Bony morphologic factors affecting injury risk, rotatory stability, outcomes, and re-tear rate after anterior cruciate ligament reconstruction

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Abstract: A growing body of evidence has demonstrated that factors contributing to anterior cruciate ligament (ACL) injury risk are multifactorial. Recent studies have suggested that bony morphologic features play a sizeable role in this injury risk. Posterior tibial slope and posterior femoral condyle characteristics have been correlated to rotatory knee stability. Tibial slope, increased posterior femoral condylar depth, deepened lateral femoral notch, and intercondylar notch morphology have all been associated with increased ACL injury risk, and in some cases ACL reconstruction failure rates. It is crucial that surgeons understand the influence of these factors on ACL injury and their implications in ACL reconstruction. In select cases, these bony factors can be modified (e.g., osteotomy to decrease the tibial slope). In other cases, surgical, rehabilitation, and return to play strategies may need to be altered (e.g., close evaluation for lateral meniscal tears in the setting of deepened lateral femoral notch, careful graft choice and positioning in the setting of a narrow intercondylar notch). In summary, careful assessment and understanding of bony morphology is paramount to optimizing ACL reconstruction outcomes.

Keywords: Anterior cruciate ligament (ACL); rotatory stability; lateral femoral notch; intercondylar notch; bony morphology

Introduction

Anterior cruciate ligament (ACL) reconstruction is an increasingly common orthopaedic procedure (1,2). Outcomes after ACL reconstruction have improved considerably as surgical technique, implant and imaging technology, and scientific understanding have advanced over the past few decades of modern ACL reconstruction. However, there remains a subset of patients that have subpar outcomes after ACL reconstruction such as residual rotatory instability, graft re-tear, and premature arthritis (3-5). The underlying etiology for these unsatisfactory outcomes is multifactorial, and anatomic, biologic, neuromuscular, and technical factors all play a role (6-12).

Recently, several studies have demonstrated that certain bony characteristics of the patient's native anatomy may contribute to rotatory knee stability (*Table 1*) (13-17). As surgeons strive to improve treatment of ACL injuries, knowledge of these bony factors which affect knee stability is crucial to optimize patient outcomes.

Tibial slope

The unique shapes of the medial and lateral tibial plateaus contribute to the characteristic rotatory instability associated with ACL injury. The lateral tibial plateau is convex and has a smaller surface area than the medial plateau. The

Table 1 Summary of bony morphologic characteristics related to ACL injury

Morphologic characteristic	Normal range	Substantially elevated risk	Increased rotatory laxity	Increased ACL injury risk	Increased re-tear risk after ACL reconstruction	Treatment options
Posterior tibial slope	5°–7°	>12°	Yes	Yes	Yes	Osteotomy; adjust postoperative rehab and return to play
Lateral tibial plateau width	32–39 mm	ISD	Yes	Unknown	Unknown	Adjust postoperative rehab and return to play; consider lateral extra-articular procedures in revision cases or cases of excessive rotatory laxity
Posterior condylar depth/ratio	ISD	ISD	Yes	Yes	Yes	Adjust postoperative rehab and return to play; consider lateral extra-articular procedures in revision cases or cases of excessive rotatory laxity
Lateral femoral notch depth	0.5–1 mm	>1.5–2.0 mm	No	Yes	Unknown	Assess for lateral meniscus injury; adjust postoperative rehab and return to play
Intercondylar notch	ISD	NWI <0.27 or absolute width <15 mm; A-shaped notch	No	Yes	Yes	Optimize graft placement and graft size

ISD, insufficient data; NWI, notch width index (notch width over distal femoral width, measured on tunnel view posteroanterior radiograph at the level of the popliteal groove); ACL, anterior cruciate ligament.

complex interaction of the lateral tibial plateau and lateral femoral condyle leads to the prototypical pivot shift sign, or "*clunk*", observed in the setting of ACL deficiency. In fact, the slope of the lateral tibial plateau plays an important role in rotatory knee stability and ACL re-injury risk (13,18-21). For instance, a study of 11 female cadaveric knees reported a mean lateral tibial slope of 7.6 degrees, and the authors reported that increasing the tibial slope was significantly associated with anterior tibial acceleration and ACL strain during dynamic impact testing (21).

The effect of tibial slope on rotatory knee stability and injury risk have also been observed in clinical studies. For instance, one study demonstrated that ACL tear patients with high grade rotatory laxity have a higher tibial slope than those with low grade rotatory laxity (13). A separate study of 200 consecutive patients who underwent ACL reconstruction reported a mean tibial slope of 8.5 degrees, although patients who had sustained a second ACL injury at 15-year follow-up had a tibial slope of 9.9 degrees (P=0.001) (22). Hashemi *et al.* demonstrated that for each degree increase in lateral tibial slope, ACL injury risk increased by 1.17-fold (23). In a separate study comparing 88 ACL reconstruction patients to 88 control population, authors reported a 21.7%

increased risk of noncontact ACL injury with each degree of increased slope in females, but not males (20). However, other studies have reported increased injury risk in males with increased tibial slopes. In fact, a recent study in division-1 collegiate football athletes found that lateral tibial slope predicted ACL injury risk (19). Unpublished data from our institution has shown that increased tibial slope (*Figure 1*) leads to altered gait kinematics and tibial rotation during downhill running. As demonstrated by the previous studies, increased lateral compartment tibial slope results in increased rotatory knee laxity, ACL strain, and ultimately ACL injury risk.

Tibial plateau size

Musahl *et al.* studied size parameters of the femoral condyle and tibial plateau. The authors studied a total of 49 patients (males and females). They performed pivot shift testing in patients with ACL tears under anesthesia. The authors reported that patients with a smaller lateral tibial plateau diameter in the medial to lateral direction also had higher grade pivot shifts. When analyzed by sex, this applied to females, but not males. They did not find
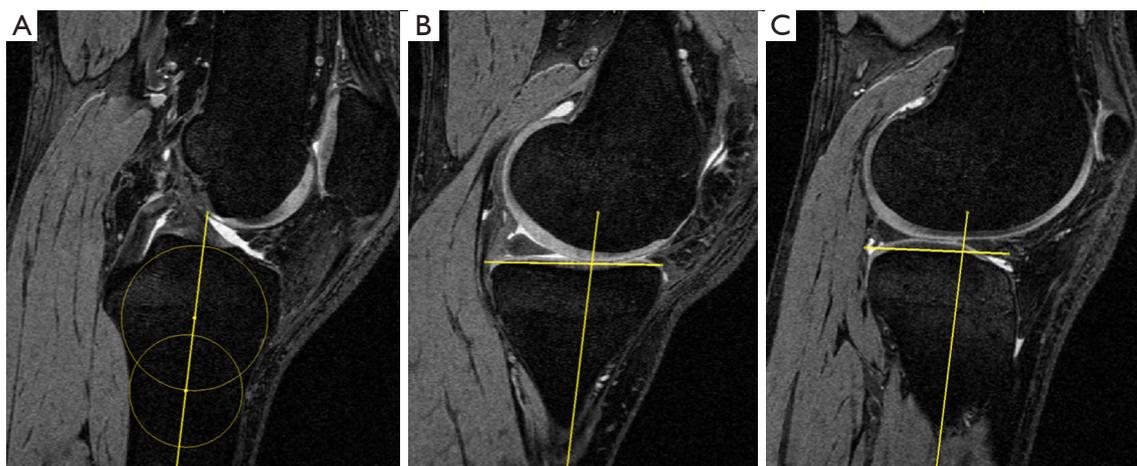
Figure 1 Posterior tibial slope. Sagittal MRI scans demonstrating the method of identifying the tibial shaft (A), and then measuring the medial (B) and lateral (C) tibial slopes.

Figure 2 Posterior condylar offset. One method of measuring the posterior condylar offset on lateral radiograph. Distance A is divided by A + B, which results in the posterior condylar offset ratio.

associations between other morphologic parameters and pivot shift grade. The authors originally hypothesized that the anterior to posterior dimensions of the tibia would be most associated with rotatory stability. They explained the discrepancy between the original hypothesis and their finding by reasoning that the orientation of the tibia relative to the femoral condyle changes during the pivot shift mechanism, and the medial to lateral dimensions are likely oriented in more of an anterior to posterior direction during this phenomenon (24).

Posterior condylar offset

While distal femoral posterior condylar dimensions have long been discussed in joint arthroplasty literature (25), this specific anatomic feature has just recently been studied in the setting of ACL injury (26). In a study of *in vivo* knee kinematics using dynamic stereo radiographs and 3D CT scans, a higher posterior condylar offset ratio (COR) was positively correlated with increased anterior tibial translation. A cadaveric study reported a link between posterior condylar offset and posterior tibial slope (27). In ongoing but unpublished research at our institution, increased posterior condylar depth (*Figure 2*), relative to overall condyle depth in the anterior to posterior direction, as measured on lateral radiographs, has been correlated with an increased risk of non-contact ACL injury and re-injury after ACL reconstruction. Furthermore, quantitative pivot shift analysis of patients with ACL tears utilizing video image analysis software and inertial sensors (28) demonstrated increased rotatory knee laxity in patients with high posterior condylar offset ratios. The mechanism behind the increased knee laxity and injury risk are currently unknown. It is possible that the increased condylar offset results in more of a stretch of the lateral tissues and relative low density when the knee is at lower flexion angles, such as those commonly encountered in non-contact ACL injury. On the other hand, perhaps the injuries occur when the knee is in greater degrees of flexion and the lateral soft tissue structures are at maximum tension and therefore are most likely to fail. Studies have suggested that femoral

Figure 3 Lateral femoral notch. The lateral femoral notch depth is measured by drawing a line tangential to the articular surface of the lateral femoral condyle, and then measuring the distance from this line to the deepest point of the notch.

condyle geometry is important in rotatory stability (29), though future studies will be needed to better understand this relationship.

Lateral femoral notch sign

The lateral femoral notch sign (LFN) sign has long been recognized as an indicator of ACL injury. The LFN occurs close to the location of the native condylopatellar sulcus (*Figure 3*). Supraphysiologic depth and length of this condylopatellar sulcus, as measured on lateral radiographs or sagittal MRI, is referred to as "*positive notch sign*". In 1992, Cobby *et al.* reported that patients with normal ACLs had a LFN depth of 0.45 mm on lateral radiographs, while patients with torn ACL's had LFN depth of 0.89 mm. The authors considered LFN depth of greater than 1.5 mm to be a sign of ACL injury. A later MRI study observed that 83% of acute ACL patients had an osseous contusion at the area of the sulcus, and that most involved injury to the subchondral bone (30). Gimberg *et al.* confirmed that the LFN was associated with ACL injury and further reported that a "double notch" sign was 17% sensitive and 100% specific for complete ACL tear (31).

More recently, Herbst *et al.* reviewed MRIs and X-rays for 500 acute arthroscopically confirmed ACL tears. They observed that ACL tears sustained during high intensity cutting sports were more likely to be accompanied by a deep

lateral femoral notch (>2.0 mm) than non-cutting sports. They also found a significant correlation between LFN >2.0 mm and presence of a lateral meniscus tear (15). Recent research from the authors' institution has corroborated the association between LFN depth and lateral meniscal tears. However, there was no significant correlation between LFN depth and quantitative pivot shift measurements. While the relationship between LFN depth and rotatory injuries such as ACL and lateral meniscal tears is clear, more research is needed to elucidate the pathogenesis of the LFN.

Intercondylar notch

Perhaps no bony morphologic feature has been more studied in the context of ACL injury than the intercondylar notch (*Figure 4*). In fact, a PubMed search in June 2017 reveals over 350 articles on the topic of intercondylar notch and ACL. As early as 1983, the intercondylar notch was implicated in ACL injury (32,33). Subsequently in 1987, Houseworth *et al.* used computer graphic analysis to suggest that narrow notch width may predispose the individual to ACL injury (34). Then in 1988, Souryal *et al.* reported that individuals with bilateral ACL tears had significantly narrower notches than a control group (35). The authors also described the measurement of the notch width index (NWI), which was the ratio of the width of the intercondylar notch relative to the notch of the distal femur, measured at the level of the popliteal groove on posteroanterior "tunnel view" radiographs. A separate study performed by the same group reported that high school athletes sustaining noncontact ACL injuries had lower NWI than the uninjured cohort (36). The relationship between narrow notch width and increased ACL injury risk has been confirmed not just in young patients with acute ACL tears, but also in older patients with knee arthritis (37). In general, an NWI of <0.27 or an absolute notch width of <15 mm is considered a significant risk factor for ACL injury (38).

Since these early studies, our understanding of the intercondylar notch has continued to evolve. Studies have shown that a smaller notch size often correlates with a smaller ACL, suggesting that the increased injury risk could partially be due to a weaker ACL (39-41). Other studies characterized the various shapes of notches, and linked "A-shaped" notches to increased risk of ACL injury (16,42). Multiple research articles have analyzed notch differences among various populations. For instance, some studies reported that females have narrower notches, a higher proportion of A-shaped notches, and less notch
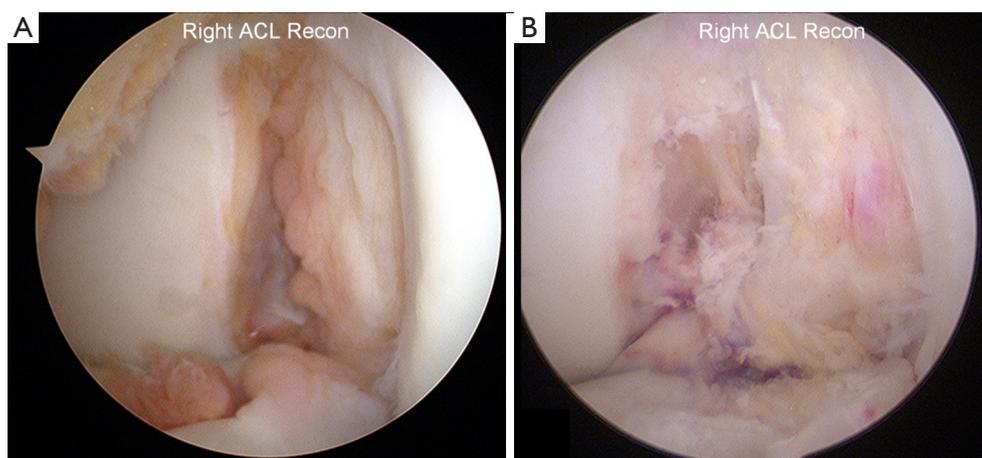
Figure 4 Comparison of narrow and normal intercondylar notch. Arthroscopic views of a narrow (A) and normal (B) intercondylar notch.
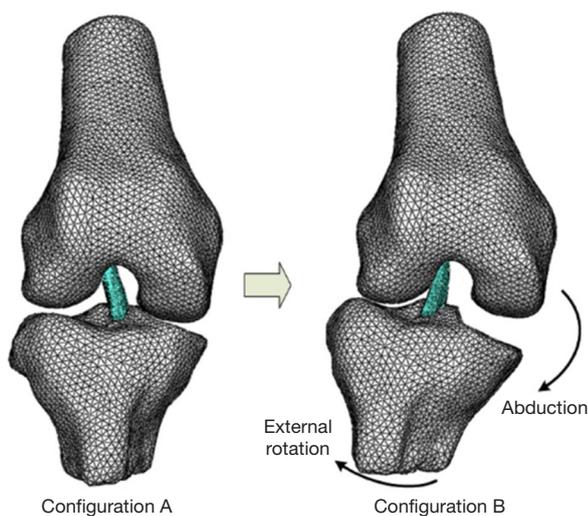

Figure 5 Mechanism for impingement of the ACL against the intercondylar notch [reprinted with permission from (46)]. ACL, anterior cruciate ligament.

volume than their male counterparts (16,41-43). Similarly, Caucasian males and females were found to have narrower notches than African American men (44). In both cases, the populations with characteristic notch morphology have correspondingly higher risks of non-contact ACL injury.

Using cadaveric specimens, robotic loading and 3-D mathematical models, Fung *et al.* demonstrated the impingement of the ACL against the intercondylar notch. They determined that slight knee flexion, tibial external rotation, and knee abduction resulted in the greatest degree of impingement. The authors noted that although tibial

internal rotation results in direct ACL strain, it decreases the distance to the notch wall and thus lowers the risk of impingement (45). Park *et al.* followed up on this earlier work and expounded upon its findings. They reported that ACL impingement was first detected at 15° of tibial external rotation and 4° of abduction. Further abduction and external rotation increased the impingement force. In fact, the model showed that 29° of external rotation and 10° of abduction resulted in ACL stretching and deformation (46). An animal model showed that repetitive impingement of the ACL in this position of tibial external rotation and abduction resulted in cell death and cumulative ligament damage (47), and more recent studies have corroborated this mechanism of notch impingement (*Figure 5*) (48).

This knowledge of notch morphology should encourage thorough assessment of the notch during preoperative planning and during the surgical procedure. In addition to the relationship between narrower notches and smaller native ACLs, studies have shown that larger grafts used during ACL reconstruction could lead to increased impingement on the notch (49). In fact, ongoing research at our own institution has demonstrated that increased graft size relative to notch width at the apex can result in increased failure rate. This is important as most of the literature to date on graft size has focused on risk of re-tear risk when smaller grafts have been used (50).

Graft positioning also influences the risk of graft impingement. Non-anatomic placement of the femoral tunnel has been cited as the leading technical cause of ACL reconstruction failure (51,52). Several studies have demonstrated that high and anterior placement of the

femoral tunnel can result in increased impingement against the notch (49,53). Similarly, anterior and lateral positioning of the tibial tunnel results in increased graft impingement (49,53,54). As such, surgeons should consider tibial tunnel-independent methods of femoral tunnel placement, such as anteromedial portal or outside-in drilling (55). These techniques have demonstrated more anatomic positioning of both the tibial and femoral tunnels, and thus decreasing the risk of graft impingement (56-60).

Discussion

As demonstrated above, a variety of bony morphologic factors can impact the risk of primary or repeat ACL injury. Some of these can be addressed surgically, and others are merely harbingers of ACL injury or rotatory laxity. Some of these bony characteristics are part of the normal developmental process, while others result from injury, and still others may develop as a result of chronic microtrauma or altered gait patterns. Wolff hypothesized the relationship between bone structure and function as early as 1867 (61). In fact, Wolff's law has remained a cornerstone in modern understanding of bone and its dynamic responses to pressure, tension, and its surrounding environment (62,63).

While the Mechanostat model of bone has been known for nearly 150 years, and has been studied in-depth in other settings, the study of bone morphology and its interaction with ACL function is in a stage of relative infancy. McNeill Ingham, Lovejoy, and others have provided crucial insight into the evolutionary development of the human distal femur, and its comparison to other bipedal species (64). For instance, cows have demonstrated a similar NWI to humans, while goats, dogs, and other animals did not. However, pigs showed sex-specific differences in notch morphology that mirrored that of the human differences in male and female notches. Furthermore, most quadrupeds have a steeper tibial slope and narrower intercondylar notch relative to bipedal species such as humans. Spending more time in deep knee flexion, and thus necessitating different demands on their knee joints than that of humans, quadrupeds have different knee morphology that is more advantageous to their functional demands (64).

Until recently, bony morphology has been underappreciated in the field of ACL research. In fact, there is still much that is unknown about the causes, consequences, and variations in bony morphology relative to ACL injury. It is crucial that surgeons and scientists continue their pursuit of knowledge and understanding of these factors. As there exists great variability among individuals, incorporation of bony morphology into preoperative planning, operative techniques, and postoperative rehabilitation and return-to-play will be crucial to providing individualized treatment of ACL injuries. For example, in patients with an A-shaped or narrow notch, graft size and positioning must be performed with meticulous attention to detail to ensure that the risk of graft impingement is minimized. In patients with excessive LFN depth, surgeons should assess the preoperative imaging and intraoperative exam for lateral meniscus injuries that might otherwise be missed. Preoperative x-rays with a deep LFN should alert clinicians of a likely ACL injury in the absence of an MRI or with equivocal MRI findings. Patients with excessive posterior tibial slope or posterior condylar offset/depth should be considered to have higher rotatory laxity and increased re-injury risk. Tibial slope can be addressed with a slope-reducing osteotomy, especially during revision ACL reconstruction (65). Although no surgical treatments are known to address the distal femoral condylar anatomy, surgeons may consider additional procedures such as extra-articular tenodesis or more conservative postoperative protocols.

Conclusions

In conclusion, numerous bony morphologic features have shown association with ACL injury risk, rotatory knee laxity, and outcomes after ACL reconstruction. Posterior tibial slope and posterior femoral condyle characteristics have been correlated to measurements of rotatory knee stability, with increasing slope and greater condylar depth resulting in greater knee laxity. Increased tibial slope, increased posterior femoral condylar depth, a deepened lateral femoral notch (condylopatellar sulcus), and smaller intercondylar notch morphology have demonstrated increased ACL injury risk, and in some cases ACL reconstruction failure rates. Although historically underappreciated, it is important that surgeons consider these individual anatomic bony features when treating patients with ACL injury. Furthermore, future research should continue to focus on elucidating the pathogenesis behind abnormal bony morphology and its relationship with ACL injury risk. ACL reconstruction is not a one-sized fitting all surgery, and understanding the impact of subtle bony morphologic variations will guide surgeons to deliver more individualized treatment options.

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Footnote

Conflicts of Interest: The authors have no conflicts of interest to declare.

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