ACTA ORTHOPAEDICA et TRAUMATOLOGICA TURCICA

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Invited Review

The effect of bony morphology on anterior cruciate ligament injury and surgery

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ARTICLE INFO

Article history:
Submitted January 9, 2024
Accepted March 7, 2024
Publication Date April 26, 2024

Keywords:
Bony morphology
Anterior cruciate ligament injury
Tibial slope
Alignment
Osteotomy

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ABSTRACT

The exploration of underlying biological risk factors for anterior cruciate ligament (ACL) injury has generated a substantial body of literature describing the role of bony morphology of the knee. Morphological risk factors, such as poor tibiofemoral joint congruity, a narrow femoral intercondylar notch, and an increased posterior tibial slope (PTS), have been implicated in contributing to knee instability and biomechanical abnormalities. Additionally, investigations into sex-specific differences in bony morphology have unveiled distinct risk profiles for males and females. In light of these findings, surgical considerations for individuals with high-risk bony morphology have been developed. Procedures like anterior closing wedge high tibial osteotomy, aiming to address increased PTS, and lateral extra-articular tenodesis for patients with specific risk factors, have been established. The aim of this review is to provide an overview of the current evidence describing the relationship between bony morphology and ACL injury. Moreover, this review aims to discuss the surgical management and outcomes concerning patients exhibiting high-risk anatomic features.

Introduction

Investigations of underlying biologic risk factors for anterior cruciate ligament (ACL) injury have resulted in a substantial body of literature describing the role of bony morphology. Tibiofemoral congruity, in particular, has been shown to contribute to knee stability and subsequent biomechanical abnormalities, including an increased grade of pivot shift.[1,2] Commonly reported morphologic features that increase the risk of ACL injury or graft failure following ACL reconstruction (ACLR) include poor tibiofemoral joint congruity, a narrow intercondylar notch, and an increased posterior tibial slope (PTS).[3-7] Consequently, preoperative planning often involves extensive imaging and considerations regarding the bony anatomy, specifically in revision settings. Additionally, procedures such as PTS-reducing osteotomies and lateral extra-articular tenodesis (LET) have been developed and described to successfully correct predisposing anatomic risk factors for recurrent ACL graft failure. This has sparked a growing interest in assessing bony morphology among patients with ACL injuries. Therefore, the purpose of this review is to provide an overview of the current evidence describing the relationship between bony morphology and ACL injury and discuss the surgical management and outcomes of patients with high-risk anatomic features.

Specific morphological risk factors

Femoral morphology

Numerous studies have delved into the examination of how distal femoral morphology influences knee kinematics, the risk of ACL injury, and the observed rotatory knee laxity subsequent to an ACL injury.[2,6,8-14] The femoral notch has been categorized into 3 distinct shapes: A-, U-, and W-shaped.[8] An "A-shaped" notch is visually defined as narrowing from the base to midsection and reaching the apex. Conversely, a "U-shaped" notch is characterized by a midsection that does not taper from the base. Furthermore, a "W-shaped" notch not only shares characteristics with a "U-shaped" notch but also exhibits 2 apparent apices rather than the conventional flat roof.[10]

It has been reported that the risk of ACL injury is higher in an A-shaped notch, where the notch roof is narrow, and anatomical femoral tunnel placement may be technically difficult (Table 1).[8-10] In order to better evaluate the effect of femoral notch morphology on ACL injury risk, magnetic resonance imaging (MRI) measurement methods such as "notch width" and "notch width index" have been described.[6,14] In the T1 coronal MRI section where the distal borders of the femoral condyle are most prominent, the bicondylar width of the femur can be measured by drawing a line from the popliteal groove parallel to the line passing through the distal femoral condyles

Cite this article as: *Kaarre J, Ahrendt G, Giusto JD, Özbek EA, Apseloff NA, Musahl V. The effect of bony morphology on anterior cruciate ligament injury and surgery. Acta Orthop Traumatol Turc., 2024;58(2):83-88.*

DOI: 10.5152/j.aott.2024.24005

Table 1. Morphologic risk factors for ACL injury and corresponding treatment options

Bony morphologic risk factor	Surgical management
Narrow femoral notch	• Consider using a smaller diameter ACL graft
"A" shaped femoral notch	• Consider notchplasty
Increased PTS	• ACW-HTO for PTS >12° (typically in revision setting) • LET (typically in revision setting, but may be considered in certain primary cases)
Lateral tibial plateau convexity	• Currently no known corrective surgery
Lateral femoral condyle index	• Currently no known corrective surgery

ACL, anterior cruciate ligament; ACW-HTO, anterior closing wedge high tibial osteotomy; LET, lateral extra-articular tenodesis; PTS, posterior tibial slope.

and ending at the medial border of the medial femoral condyle. The length of the portion of the intercondylar notch within the bicondylar line is the "notch width." The "notch width index" measurement is obtained by dividing the "notch width" by the length of the bicondylar line (Figure 1).[9,10] However, even though various cutoff values have been reported for these measurements, there is a lack of consensus on whether a narrow notch width or a low notch width index is associated with ACL injury. While previous literature has demonstrated an association between ACL injuries and narrow femoral intercondylar notch, smaller notch width index, and "A" shaped notch, other literature has raised concerns about the lack of precise definitions of these anatomic risk factors.[6,9,10]

Posterior femoral condyle depth and sphericity represent additional morphological features in the distal femur that may impact knee kinematics and the risk of ACL injury. Assessing the condyle depth involves utilizing the "lateral femoral condyle (LFC) ratio," a measurement calculated on a lateral knee radiograph (Figure 2).[1,2,12] To establish the long axis of the distal femur, 2 circles separated by 5 centimeters (cm) are drawn centered on the femoral shaft. The distal circle is placed at the trochlea's most proximal aspect, and a line through both circles defines the long axis. The LFC axis is then determined by drawing a line between the lateral condyle's most posterior and anterior points. The LFC ratio is calculated by dividing the distance from the intersection of these lines to the condyle's most posterior point by the total anteroposterior diameter of the condyle.[1,2] It has been reported that ACL injuries are more frequent in individuals with an LFC ratio exceeding 63%, with a sensitivity of 77% and specificity of 72%.[1] Additionally, a high LFC ratio has been reported to contribute to increased rotatory knee laxity in ACL-injured knees.[2,12]

For evaluating posterior condyle sphericity, the "LFC index" can be calculated on T1 sagittal MRI.[2,6,11] The midsagittal plane of the LFC is defined at the popliteal femoral insertion point on a coronal T1 image. Two best-fit circles, positioned at 6 and 9 o'clock (anterior; extension circle) and 6 and 3 o'clock (posterior; flexion circle), align with the LFC's spherical shape. The LFC index is calculated by dividing the flexion circle's diameter by the extension circle's diameter.[2] When the LFC index exceeds 0.7, ACL and ACL graft rupture rates increase with a sensitivity of 78% and a specificity of 80%.[11] However, a study of 382 adult patients found no correlation between the LFC index and ACL injury,[6] while another study reported no association between the LFC index and tibial acceleration during a pivot shift.[4]

Tibial morphology

The geometry of the tibial plateau is complex, though characterized clinically by simple measurements including PTS, medial tibial plateau depth, and lateral tibial plateau convexity. These morphologic features contribute to tibiofemoral joint stability, and variation in these parameters may portend a higher intrinsic risk for ACL injury. Specifically, steep PTS,[4,7,15-19] shallow medial plateau depth,[20-22] and greater convexity of the lateral plateau[23] have been associated with increased risk of ACL injury.

Biomechanical studies have demonstrated that a steeper PTS (>12°) results in the tibia resting in an anterior position relative to the femur, increased anterior tibial translation with axial loading, and increased force across the ACL.[24-27] In ACL-deficient knees, anterior tibial translation has been shown to increase by 6 millimeters (mm) per 10° incremental increase in PTS.[28] Additionally, a high lateral plateau PTS is associated with higher-grade rotatory instability after ACL tear.[29,30] These findings support that the posterior tibial slope affects tibiofemoral joint stability.

Numerous retrospective and case-control studies have evaluated differences in PTS between ACL-injured and uninjured control cohorts. While some studies have demonstrated no significant difference in PTS between ACL-injured knees and uninjured controls,[14] 2 recent systematic reviews support PTS as a morphologic risk factor for ACL rupture.[7,15] One retrospective study compared MRIs of 100 ACL-injured knees to 100 uninjured knees and found

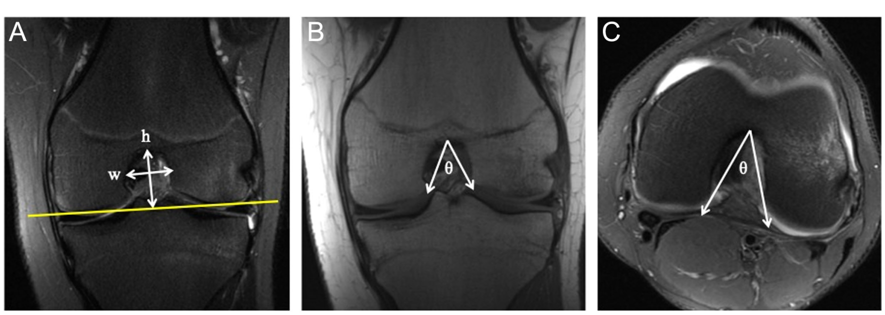

Figure 1. Femoral intercondylar notch measurements using MRI. (A) Coronal T2-weighted MRI image shows the determination of the intercondylar notch height (h) and intercondylar notch width (w). A reference axis (yellow line) using the most inferior aspect of the bilateral femoral condyles is used to draw a line to the most superior point of the notch (h). A line marking the internal borders of the notch (w) is drawn to calculate the notch width. (B) Coronal T1-weighted MRI image shows the determination of the intercondylar notch angle (θ). Two lines extending out to the distal medial and lateral notch borders are drawn to calculate the angle. (C) Axial T2-weighted MRI image shows the determination of the intercondylar notch angle (θ). Two lines extending out to the posterior aspect of the medial and lateral notch borders are drawn to calculate the angle. MRI, magnetic resonance imaging

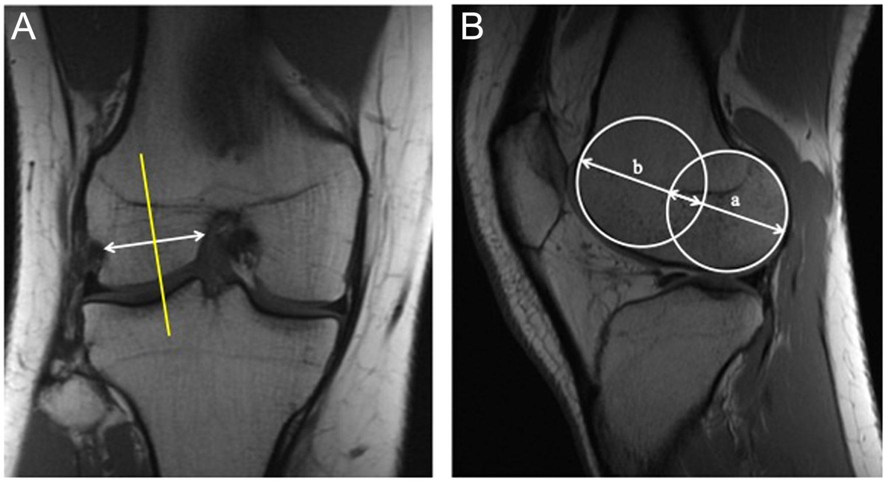

Figure 2. Lateral femoral condylar index measurement using MRI. (A) Coronal T1-weighted MRI image shows the reference axis for the middle of the lateral femoral condyle (yellow line) at the point where the popliteal groove is best visualized. (B) Sagittal T1-weighted MRI image in the plane of the reference yellow line is used to draw 2 circles: an anterior extension circle with the diameter “b” (6 and 9 o’clock position) and a posterior flexion circle with the diameter “a” (6 and 3 o’clock position). The lateral femoral condylar index is calculated by dividing diameters a/b. MRI, magnetic resonance imaging.

a significantly greater lateral tibial slope (LTS) and medial tibial slope (MTS) in ACL-injured knees compared to uninjured knees (10.4 ± 3.1 ACL-injured vs. 7.3 ± 3.4 uninjured for LTS; 9.4 ± 3.3 ACL-injured vs. 7.0 ± 3.7 uninjured for MTS).[16] In a multivariate analysis, a 1° increase in PTS was associated with an 11% increased risk of ACL injury.[18]

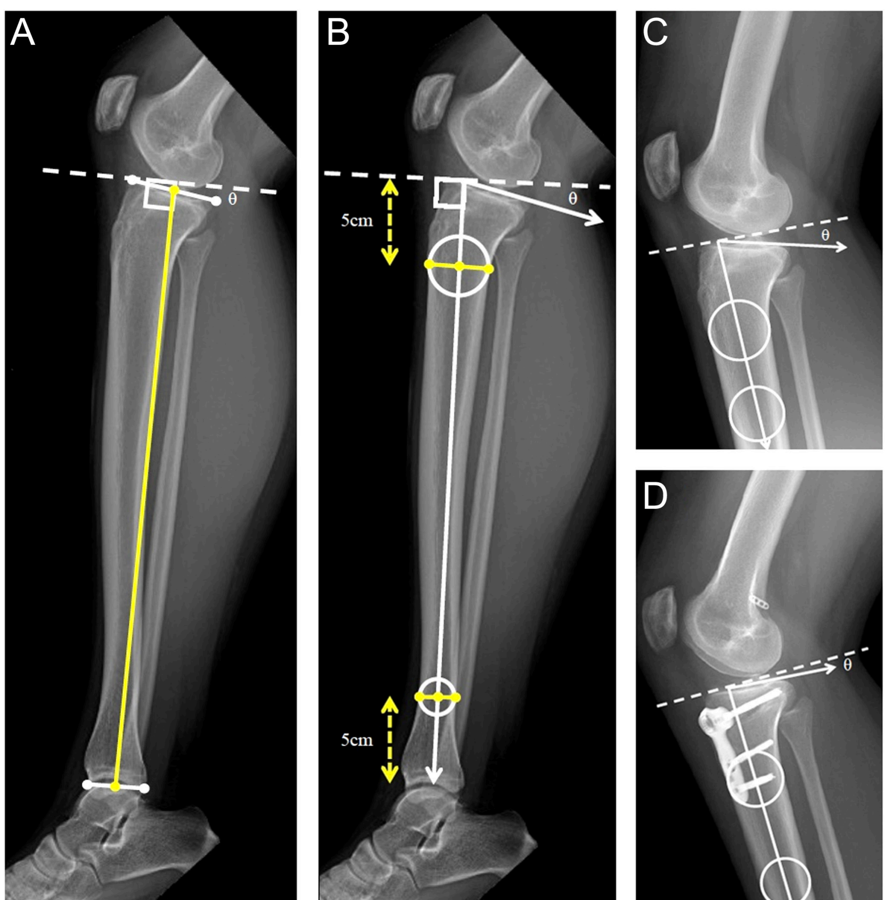

Figure 3. Calculation of posterior tibial slope using plain radiographs and corresponding changes following a slope-reducing HTO. (A) Lateral x-ray illustrates a weightbearing axis of the tibia. A line tangential to the proximal and distal tibia joint lines is drawn with the weight-bearing axis (yellow line) intersecting the middle of the 2 axes. (B) Lateral x-ray illustrating the anatomical axis of the tibia. Two reference circles are drawn at a proximal and distal point 5cm from the joint line. The center of each circle (yellow lines) creates an axis that intersects a line tangential to the medial tibial plateau, creating the posterior tibial slope (PTS) (θ). (C) Lateral x-ray illustrates a preoperative lateral view for an ACL-deficient patient with an increased PTS (PTS=16°). (D) Lateral x-ray illustrates nine-day postoperative imaging following an ACW-HTO with concomitant revision ACL reconstruction (PTS=5°). ACL, anterior cruciate ligament; ACW-HTO, anterior closing wedge high tibial osteotomy; PTS, posterior tibial slope.

Steep PTS has also been associated with a higher risk of bilateral ACL rupture.[4,17] The prevalence of PTS >12° has been reported to be 32% among individuals with bilateral ACL ruptures compared to 13% among individuals with unilateral injuries; furthermore, individuals with PTS >12° were 2.4 times more likely to injure their contralateral ACL.[17] The rate of contralateral ACL rupture for patients with a primary ACL injury and medial PTS >12° has been found to be 19% compared to 4% among patients with normal range PTS.

The biomechanical effects of a high PTS also alter the forces experienced by the ACL graft after reconstruction, where ACL graft force with axial loading was found to have a positive linear relationship with increasing PTS.[19] Furthermore, a PTS >12° has been associated with a 5-fold increased risk of ACL graft failure.[5] It is therefore important to evaluate PTS at the time of primary ACL reconstruction to assess graft failure risk and in the revision setting to determine if a slope correction osteotomy or other adjunctive procedure may be necessary.

Medial tibial plateau depth (MTPD) has also been associated with ACL injury; specifically, a shallower MTPD increases ACL injury risk.[20-22] In 1 study, females with a shallow MTPD had a higher risk of ACL injury [odds ratio (OR) 4.13],[20] while another study found an increased risk of ACL injury with a shallow MTPD regardless of sex (OR 3.03).[21] In adolescents, MTPD was found to be significantly higher in the ACL-injured cohort compared to controls (2.6 vs. 2.2 mm; $P=.015$).[22] In the lateral compartment, greater convexity of the lateral tibial plateau is associated with a higher grade pivot shift.[2,23] Lateral plateau surface geometry contributes to tibiofemoral rotatory stability, but this has not yet been directly analyzed as a risk factor for ACL injury.

Sex differences in morphology

The intrinsic bony morphology of the tibiofemoral joint differs between males and females when controlled for height and weight,[31] and the morphologic risk factors for ACL injury have been found to differ between sexes.[31-33] On average, adolescent female patients have narrower femoral notches, shallower medial tibial plateaus, steeper LTS, and smaller tibial spines compared with age-matched male patients.[34] One study comparing 88 ACL-injured patients with matched uninjured controls found different combinations of risk factors for males and females: decreased notch width and increased lateral tibial plateau cartilage slope were risk factors for females, whereas volume of the ACL and lateral compartment meniscus bone angle were risk factors for males.[32] Furthermore, a decreased medial tibial eminence volume, decreased LFC radius of curvature, and decreased tibial plateau anteroposterior width were associated with increased injury risk in males, but not females.[31,33] In contrast, ACL-injured female patients had steeper lateral PTS compared to uninjured controls, but no difference was found between male injured and uninjured patients.[31] These findings suggest that the morphologic profiles associated with ACL injury are sex-specific.

Surgical considerations of "high-risk" morphology

Increased posterior tibial slope

As increased PTS has been demonstrated to be a risk factor for ACL graft failure, several techniques have been described to address this anatomical issue. One of the most commonly used techniques to decrease PTS is an anterior closing wedge high tibial osteotomy (ACW-HTO), also referred to as a "slope-reducing osteotomy" (Figure 3). Slope-reducing osteotomies are often considered "salvage procedures" as they are usually performed in the setting of revision ACLR,[35] and the rates of return to a high level of sports activity are not well established.[36] Thus, the surgical indications for ACW-HTO include increased PTS (>12°) and >10 mm of anterior tibial translation in the setting of revision ACLR. While controversial, ACW-HTO can be considered in primary ACLR, particularly in individuals with failed contralateral ACLR and slopes of >16°-20° to decrease the future risk of ACL graft failure.[37,38]

Notch width

As mentioned earlier, notch stenosis, including a narrow intercondylar notch and decreased notch width index, has been identified as a risk factor for sustaining an ACL injury in previous studies.[39-41] Therefore, it is important to consider measuring notch width both preoperatively and intraoperatively. A narrow notch has been linked to the risk of placing the femoral tunnel too anteriorly, potentially resulting in a non-anatomic ACLR. Current literature has further demonstrated the possible risks associated with graft impingement, particularly in cases involving smaller notches[42] or the use of excessively large-diameter grafts. Consequently, it is sometimes recommended to consider performing a notchplasty or the use of a smaller diameter graft in cases where the notch is narrow. Additionally, outside-in tunnel drilling technique can also be utilized. The goal of notchplasty is to widen and reshape the intercondylar notch to provide better visualization within the notch for accurate anatomic femoral tunnel placement, and to theoretically increase the space available for the ACL graft. However, there are also concerns related to postoperative bone regrowth, which could potentially lead to the narrowing of the notch over time.[43]

Lateral extra-articular tenodesis

In the case of certain non-modifiable bony features, LET may be performed as an adjunct to ACLR to increase rotational stability. Common indications for LET include younger patients with a desire to return to contact or pivoting sports, patients with high-grade anterolateral rotatory laxity (> grade 2 pivot shift), generalized ligamentous laxity (Beighton score >4), increased PTS (>12°), and revision ACLR surgery.[44-47]

Furthermore, the benefits of LET in patients with a greater lateral distal femur angle have been discussed, suggesting this as a potential indication for performing concomitant LET with ACLR. However, current evidence is scarce regarding whether LET should be reserved for revision settings or considered in primary ACLR among the high-risk population. While previous literature suggests a reduced rate of graft ruptures and rotatory knee instability following primary hamstring ACLR combined with LET in high-risk patients,[44] concerns persist about increased postoperative pain and reduced quadriceps strength, albeit resolving by 1 year.[48] Overall, the current literature suggests improved early stability with reduced anterior tibial translation following ACLR in combination with LET, while the long-term benefits remain a topic of debate.[49,50]

Future directions

As our understanding of the intricate relationship between the bony morphology of the knee and ACL injury continues to evolve, future research directions may focus on refining and expanding our knowledge in several key areas. Establishing quantitative thresholds for morphological parameters, such as femoral notch width and PTS, could contribute to a more standardized and universally applicable assessment of ACL injury risk. Thus, future studies should focus on identifying specific cutoff values for various morphological features, aiding clinicians in preoperative planning and risk stratification.

Conducting longitudinal studies to track changes in bony morphology over time and their correlation with ACL injury occurrence could provide valuable insights as the development of predictive models incorporating multiple morphological variables, along with demographic and biomechanical factors, could enhance clinicians' ability to identify individuals at heightened risk of ACL injuries. Thus, by addressing these future directions, researchers may contribute to a more nuanced and evidence-based approach to understanding and mitigating the risk of ACL injuries based on bony morphology.

Conclusion

Assessment of the bony morphology of the knee is essential in the setting of ACL injuries, since individual bony morphology can impact surgical treatment and guide counseling of patients on the risk of recurrent ACL injury. The future of the field of ACL bony morphology should focus on identifying specific cutoff values for various bony morphological features, facilitating preoperative planning and risk stratification for clinicians. Additionally, conducting longitudinal studies to track changes in bony morphology over time and correlating them with ACL injury occurrence could offer valuable insights. The development of predictive models incorporating morphological variables and demographic and biomechanical factors holds the potential to enhance clinicians' ability to identify individuals at heightened risk of ACL injuries and choose a surgical approach with the least likelihood of graft failure.

Peer-review: Externally peer-reviewed.

Author Contributions: Concept – J.K., G.A.; Design – J.K., G.A., J.G.G.; Supervision – E.A.Ö., N.A.A., V.M.; Resources – N/A; Materials – N/A; Data Collection and/or Processing – N/A; Analysis and/or Interpretation – N/A; Literature Search – J.K., G.A., J.D.G.; Writing – J.K., G.A., J.D.G., E.A.Ö.; Critical Review – N.A.A., V.M.

Declaration of Interests: The authors declare the following potential conflicts of interest or sources of funding: V.M. received consulting fees from Smith & Nephew, educational fees from Arthrex, DePuy Synthesis, and Conmed, and is the Assistant Editor-in-Chief of Knee Surgery, Sports Traumatology, Arthroscopy (KSSTA). Also, V.M. has a patent, U.S. Patent No. 9,949,684, issued on April 24, 2018, to the University of Pittsburgh. The other authors have no conflicts of interest to declare.

Funding: The authors declare that this study received no financial support.

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