characteristics Comparison Between Failed ACLR Group and Control Group**

|                      | Failed ACLR Group (n = 9) | Control Subject Group (n = 15) | P   |
|----------------------|--------------------------|--------------------------------|-----|
| Chronological age, median (range) | 14.9 (13.3-17.1)         | 14.0 (12.4-16.7)                | 0.107 |
| Bone age, median (range)           | 14.0 (12.0-15.0)         | 13.5 (12.0-16.6)                | 0.264 |
| Male: female                    | 7: 2                     | 12: 3                          | 0.897 |

ACLR = anterior cruciate ligament reconstruction

**Table 2. MRI Knee Measurement Comparison Between Failed ACLR Group and Control Group**

|                     | Failed ACLR Group         | Control Subject Group          | P   |
|---------------------|---------------------------|--------------------------------|-----|
| Coronal NWI         | 0.23 (0.16-0.27)          | 0.27 (0.20-0.31)               | 0.017 |
| Axial NWI           | 0.25 (0.20-0.29)          | 0.27 (0.21-0.33)               | 0.055 |
| Coronal NA          | 49.6° (35.3°-57.9°)       | 61.0° (43.8°-71.9°)            | 0.008 |
| Axial NA            | 48.6° (37.4°-55.3°)       | 54.9° (41.9°-71.9°)            | 0.036 |
| RA                  | 132.0° (147.1°-123.4°)    | 125.7° (146.8°-113.9°)         | 0.021 |

ACLR = anterior cruciate ligament reconstruction, NWI = notch width index, NA = notch angle, RA = notch roof angle

Data shown as median (range).
albeit a 2-dimensional feature, correlates with ACLR failure and support the conclusion that less space in the notch may be a risk factor for reinjury.

Some authors have attempted to set cutoff NWI values that define notch stenosis. Domzalski et al.\textsuperscript{18} in their pediatric MRI-based study, proposed an average NWI of 0.24 as a risk factor for ACL tears. Souryal et al.\textsuperscript{25} determined that a NWI of 0.231 ± 0.044 should be considered a normal intercondylar notch ratio and that values < 0.2 represent risk for ACL injury. Other reports have established the cutoff value for NWI as 0.25 or 0.21, ranges that would be reasonable given the values considered a normal intercondylar notch ratio and that the risk of injury.29,35 whereas others do not report a notable association.28 The results of this study support the potential role of NA as a risk factor because the average NA of the failed ACLR group was fewer than 50\(^{\circ}\), whereas the control subject group average was above that cutoff. Further studies are needed to establish whether an association between a smaller NA and ACL injuries exists.

The inclination of the intercondylar notch roof angle is a novel radiographic parameter that describes the orientation of the notch in relation to the distal femoral metaphysis. Some studies have evaluated this metric, but using varied and nonstandardized methodologies, which makes comparison difficult. The orientation of the roof angle might predispose to graft failure by impinging the tissue or by leading to misplacement of the femoral tunnels.\textsuperscript{30} RA, measured as previously described, ranges from 135\(^{\circ}\) to 147\(^{\circ}\) in reports based on plain radiographs, MRIs, and cryosectional anatomic studies.\textsuperscript{38} The results in our study likely differ from previously reported RA values because RA is a relatively new parameter, and there is not yet a consensus regarding how to best measure it. Some publications use a line parallel to the posterior femoral cortex, whereas other studies, such as ours, use the long axis of the knee. Extension lag in injured knees might also affect our measurements of RA. Further studies are needed to standardize how to measure the RA and test the validity and reproducibility of this metric.

This study has several limitations. Many patients were excluded from the study because they had fewer than two years of follow-up or had two years of clinical follow-up but lacked follow-up imaging, which limited the size of the cohort. Additional patients were excluded because they did not undergo a physeal-sparing surgical approach. Moreover, measurements were performed by one observer, which did not allow reliability testing, although NWI and NA have been validated previously in pediatric patients.29,39,40 In addition, the validity and reproducibility of roof angle parameters have not yet been evaluated. Importantly, although a larger sample size would increase the power of the study, the sample used in this study was sufficient to generate statistically significant results while restricting the injured cohort to age- and sex-matched comparisons.

**Conclusion**

This study is the first to suggest that NWI and NA may be predictors for physeal-sparing ACLR failure in skeletally immature athletes. A steeper inclination of the notch roof was also related to ACLR failure in this population, possibly because of altered biomechanics of the reconstructed ACL.
Stenotic Intercondylar Notch

References

1. Dodwell ER, Lamont LE, Green DW, Pan TJ, Marx RG, Lyman S: 20 years of pediatric anterior cruciate ligament reconstruction in New York State. Am J Sports Med 2014;42:675-680.

2. Werner BC, Yang S, Looney AM, Gwathmey FW Jr: Trends in pediatric anterior cruciate ligament injury and reconstruction. J Pediatr Orthop 2016;36:447-452.

3. Fauno P, Rahr-Wagner L, Lind M: Risk for revision after anterior cruciate ligament reconstruction is higher among adolescents: Results from the Danish Registry of knee ligament reconstruction. Orthop J Sports Med 2014;2:1-7.

4. Lohmander LS, Ostenberg A, Englund M, et al: High prevalence of knee osteoarthritis, pain, and functional limitations in female soccer players twelve years after anterior cruciate ligament injury. Arthritis Rheum 2004;50:3145-3152.

5. Nebelung W, Wuschech H: Thirty-five years of follow-up of anterior cruciate ligament-deficient knees in high-level athletes. Arthroscopy 2005;21:696-702.

6. von Porat A, Roos EM, Roos H: High prevalence of osteoarthritis 14 years after an anterior cruciate ligament tear in male soccer players: A study of radiographic and patient relevant outcomes. Ann Rheum Dis 2004;63:269-273.

7. Lind M, Lund B, Fauno P, Said S, Miller LL, Christiansen SE: Medium to long-term follow-up after ACL revision. Knee Surg Sports Traumatol Arthrosc 2012;20:166-172.

8. Magnusson RA, Lawrence JT, West RL, Toth AP, Taylor DC, Garrett WE: Graft size and patient age are predictors of early revision after anterior cruciate ligament reconstruction with hamstring autograft. Arthroscopy 2012;28:526-531.

9. Cordasco FA, Mayer SW, Green DW: All-inside, all-epiphyseal anterior cruciate ligament reconstruction in skeletally immature athletes: Return to sport, incidence of second surgery, and 2-year clinical outcomes. Am J Sports Med 2017;45:856-863.

10. Cordasco FA, Black SR, Price M, et al: Return to sport and reoperation rates in patients under the age of 20 after primary anterior cruciate ligament reconstruction: Risk profile comparing 3 patient groups predicated upon skeletal age. Am J Sports Med 2019;47:628-639.

11. Kaeding CC, Pedroza AD, Reinke EK, Huston LJ, Spindler KP: Risk factors and predictors of subsequent ACL injury in either knee after ACL reconstruction: Prospective analysis of 2488 primary ACL reconstructions from the MOON cohort. Am J Sports Med 2015;43:1583-1590.

12. Dekker T, Godin J, Dale M, Garret W, Taylor D, Riboh J: Return to sport after pediatric anterior cruciate ligament reconstruction and its effect on subsequent anterior cruciate ligament injury. J Bone Joint Surg 2017;99:897-904.

13. Shen L, Jin ZG, Dong QR, Li LB: Anatomical risk factors of anterior cruciate ligament injury. Chin Med J 2018;131:2960-2967.

14. Gwinn DE, Wickersen JH, McDevitt ER, et al: The relative incidence of anterior cruciate ligament injury in men and women at the United States Naval Academy. Am J Med Sports 2000;28:98-102.

15. Al-Saeed O, Brown M, Athyral R, Sheikh M: Association of femoral intercondylar notch morphology, width index and the risk of anterior cruciate ligament injury. Knee Surg Sports Traumatol Arthrosc 2013;21:678-682.

16. Blisson LJ, Gurske-DePerio J: Axial and sagittal knee geometry as a risk factor for noncontact anterior cruciate ligament tear: A case-control study. Arthroscopy 2010;26:901-906.

17. Palmer I: On the injuries to the ligaments of the knee joint: A clinical study. 1938. Clin Orthop Relat Res 2007;454:17-22.

18. Domzański M, Grzelak P, Gabos P: Risk factors for anterior cruciate ligament injury in skeletal immature patients: Analysis of intercondylar notch width using magnetic resonance imaging. Int Orthop 2010;34:703-707.

19. Fernández-Jaén T, López-Alcorocho JM, Rodri guez-Iñigo E, Castellán F, Hernández JC, Guillen-Garcia P: The importance of the intercondylar notch in anterior cruciate ligament tears. Orthop J Sports Med 2015;3:2325967115597882.

20. Hoteya K, Kato Y, Motojima S, et al: Association between IGN narrowing and bilateral ACL injury in athletes. Arch Ortho Trauma Surg 2011;131:371-376.

21. Ireland ML, Ballantyne BT, Little K, McClay IS: A radiographic analysis of relationship between the size and shape of IGN and ACL injury. Knee Surg Sports Traumatol Arthroscos 2001;9:200-205.

22. La prade RF, Burnett QM: Femoral intercondylar notch stenosis and correlation to anterior cruciate ligament injuries. Am J Sports Med 1994;22:198-202.

23. Lombardo S, Sethi PM, Starkey C: Intercondylar notch stenosis is not a risk factor for anterior cruciate ligament tears in professional male basketball players: An 11-year prospective study. Am J Sports Med 2005;33:29-34.

24. Souyal TO, Freeman TR: Intercondylar notch size and anterior cruciate ligament injuries in athletes. A prospective study. Am J Sports Med 1993;21:535-539.

25. Teitz CG, Lind BK, Sacks BM: Symmetry of the femoral notch width index. Am J Sports Med 1997;25:687-690.

26. Swami VG, Mabee M, Hui C, Jaremko JL: Three-dimensional intercondylar notch volumes in a skeletally immature pediatric population: A magnetic resonance imaging based anatomic comparison of knees with torn and intact anterior cruciate ligaments. Arthroscopy 2013;29:1954-1962.

27. Kocher MS, Mandiga R, Klingele K, et al: Anterior cruciate ligament injury versus tibial spine fracture in the skeletally immature knee. A comparison of skeletal maturation and notch width index. J Pediatr Orthop 2004;24:185-189.

28. Stein V, Li L, Guermazi A, et al: The relation of femoral notch stenosis to ACL tears in persons with knee osteoarthritis. Osteoarthritis Cartilage 2010;18:192-199.

29. Alentorn-Geli E, Pelfort X, Mingo F, et al: An evaluation of the association between radiographic intercondylar notch narrowing and anterior cruciate ligament injury in men: The notch angle is a better parameter than notch width. Arthroscopy 2015;31:2004-2013.

30. Schefel PT, Henninger HB, Burks RT: Reconstruction relationship of the intercondylar roof and the tibial footprint of the ACL: Implications for ACL. Am J Sports Med 2013;41:396-401.

31. Herzog RJ, Silliman JF, Hutton K, Rodkey WG, Steadman JR: Measurements of intercondylar notch by plain film radiography and magnetic resonance imaging. Am J Sports Med 1994;22:204-210.

32. Kropf EJ, Shen W, van Eck CF, Musahl V, Irrgang JJ, Fu FH: ACL–PCL interchangeability and intercondylar notch impingement: Magnetic resonance imaging of native and double-bundle ACL reconstructed knees. Knee Surg Sports Traumatol Arthrosc 2013;21:720-725.

33. Zeng C, Gao SG, Wei J, et al: The influence of the intercondylar notch dimensions on injury of the anterior cruciate ligament: A meta-analysis. Knee Surg Sports Traumatol Arthrosc 2013;21:804-815.

34. Sonnery-Cottet B, Archbold P, Cucurullo T, et al: The influence of the tibial slope and the size of the intercondylar notch on rupture of the anterior cruciate ligament. J Bone Joint Surg Br 2011;93:1475-1478.
35. Anderson AF, Lipscomb AB, Liudahl KJ, Addlestone RB: Analysis of the intercondylar notch by computed tomography. Am J Sports Med 1987; 15:547-552.

36. Charlton WP, St John TA, Ciccotti MG, Harrison N, Schweitzer M: Differences in femoral notch anatomy between men and women: A magnetic resonance imaging study. Am J Sports Med 2002;30:329-333.

37. Hefzy MS, Grood ES: Sensitivity of insertion locations on length patterns of anterior cruciate ligament fibers. J Biomech Eng 1986;108:73-82.

38. Howell SM, Barad SJ: Knee extension and its relationship to the slope of the intercondylar roof. Am J Sports Med 1995;23:288-294.

39. Domzalski ME, Keller MS, Grzelak P, Gabos P: MRI evaluation of the development of intercondylar notch width in children. Surg Radiol Anat 2015;37:609-615.

40. Shen X, Xiao J, Yang Y, Liu T, Chen S, Gao Z: Multivariable analysis of anatomic risk factors for anterior cruciate ligament injury in active individuals. J Arch Orthop Trauma Surg 2019;139:1277-1285.