Anatomy and Biomechanics of the Lateral Side of the Knee and Surgical Implications

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Abstract: A detailed understanding of the anatomy and biomechanics of the lateral knee is essential for the clinical diagnosis and surgical treatment of lateral-sided knee injuries. In the past, the structure and function of the lateral and posterolateral knee was poorly understood and was dubbed by some as "the dark side of the knee." However, recent advances in quantitative anatomy and biomechanics of this region have led to the development of anatomic-based reconstruction techniques and improved objective and subjective patient-based outcomes. Although the lateral knee consists of 28 unique structures, the primary lateral knee stabilizers include the fibular collateral ligament, popliteus tendon, and popliteofibular ligament. Together, these structures function to resist lateral compartment varus gapping and rotatory knee instability. This work will summarize the current state of knowledge regarding the anatomy and biomechanics of the lateral knee structures, while emphasizing implications for surgical treatment.

Key Words: lateral knee, posterolateral knee, anatomy, biomechanics, surgical treatment

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The complexity of posterolateral corner knee anatomy has been widely documented.[1,2] Adding to the confusion, posterolateral corner nomenclature has varied across studies in the anatomy and imaging literature. However, over the past 2 decades, advancements in the understanding of lateral knee anatomy have led to more consistent definitions of structures, and biomechanical advances have led to clearer understanding of the functional contributions of individual posterolateral corner structures. Quantitative descriptions of posterolateral corner anatomic footprints enabled the development of anatomic surgical techniques.[3–8] In turn, these advances have led to improved patient outcomes using anatomic principles for lateral knee repair and reconstruction techniques.[9,10] The lateral knee consists of numerous static and dynamic stabilizers that together provide lateral knee stability. The 3 primary static stabilizers include the fibular collateral ligament (FCL), popliteofibular ligament (PFL), and the popliteus tendon (PLT). Other important structures include the iliotibial band, long and short heads of the biceps femoris muscle, lateral gastrocnemius tendon, anterolateral ligament, fabellofibular ligament, proximal tibiofibular ligaments, and coronary ligament of the lateral meniscus.[11,12] Neurovascular structures such as the common peroneal nerve and lateral inferior genicular artery are also important to evaluate during assessment and treatment of posterolateral corner injuries.

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ANATOMY OF THE LATERAL KNEE

The lateral knee is comprised of 28 unique static and dynamic stabilizers. The 3 primary stabilizers that are commonly reconstructed surgically include the FCL, PFL, and PLT (Fig. 1).[6] The peroneal nerve also courses through the posterolateral aspect of the knee. Avoiding iatrogenic injury to the nerve is critical and is largely based on understanding its location relative to surgically relevant lateral knee structures. Many of the anatomic relationships in the lateral aspect of the knee are very small and therefore the quantitative descriptions are reported to a tenth of a millimeter. It should be noted that the size of knees are variable across a typical population, and these reported numbers should be used as an approximation of the average distance.

Lateral Knee Bony Anatomy

The bony anatomy of the lateral knee is essential for understanding not only key relationships of soft tissue structures but also functions as a key determinant of the inability of many lateral knee injuries to heal over time. Soft tissue structures of the lateral knee attach to the distal femur, proximal tibia, and fibular head. The opposing bony surfaces of the tibiofemoral joint in the lateral knee articulate in a convex on convex manner, creating inherent instability in this region of the knee. Numerous animal model studies have investigated the role of lateral knee bony geometry in the natural history of lateral knee injuries, which revealed that lateral knee injuries rarely heal, leading to lateral compartment gapping, medial compartment osteoarthritis, and medial meniscus tears.[13–15] In contrast, the medial tibiofemoral joint articulation has a convex on concave bony geometry that confers an inherent stability to this region of the knee, contributing to the propensity for many medial knee injuries to heal over time. Other key bony landmarks of the lateral knee include the lateral epicondyle, the fibular head, the popliteal sulcus, and the Gerdy tubercle.

FCL

The FCL originates on the lateral aspect of the femur and inserts on the fibula. At its femoral attachment, the FCL is located 1.4 mm proximal and 3.1 mm posterior to the lateral epicondyle in a small bony depression.[6] This attachment is approximately 18.5 mm proximal and posterior to the PLT attachment, which represents an important relationship in posterolateral anatomic reconstruction techniques (Fig. 2). Using an open surgical approach

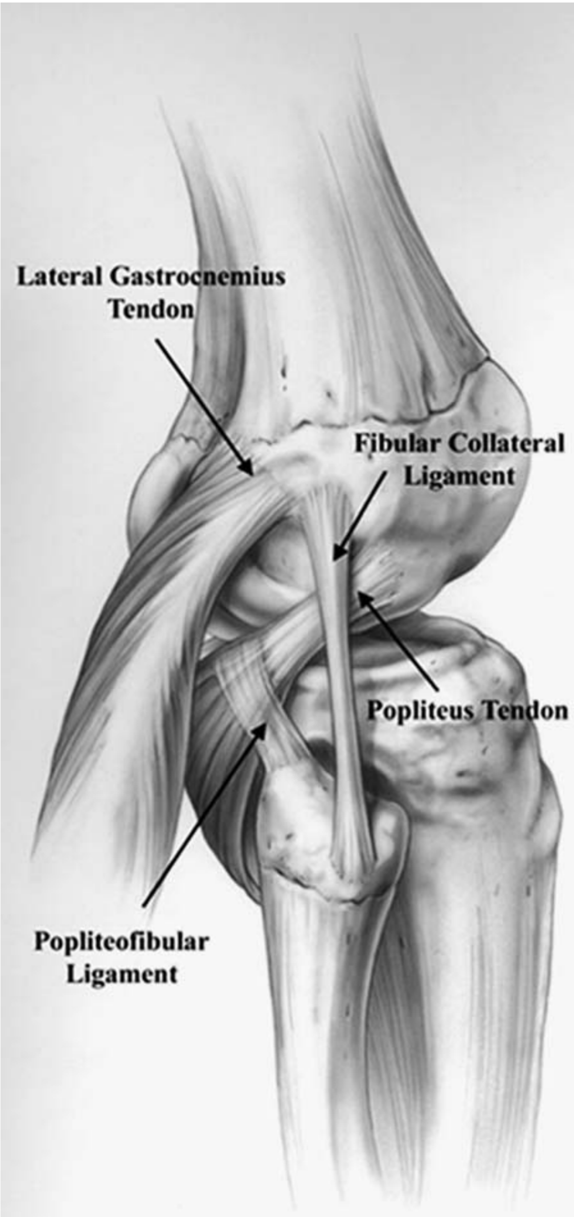

FIGURE 1. The primary posterolateral corner static stabilizers include the fibular collateral ligament, popliteofibular ligament, and popliteus tendon. Reprinted with permission from LaPrade et al.[6]

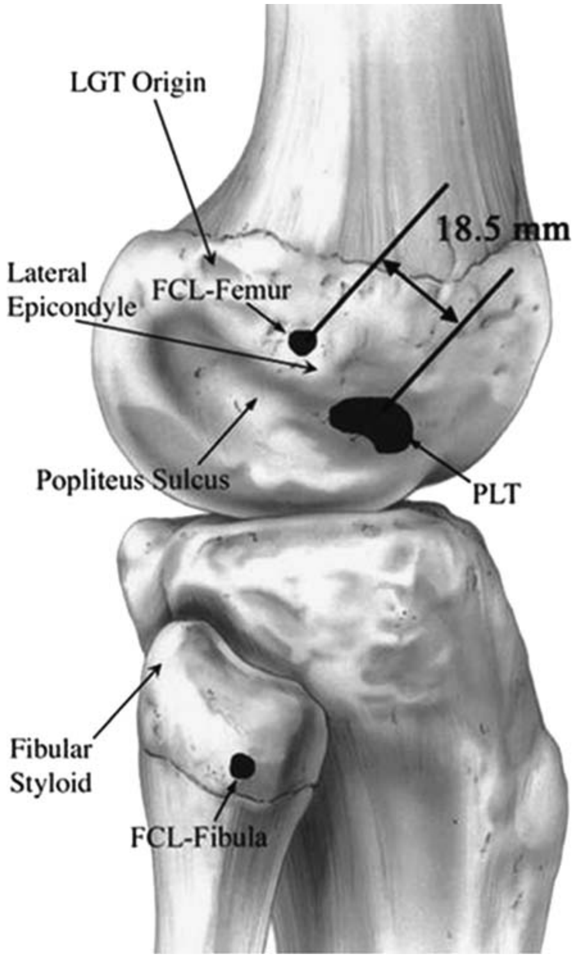

FIGURE 2. An illustration of the attachment locations of the fibular collateral ligament (FCL), popliteofibular ligament (PFL), and popliteus tendon (PLT) attachment sites. LGT indicates lateral gastrocnemius tendon. Reprinted with permission from LaPrade et al.[6]

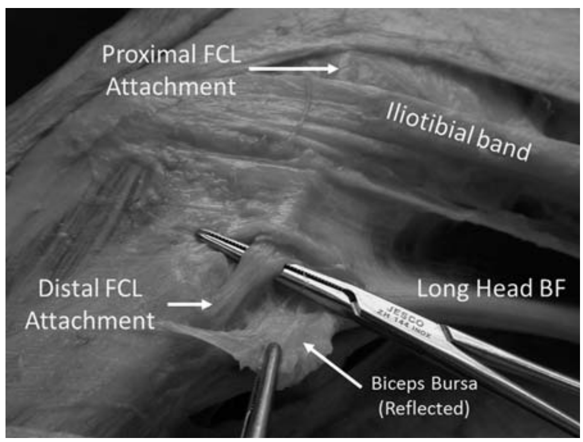

FIGURE 3. The distal attachment of the fibular collateral ligament (FCL) can be found by accessing the biceps bursa, whereas the proximal FCL attachment can be identified through a longitudinal incision in the iliotibial band. BF indicates biceps femoris.

through a laterally based hockey stick incision,[12] the proximal FCL attachment can be identified through a longitudinal incision in the iliotibial band (Fig. 3). The distal FCL attachment is located in a small depression on the lateral aspect of the fibular head approximately 8.2 mm posterior to the anterior margin of the fibular head and 28.4 mm distal to the fibular styloid tip. The distal FCL attachment can be identified surgically through an incision in the biceps bursa of the long head of the biceps femoris. On average, the FCL measures 69.6 mm in length.

PLT

The popliteus muscle originates at a tendon on the lateral aspect of the femur and inserts in a broad attachment at the posterior aspect of the tibia.[16] The PLT attachment has a relatively broad footprint (0.59 cm^2) located just posterior to the margin of the lateral femoral condyle articular cartilage.[6] This attachment is found at the anterior fifth and proximal half of the popliteal sulcus and can be visualized arthroscopically or through an arthrotomy incision in the anterolateral joint capsule. From this attachment, the tendon courses obliquely in the posterior and inferior directions and becomes extra-articular near the popliteal hiatus before wrapping around the posterior capsule in the medial direction (Fig. 4). As the tendon passes through the popliteal hiatus, it is anchored to the lateral meniscus by 3 popliteomeniscal fascicles. These consist of the anteroinferior, posterosuperior, and posteroinferior fascicles, or bundles.[17–19] Together, these structures form the boundaries of the popliteal hiatus, which averages 1.3 cm in length.[17]

From full extension to approximately 112 degrees of flexion, the PLT rests proximal to the popliteal sulcus on the lateral femoral condyle.[6] Beginning at 112 degrees and higher knee flexion angles, the PLT engages in the popliteal sulcus. Just medial to the posteromedial aspect of the fibular head in the posterior knee, the PLT connects to the popliteus muscle belly at its musculotendinous junction. As previously stated, the PLT attachment is separated from the proximal FCL attachment by approximately 18.5 mm (Fig. 2). This represents a key anatomic relationship that is important to reproduce during anatomic total posterolateral reconstructions.

PFL

The PFL consists of distinct anterior and posterior divisions and anchors the musculotendinous junction of the popliteus muscle to the fibular head.[6] At its junction with the PLT, the PFL forms an 83-degree angle to the PLT. The anterior division of the PFL attaches 2.8 mm distal to the tip of the fibular styloid process, whereas the posterior division attaches 1.6 mm distal to the tip of the fibular styloid process. Overall, it is a thin, stout attachment between the PLT and the fibular styloid (Fig. 4). Both attachments wrap along the posteromedial downslope of the fibular styloid process. The posterior division has a consistently larger width (5.8 mm) than the width of the anterior division (2.6 mm). Anatomic total posterolateral corner reconstructions reproduce the PFL using a graft extending from the posteromedial aspect of the fibular head to a transtibial tunnel beginning posteriorly 1 cm medial and distal to the fibular tunnel and exiting anteriorly at the flat spot near the Gerdy tubercle.[5,8]

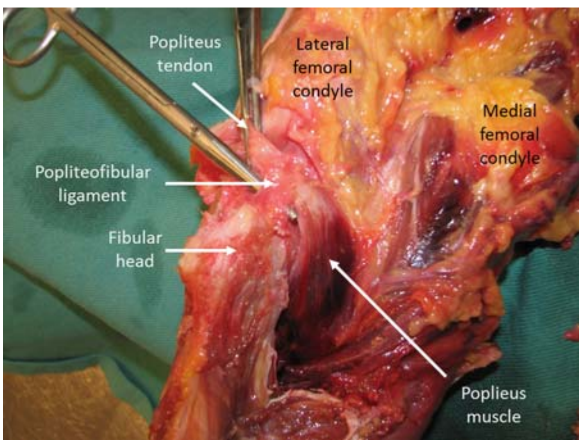

FIGURE 4. The popliteofibular ligament connects the popliteus musculotendinous junction to the fibular head (left knee). The popliteus muscle and tendon can be seen coursing proximally and laterally.

Iliotibial Band

The iliotibial band is a broad fascial structure that connects the pelvis to the tibia and covers the lateral thigh. Interestingly, humans are the only species with an iliotibial band over the anterolateral aspect of the knee.[1] The iliotibial band originates at the anterolateral external lip of the iliac crest and has a primary insertion on the anterolateral aspect of the tibia at Gerdy's tubercle. In addition to its attachment at Gerdy's tubercle, the iliotibial band also attaches distally via an iliopatellar band and deep and capsulo-osseous layers. The iliopatellar band is an anterior extension of the iliotibial band that extends to the patella.[1] Fulkerson and Gossling[20] have also described this band as the "superficial oblique retinaculum." The deep layer attaches the iliotibial band to the distal femur, whereas the capsule-osseous layer has attachments to the lateral head of the gastrocnemius, the short head of the biceps femoris, and the tibia posterior to Gerdy's tubercle.[1] During open posterolateral corner surgical procedures, the iliotibial band must be incised longitudinally to identify the femoral FCL and PLT attachments.

Long Head of the Biceps Femoris Muscle

The biceps femoris consists of a long and short head. The long head of the biceps femoris originates at the ischial tuberosity of the pelvis and courses laterally through the posterior and lateral aspect of the thigh.[21] The long head attaches using a direct and anterior arm. In addition, 3 fascial connections also contribute to the distal attachment: the reflected arm, lateral aponeurosis, and anterior aponeurosis. The direct arm attaches lateral to the fibular styloid on the lateral aspect of the fibular head. The anterior arm attaches lateral to the FCL fibular attachment on the fibular head. A bursa called the biceps bursa, or the FCL-biceps bursa, is formed between the anterior and direct arms of the long head of the biceps distal attachment.[22] This interval must be accessed through a small longitudinal incision in the distal long head of the biceps femoris during an FCL repair or reconstruction or total posterolateral corner reconstruction to identify the distal FCL attachment.[3,5]

Short Head of the Biceps Femoris Muscle

The short head of the biceps femoris muscle originates medial to the linea aspera on the distal femur, traverses in the distal and lateral direction, and attaches distally through several connections. Distal attachments include connections to the anteromedial side of the long head of the biceps tendon, posterolateral aspect of the joint capsule, capsulo-osseous layer of the iliotibial band, a lateral aponeurosis, and a direct and anterior arm.[21] The capsular attachment is typically located in the region between the lateral head of the gastrocnemius and the FCL. The most prominent attachment is a direct arm located at the fibular head between the fibular styloid and the distal FCL attachment. In addition, there is an anterior arm of the short head of the biceps femoris, which attaches 1 cm posterior to Gerdy's tubercle.

Lateral Gastrocnemius Tendon

The gastrocnemius muscle is anchored laterally and proximally by the lateral gastrocnemius tendon. The gastrocnemius tendon emerges from the far lateral portion of the gastrocnemius muscle belly in the region of the posterior fibular head. The tendon first attaches to either a bony or cartilaginous fabella and continues to attach to the femur near the supracondylar process.[12] In a study by LaPrade et al,[6] the lateral gastrocnemius tendon attached on the supracondylar process in 80% of specimens studied. The femoral attachment is located approximately 13.8 mm posterior to the proximal FCL attachment and 28.4 mm from the PLT attachment. In the region between the fabellar and femoral attachments, the gastrocnemius adheres to the meniscofemoral portion of the posterolateral joint capsule. During some surgical procedures, the tendon must be separated from the posterior capsule and this can be accomplished using sharp dissection. The gastrocnemius muscle and tendon are also important landmarks for isolated PLT and total posterolateral corner reconstructions. Using blunt dissection after a common peroneal neurolysis, the interval between the lateral gastrocnemius (posterior) and soleus muscle (anterior) can be expanded through with the musculotendinous junction of the popliteus muscle is readily visualized.

Anterolateral Ligament

The anterolateral ligament[12,23–25] has been previously called the mid-third lateral capsular ligament[1,26,27] and the capsule-osseous later of the iliotibial band. According to Claes and colleagues, the anterolateral ligament was first described by French surgeon Segond as a "pearly, resistant, fibrous band" along the anterolateral aspect of the knee.[11,28] Claes et al[11] dissected 41 unpaired formalin preserved cadaveric knees and reported the ligament to be present in 97% of specimens. The ligament originates on the prominence of the lateral femoral epicondyle, courses obliquely in the anteroinferior direction, and inserts on the proximal tibia between Gerdy's tubercle and the fibular head (Fig. 5). Along its course, it encases the lateral inferior genicular artery and attaches to the peripheral rim of the lateral meniscus.

FIGURE 5. The anterolateral ligament (anterior to scissors), also called the midthird lateral capsular ligament, is believed to provide rotatory stability to the knee and a distal avulsion fracture of the ligament has been correlated with the Segond fracture commonly seen with anterior cruciate ligament injuries (right knee).

There has been some debate regarding the correlation between anterolateral ligament injury and the Segond avulsion fracture, which has been widely correlated with anterior cruciate ligament injuries.[23,29] Some have hypothesized that the presence of a Segond fracture, indicative of injury to the anterolateral ligament, in patients with concurrent anterior cruciate ligament injury contributes to the presence of chronic rotatory stability and a residual positive pivot shift test following anterior cruciate ligament reconstruction.[11,30,31] In light of this, some are now advocating for repair or reconstruction of the anterolateral ligament in these patients.

Fabellofibular Ligament

The fabellofibular ligament is defined as the distal edge of the capsular arm of the short head of the biceps femoris.[1,6,12,21] The fabellofibular ligament has been reported to exist both only in the presence of a fabella by some authors[32,33] and in cases of either the presence or absence of a fabella by other authors.[12,34,35] The fabella is a sesamoid structure located in the lateral head of the gastrocnemius muscle. However, fabellae have also been documented in the medial head of the gastrocnemius muscle in approximately 2% to 10% of individuals.[36,37] The fabella is found in most, but not all, individuals and can be comprised of either cartilaginous or bony tissue.[36–38] Zeng et al[37] reported in a cadaveric study that presence of a fabella was not predictive of presence of a fabellofibular ligament. The fabellofibular ligament originates at the fabella proximally, coursing distally in a vertical orientation, before attaching just lateral to the lateral aspect of the fibular styloid process.[1,39] In the absence of a fabella, the fabellofibular ligament often is less substantial, originating on the posterolateral lateral femoral condyle and inserting lateral to the lateral fibular styloid process.[39]

Proximal Tibiofibular Joint Ligaments

The proximal tibiofibular joint is comprised of anterior and posterior tibiofibular joint ligaments.[40] These structures connect the proximal aspect of the medial fibular head and the lateral aspect of the tibia and confer stability to the joint. See and colleagues reported that the anterior tibiofibular ligament attaches 15.6 mm posterolateral to Gerdy's tubercle on the tibia and 17.3 mm anteroinferior to the fibular styloid. The posterior tibiofibular ligament attaches 15.7 mm interior to the lateral tibial plateau articular cartilage and 14.2 mm medial to the fibular styloid. These structures are important for tibiofibular joint stability and isometric reconstruction techniques have been developed to reconstruct the tibiofibular ligament complex in cases of significant acute or chronic tibiofibular joint instability.[4]

Coronary Ligament of the Lateral Meniscus

The coronary ligament of the lateral meniscus is defined as a meniscotibial portion of the posterolateral joint capsule that connects the lateral meniscus to the lateral edge of the tibial plateau distal to the articular cartilage.[1,12] The medial aspect of the coronary ligament begins laterally at the tibial attachment of the posterior cruciate ligament and forms the medial border of the popliteal hiatus as it continues laterally to the lateral meniscus. The coronary ligament of the lateral meniscus is best visualized arthroscopically by elevating the lateral meniscus with a probe.

Neurovascular Structures

Common Peroneal Nerve

The common peroneal nerve provides innervation to the lower extremity and is supplied by branches of L4-S2 spinal nerve roots. The common peroneal nerve emerges from a bifurcation of the sciatic nerve in the posterior aspect of the thigh, courses along the biceps femoris and around the neck of the fibula, and splits into the superficial and deep peroneal nerves. Sensory divisions of the common peroneal nerve include 2 articular branches, 1 recurrent articular nerve, and the lateral sural cutaneous nerve. Motor function of the nerve includes foot eversion and plantar flexion via innervation of the peroneus longus and peroneus brevis muscles, foot dorsiflexion and toe extension via the tibialis anterior, extensor hallucis longs, and extensor digitorum longus muscles, and intrinsic foot movements via the intrinsic muscles of the foot. During posterolateral corner procedures, a common peroneal nerve neurolysis is typically performed to minimize the risk of foot drop postoperatively due to swelling (Fig. 6). Common peroneal nerve neuropraxia has been reported due to hematoma formation at the fibular head after primary injury and is also a concern in cases where a postoperative hematoma leads to nerve compression.[41]

Lateral Inferior Genicular Artery

The lateral inferior genicular artery emerges from the popliteal artery in the posterior aspect of the knee and courses extra-articularly along the joint capsule. At the lateral knee, the artery winds anteriorly, anterior to the fabellofibular ligament, and posterior to the PFL.[1,12,19,33,42] Along the anterior aspect of the knee, the artery travels anterior either within or just adjacent to the anterolateral ligament.[1,11] During lateral knee surgery, identification of the lateral inferior genicular artery serves a dual purpose. For one, it can help differentiate between the fabellofibular ligament and the PFL intraoperatively or on imaging examinations.[1,29] In addition, it is important to stop bleeding from the artery before closing of a lateral knee surgical incision site as hematoma formation at the fibular head has been reported to cause transient peroneal neuropraxia secondary to hematoma formation.[41]

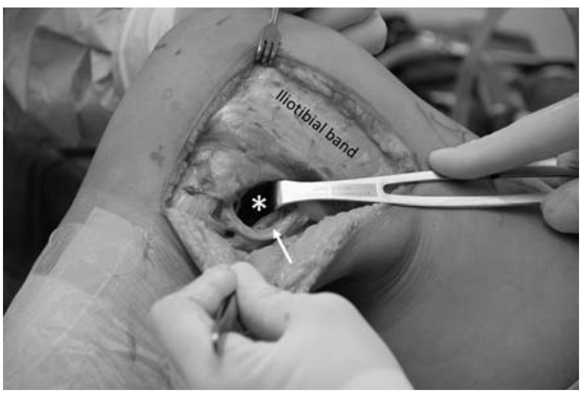

FIGURE 6. A peroneal neurolysis is performed to gently release and retract the peroneal nerve during a posterolateral corner reconstruction (arrow). The popliteus musculotendinous junction can be readily visualized through the interval between the lateral gastrocnemius tendon and soleus (star) (left knee).

BIOMECHANICS OF THE LATERAL KNEE

Recent biomechanical studies have demonstrated the importance of 3 essential structures of the lateral side of the knee: the FCL, PLT, and PFL. As demonstrated in early biomechanical cutting studies, the lateral structures of the knee function as the primary stabilizers against varus gapping, external rotation, and coupled posterolateral tibial translation.[43,44] In addition, these lateral knees structures also perform an important role in stabilizing against internal rotation.[3,45] Overall, the 3 primary lateral knee stabilizers and other lateral knee structures function to preserve normal knee kinematics and, therefore, the health of the entire knee. Furthermore, preservation or restoration of lateral knee stability is especially important in patients who received anterior cruciate ligament and posterior cruciate ligament reconstructions, as chronic lateral knee instability has been associated with increase strain on cruciate ligament grafts and an increased risk of graft failure.[46–48] This section will review the individual and collective functions of the FCL, PLT, and PFL along with an emphasis on the biomechanics of grade III (complete) lateral knee injury.

FCL

The FCL is the primary restraint to varus instability in the knee.[3,43,44] In response to applied loads, the FCL is loaded by varus-directed forces and internal and external rotational torques, of the tibia on the femur, whereas anterior and posterior drawer forces and valgus stress do not load the FCL (Fig. 7).[45] The highest forces exerted on the FCL reportedly occur with the knee in full extension coupled with external rotation. In a sectioning study performed by Coobs et al,[3] the function of the FCL was investigated by comparing intact knees to FCL-sectioned knees by applying a varus moment and internal and external torques. Results demonstrated that sectioning the FCL resulted in significantly increased varus rotation and internal rotation at all tested flexion angles (0, 15, 30, 60, and 90 degrees). Conversely, external rotation was only significantly increased at 60 and 90 degrees of knee flexion. Lateral compartment gapping of 2.7 mm to 4.0 mm on stress radiographs taken at 20 degrees of knee flexion is commonly seen in FCL-deficient knees (Table 1).[49] In an ACL-deficient knee, the FCL has been reported to function as a primary restraint to varus gapping and a secondary restraint to anterior translation and internal rotation.[50] Thus, the functional contributions of the FCL are dependent on both knee flexion angle and the presence of other knee stabilizers including the anterior cruciate ligament. Furthermore, understanding of the functional contributions of the FCL have laid the groundwork against which anatomic FCL reconstruction techniques have been evaluated for their ability to restore normal knee kinematics.[3]

As for the structural properties of the FCL, LaPrade et al[51] reported the FCL has a mean ultimate failure strength of 295 N and a stiffness of approximately 33.5 N/m. However, as noted in the study, these loads are much lower than the failure loads for the cruciate ligaments and, therefore, the FCL likely functions in combination with the other main lateral knee structures in resisting load.[51] Injuries to the FCL also place other ligament reconstructions at risk of failure. In several studies simulating FCL tears, lateral knee instability after FCL injury resulted in increased strain on anterior cruciate ligament and posterior cruciate ligament reconstruction grafts.[46–48] LaPrade et al[48] reported that FCL sectioning resulted in increased forces on the

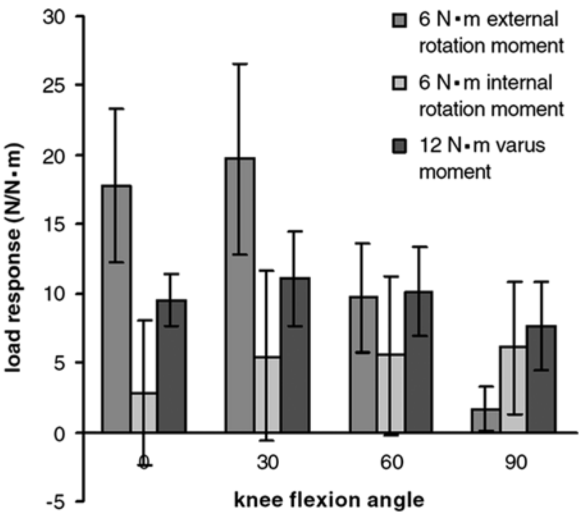

FIGURE 7. Forces on the fibular collateral ligament (FCL) during a 6 N m external rotation moment, 6 N m internal rotation moment, and 12 N m varus moment. Results demonstrate consistent loading of the FCL with a varus moment and greater loading at 0 and 30 degrees of flexion with an external rotation moment compared with higher knee flexion angles. Reproduced with permission from LaPrade et al.[45]

anterior cruciate ligament graft under varus loading at 0 and 30 degrees of knee flexion. Similar increased forces on the posterior cruciate ligament reconstruction graft[47] and increased posterior translation, external rotation, and varus rotation[46] have been reported after combined injury to lateral knee structures. Therefore, in cases of combined lateral knee and cruciate ligament injury, it is essential to surgically repair or reconstruct lateral knee injuries, such as injury to the FCL, in addition to performing a cruciate ligament reconstruction.

PLT

The PLT has been reported to perform a similar role to the FCL as a restraint to internal and external rotation of the tibia on the femur. In a cadaveric cutting study performed by Ferrari et al,[52] internal and external rotation were measured in intact knees and knees with partial and complete PLT detachment at 0, 30, 60, and 90 degrees of flexion. Results demonstrated increased internal and external rotation after internal and external moments were applied in knees where the PLT had been partially or completely detached at its femoral insertion. In a similar study, LaPrade et al[45] reported that an external rotation

TABLE 1. Mean Side-to-Side Difference in Varus Gapping on Varus Stress Radiographs and the Corresponding Injury Pattern[48]

Lateral Compartment Gapping*	Injury
0-2.4 mm	Physiologic laxity or grade I or II sprain
2.4-4 mm	Isolated grade III FCL tear
> 4 mm	Complete grade III PLC tear

*Thresholds in lateral compartment gapping are determined by obtaining a varus stress radiographs with a clinician applied force with the knee in 20 degrees of flexion.

FCL indicates fibular collateral ligament.

torque was the only applied load that substantially loaded the PLT, with the highest load seen at 60 degrees of knee flexion (Fig. 8). In a later sectioning study, LaPrade et al[7] studied the effect of internal and external rotation torques, a varus moment, and anterior and posterior forces following sectioning of the PLT. Significant differences compared with the intact state were found for external rotation at 30, 60, and 90 degrees of flexion, internal rotation at 0, 20, 30, 60, and 90 degrees of flexion, varus angulation at 20, 30, and 60 degrees of flexion, and anterior translation at 0, 20, and 30 degrees of flexion. No significant differences in posterior translation were found between the intact knee and PLT-sectioned knee. The authors concluded that the PLT has a primary role in external stability, with smaller, significant roles as a stabilizer to internal rotation, varus angulation, and anterior translation. These findings have since been used to develop and validate anatomic-based PLT reconstruction techniques for their ability to restore normal knee kinematics.

With respect to structural properties, the PLT reportedly has the highest ultimate failure and stiffness of the primary 3 lateral knee structures.[51] With ultimate failure strength of 700 N and a stiffness of 83 N/m, the PLT seems particularly able to withstand large loads. However, when injuries do occur, unrecognized PLT injuries combined with injury to other lateral knee structures results in significantly increased forces on ACL or PCL reconstruction grafts[47,48] and increased posterior translation, external rotation, and varus rotation in PCL-reconstructed knees.[46] Therefore, restoration of PLT function either via primary repair in acute cases of PLT avulsion fractures or reconstruction for midsubstance tears or chronic injuries is required.

PFL

Although the functions of the FCL and PLT have historically been appreciated as essential for preserving lateral knee stability, the PFL has received comparatively little attention.[43,44,46] Despite this, the PFL nevertheless plays an important role in lateral knee stability. The PFL reportedly undergoes substantial loading with applied

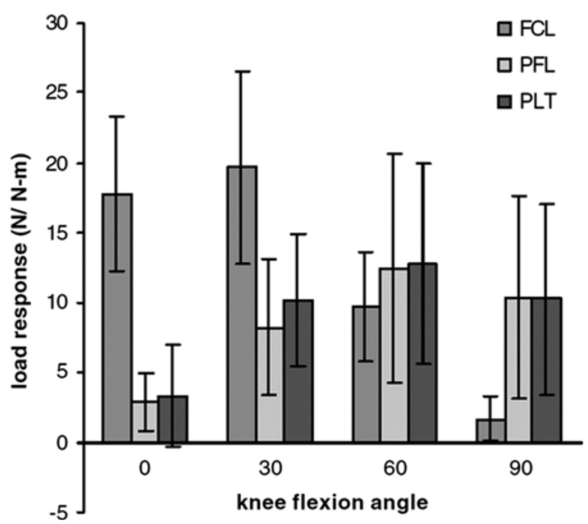

FIGURE 8. Forces measurements in response to a 6 N m external rotation torque in the fibular collateral ligament (FCL), popliteofibular ligament (PFL), and popliteus tendon (PLT). Reproduced with permission from LaPrade et al.[45]

external rotation torques, with the highest forces on the ligament observed with the knee at 60 degrees of flexion (Fig. 8).[45] Therefore, the ligament offers substantial contributions to lateral knee stability as a primary stabilizer against external rotation of the tibia on the femur. The PFL has been reported to have a mean ultimate failure strength of 298 N and a stiffness of approximately 29 N/m.[51] Just as with the FCL, the PFL is much weaker than the cruciate ligaments and therefore must function in combination with the other lateral knee structures.[51] As with injuries to the FCL and PLT, sectioning of the PFL has been shown to play a role in the increased forces seen on anterior and posterior cruciate ligament reconstruction grafts with combined posterolateral knee injuries.[47,48] A study by McCarthy and colleagues determined that reconstructing the PFL is required to restore normal lateral knee kinematics when performing a total posterolateral corner reconstruction.[5,8]

Grade III Injury to Posterolateral Structures

As described above, the FCL, PLT, and PFL all perform important roles as stabilizers in the posterolateral knee. Therefore, grade III injury to the posterolateral knee, defined as complete tears of each of these 3 structures, profoundly alters the normal biomechanics of the knee. In comparison with the intact knee, McCarthy and colleagues reported that a grade III posterolateral injury resulted in significantly increased external rotation after an applied external rotation torque and increased varus rotation after an applied varus load at all knee flexion angles (at 0, 20, 30, 60, and 90 degrees), as well as increased internal rotation after an applied internal rotation torque at 60 and 90 degrees of knee flexion.[8] A grade III posterolateral injury has been reported to significantly increase the force on reconstructed anterior cruciate ligament grafts after varus loading at 0 and 30 degrees of knee flexion, as well as with coupled varus loading and internal rotation at 0 and 30 degrees of knee flexion.[48] Lateral compartment gapping of 4.0 mm or greater on varus stress radiographs obtained at 20 degrees of flexion are indicative of a total posterolateral corner injury.[49] In addition, grade III posterolateral injury has also been reported to result in significantly increased force on posterior cruciate ligament reconstruction grafts under both an applied varus moment and a coupled posterior drawer force and external rotation torque at 30, 60, and 90 degrees of knee flexion. Furthermore, a significant increase in force on posterior cruciate ligament reconstruction grafts was seen under an external rotation torque at 60 degrees of knee flexion.[47]

As reviewed above, the individual and collective functions of the FCL, PLT, and PFL provide the knee with stabilization against varus rotation, external rotation, internal rotation, and posterior tibial translation. Injury to any or all of these structures may subsequently result in residual instability of the knee or negatively impact the success of cruciate ligament reconstructions. Therefore, special emphasis should be placed on both accurate diagnosis and repair or reconstruction of lateral knee injuries.

CONCLUSIONS

The anatomy and biomechanics of the lateral knee form an essential foundation for improving the diagnosis of lateral knee injuries, developing anatomic reconstruction techniques, and validating lateral knee surgical repair and reconstruction techniques. Recent advances in understanding of lateral knee anatomy and biomechanics have in turn led to improved patient outcomes following lateral knee injuries.

REFERENCES

1. Moorman CT III, LaPrade RF. Anatomy and biomechanics of the posterolateral corner of the knee. *J Knee Surg*. 2005;18: 137–145.
2. Thaunat M, Pioger C, Chatellard R, et al. The arcuate ligament revisited: role of the posterolateral structures in providing static stability in the knee joint. *Knee Surg Sports Traumatol Arthrosc*. 2014;22:2121–2127.
3. Coobs BR, LaPrade RF, Griffith CJ, et al. Biomechanical analysis of an isolated fibular (lateral) collateral ligament reconstruction using an autogenous semitendinosus graft. *Am J Sports Med*. 2007;35:1521–1527.
4. Horst PK, LaPrade RF. Anatomic reconstruction of chronic symptomatic anterolateral proximal tibiofibular joint instability. *Knee Surg Sports Traumatol Arthrosc*. 2010;18:1452–1455.
5. LaPrade RF, Johansen S, Wentorf FA, et al. An analysis of an anatomical posterolateral knee reconstruction: an in vitro biomechanical study and development of a surgical technique. *Am J Sports Med*. 2004;32:1405–1414.
6. LaPrade RF, Ly TV, Wentorf FA, et al. The posterolateral attachments of the knee: a quantitative and qualitative morphologic analysis of the fibular collateral ligament, popliteus tendon, popliteofibular ligament, and lateral gastrocnemius tendon. *Am J Sports Med*. 2003;31:854–860.
7. LaPrade RF, Wozniczka JK, Stellmaker MP, et al. Analysis of the static function of the popliteus tendon and evaluation of an anatomic reconstruction: the "fifth ligament" of the knee. *Am J Sports Med*. 2010;38:543–549.
8. McCarthy M, Camarda L, Wijdicks CA, et al. Anatomic posterolateral knee reconstructions require a popliteofibular ligament reconstruction through a tibial tunnel. *Am J Sports Med*. 2010;38:1674–1681.
9. LaPrade RF, Johansen S, Engebretsen L. Outcomes of an anatomic posterolateral knee reconstruction: surgical technique. *J Bone Joint Surg Am*. 2011;93(suppl 1):10–20.
10. LaPrade RF, Johansen S, Agel J, et al. Outcomes of an anatomic posterolateral knee reconstruction. *J Bone Joint Surg Am*. 2010;92:16–22.
11. Claes S, Vereecke E, Maes M, et al. Anatomy of the anterolateral ligament of the knee. *J Anat*. 2013;223:321–328.
12. Terry GC, LaPrade RF. The posterolateral aspect of the knee. Anatomy and surgical approach. *Am J Sports Med*. 1996;24: 732–739.
13. Griffith CJ, Wijdicks CA, Goerke U, et al. Outcomes of untreated posterolateral knee injuries: an in vivo canine model. *Knee Surg Sports Traumatol Arthrosc*. 2011;19:1192–1197.
14. LaPrade RF, Wentorf FA, Crum JA. Assessment of healing of grade III posterolateral corner injuries: an in vivo model. *J Orthop Res*. 2004;22:970–975.
15. LaPrade RF, Wentorf FA, Olson EJ, et al. An in vivo injury model of posterolateral knee instability. *Am J Sports Med*. 2006;34:1313–1321.
16. Mysorekar VR, Nandedkar AN. The soleal line. *Anat Rec*. 1983;206:447–451.
17. Cohn AK, Mains DB. Popliteal hiatus of the lateral meniscus. Anatomy and measurement at dissection of 10 specimens. *Am J Sports Med*. 1979;7:221–226.
18. Simonian PT, Sussmann PS, van Trommel M, et al. Popliteomeniscal fasciculi and lateral meniscal stability. *Am J Sports Med*. 1997;25:849–853.
19. Stäubli HU, Birrer S. The popliteus tendon and its fascicles at the popliteal hiatus: gross anatomy and functional arthroscopic evaluation with and without anterior cruciate ligament deficiency. *Arthroscopy*. 1990;6:209–220.
20. Fulkerson JP, Gossling HR. Anatomy of the knee joint lateral retinaculum. *Clin Orthop Relat Res*. 1980;153:183–188.
21. Terry GC, LaPrade RF. The biceps femoris muscle complex at the knee. Its anatomy and injury patterns associated with acute

anterolateral-anteromedial rotatory instability. *Am J Sports Med*. 1996;24:2–8.
22. LaPrade RF, Hamilton CD. The fibular collateral ligament-biceps femoris bursa. An anatomic study. *Am J Sports Med*. 1997;25:439–443.
23. Dodds AL, Halewood C, Gupte CM, et al. The anterolateral ligament: Anatomy, length changes and association with the Segond fracture. *Bone Joint J*. 2014;96-B:325–331.
24. Vieira EL, Vieira EA, da Silva RT, et al. An anatomic study of the iliotibial tract. *Arthroscopy*. 2007;23:269–274.
25. Vincent JP, Magnussen RA, Gezmez F, et al. The anterolateral ligament of the human knee: an anatomic and histologic study. *Knee Surg Sports Traumatol Arthrosc*. 2012;20:147–152.
26. Hughston JC, Andrews JR, Cross MJ, et al. Classification of knee ligament instabilities. Part II. The lateral compartment. *J Bone Joint Surg Am*. 1976;58:173–179.
27. Johnson LL. Lateral capsualr ligament complex: anatomical and surgical considerations. *Am J Sports Med*. 1979;7:156–160.
28. Segond P. Clinical and experimental research on blood effusions of knee sprain. *Progres Medical*. 1879:1–85.
29. LaPrade RF, Gilbert TJ, Bollom TS, et al. The magnetic resonance imaging appearance of individual structures of the posterolateral knee. A prospective study of normal knees and knees with surgically verified grade III injuries. *Am J Sports Med*. 2000;28:191–199.
30. Lane CG, Warren R, Pearle AD. The pivot shift. *J Am Acad Orthop Surg*. 2008;16:679–688.
31. Leitze Z, Losee RE, Jokl P, et al. Implications of the pivot shift in the ACL-deficient knee. *Clin Orthop Relat Res*. 2005;436: 229–236.
32. Davies H, Unwin A, Aichroth P. The posterolateral corner of the knee. Anatomy, biomechanics and management of injuries. *Injury*. 2004;35:68–75.
33. Seebacher JR, Inglis AE, Marshall JL, et al. The structure of the posterolateral aspect of the knee. *J Bone Joint Surg Am*. 1982;64:536–541.
34. Munshi M, Pretterklieber ML, Kwak S, et al. MR imaging, MR arthrography, and specimen correlation of the posterolateral corner of the knee: an anatomic study. *Am J Roentgenol*. 2003;180:1095–1101.
35. Watanabe Y, Moriya H, Takahashi K, et al. Functional anatomy of the posterolateral structures of the knee. *Arthroscopy*. 1993;9:57–62.
36. Kawashima T, Takeishi H, Yoshitomi S, et al. Anatomical study of the fabella, fabellar complex and its clinical implications. *Surg Radiol Anat*. 2007;29:611–616.
37. Zeng SX, Dong XL, Dang RS, et al. Anatomic study of fabella and its surrounding structures in a Chinese population. *Surg Radiol Anat*. 2012;34:65–71.
38. Phukubye P, Oyedele O. The incidence and structure of the fabella in a South African cadaver sample. *Clin Anat*. 2011;24:84–90.
39. Bolog N, Hodler J. MR imaging of the posterolateral corner of the knee. *Skeletal Radiol*. 2007;36:715–728.
40. See A, Bear RR, Owens BD. Anatomic mapping for surgical reconstruction of the proximal tibiofibular ligaments. *Orthopedics*. 2013;36:e58–e63.
41. Girolami M, Galletti S, Montanari G, et al. Common peroneal nerve palsy due to hematoma at the fibular neck. *J Knee Surg*. 2013;26(suppl 1):S132–S135.
42. Kaplan EB. The fabellofibular and short lateral ligaments of the knee joint. *J Bone Joint Surg Am*. 1961;43:169–179.
43. Gollehon DL, Torzilli PA, Warren RF. The role of the posterolateral and cruciate ligaments in the stability of the human knee. A biomechanical study. *J Bone Joint Surg Am*. 1987;69:233–242.
44. Grood ES, Stowers SF, Noyes FR. Limits of movement in the human knee. Effect of sectioning the posterior cruciate ligament and posterolateral structures. *J Bone Joint Surg Am*. 1988;70:88–97.
45. LaPrade RF, Tso A, Wentorf FA. Force measurements on the fibular collateral ligament, popliteofibular ligament, and popliteus tendon to applied loads. *Am J Sports Med*. 2004;32: 1695–1701.
46. Harner CD, Vogrin TM, Höher J, et al. Biomechanical analysis of a posterior cruciate ligament reconstruction: deficiency of the posterolateral structures as a cause of graft failure. *Am J Sports Med*. 2000;28:32–39.
47. LaPrade RF, Muench C, Wentorf FA, et al. The effect of injury to the posterolateral structures of the knee on force in a posterior cruciate ligament graft: a biomechanical study. *Am J Sports Med*. 2002;30:233–238.
48. LaPrade RF, Resig S, Wentorf F, et al. The effects of grade III posterolateral knee complex injuries on anterior cruciate ligament graft force. A biomechanical analysis. *Am J Sports Med*. 1999;27:469–475.
49. LaPrade RF, Heikes C, Bakker AJ, et al. The reproducibility and repeatability of varus stress radiographs in the assessment of isolated fibular collateral ligament and grade-III posterolateral knee injuries. An in vitro biomechanical study. *J Bone Joint Surg Am*. 2008;90:2069–2076.
50. Wroble RR, Grood ES, Cummings JS, et al. The role of the lateral extraarticular restraints in the anterior cruciate ligament- deficient knee. *Am J Sports Med*. 1993;21:257–263.
51. LaPrade RF, Bollom TS, Wentorf FA, et al. Mechanical properties of the posterolateral structures of the knee. *Am J Sports Med*. 2005;33:1386–1391.
52. Ferrari DA, Wilson DR, Hayes WC. The effect of release of the popliteus and quadriceps force on rotation of the knee. *Clin Orthop Relat Res*. 2003;412:225–233.

