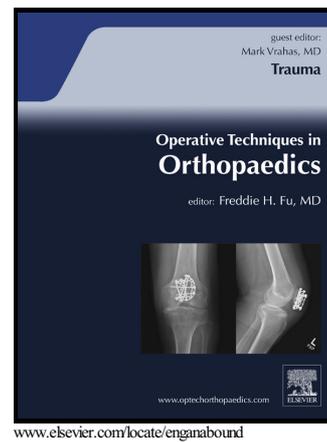# Author's Accepted Manuscript

Secondary Stabilizers of the ACL Deficient Knee

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Abstract:

Eliminating rotatory knee instability during anterior cruciate ligament (ACL) reconstruction surgery is crucial to ensure patients return to normal function after ACL injury. While the ACL is generally considered the primary soft tissue restraint to antero-posterior laxity of the knee, several additional structures, such as the anterolateral complex of the knee, lateral and medial menisci and their capsular attachments, posterolateral corner structures, and collateral ligaments, also play important roles in knee stability. While the primary goal of ACL reconstruction surgery should be to recreate the anatomic location and function of the native ACL, injuries to these other secondary restraints should also be evaluated and addressed surgically if necessary.

Introduction

Recurrent rotatory instability is the main reason patients do not return to normal function after traumatic anterior cruciate ligament (ACL) injury (1, 2). Furthermore, the grade of rotatory instability after ACL reconstruction is shown to be associated with poor patient reported outcomes and the long-term development of osteoarthritis (3, 4). Therefore, the purpose of ACL reconstruction surgery is generally aimed to eliminate the rotatory instability. However, surgeons must exercise caution not to over-constrain the knee, which could also lead to poor outcomes and premature arthritis (5). A thorough knowledge of secondary constraints and their contributions to rotatory knee stability will help surgeons maximize the outcomes of patients undergoing ACL reconstruction.

The motion of the knee joint is complex, with displacements and rotations occurring in multiple planes. Several structures work together to allow for this complex motion while still maintaining the stability of the knee joint. Joint stability is provided by: 1) the passive stabilizing function of the ligaments and capsule, 2) the active stabilizing function of the surrounding muscles, and 3) the bony geometry of the femur and tibia. The relative contribution of the passive stabilizers in each plane of the motion can be described by the concept of primary and secondary knee stabilizers. While the primary restraint has the greatest contribution to joint stability, the secondary restraints are involved to a lesser degree. Notably, the ACL is considered to be the primary stabilizer to both rotational and anterior laxity of the knee, especially at lower knee flexion angles. However, the role of secondary restraints should be acknowledged as well, since unaddressed injuries to these structures may result in residual instability after ACL reconstruction surgery. Moreover, failure to address these injuries at the time of ACL reconstruction could result in increased graft forces, and ultimately an increased risk of graft failure (6). This article will review the function of the ACL and commonly injured secondary restraints.

The Primary Stabilizer: Anterior Cruciate Ligament

The ACL consists of two functional bundles, the anteromedial (AM) and posterolateral (PL) bundles, named after their respective tibial insertion sites (7). These two bundles work synergistically to stabilize the knee throughout the entire range of motion (7-9). Apart from being the primary stabilizer to anterior translation of the knee, the ACL also plays an important role in rotational knee stability, especially in lower flexion angles (10-12). Several classic orthopedic articles have shown that in the presence of an intact ACL, injuries to other structures such as the anterolateral capsule, medial and lateral menisci, lateral collateral ligament, or posterolateral complex have a limited effect on the rotatory knee stability (11, 13). These findings highlight the importance of recreating the native anatomy of the ACL during reconstruction surgery to optimize knee stability. However, secondary stabilizers still play an important role and should be considered in all ACL injured patients.

Secondary Stabilizers:

Lateral and Medial Menisci:

The role of the menisci is not limited to shock absorption and transfer of compressive forces in the knee. The menisci also have an important role in the antero-posterior and rotational stability of the knee joint in the setting of ACL-deficiency (Figure 1) (14-16).

Injuries to the lateral meniscus happen more commonly with ACL injury (17). Cadaveric studies have demonstrated that lateral meniscectomy in ACL deficient knees result in increased rotatory laxity (14). Clinical studies have corroborated these findings by showing a higher grade of rotatory laxity during pivot shift testing in patients with concomitant ACL and lateral meniscus injury (Figure 2) (18, 19).

Likewise, medial meniscus insufficiency has been demonstrated to result in increased antero-posterior translation of the ACL deficient knee during Lachman testing (14) and increased rotatory laxity during quantitative pivot shift testing (20). Recently, studies have drawn attention to posteromedial meniscocapsular junction injuries found in conjunction with an ACL injury (21). Although it is known that the posterior horn of the medial meniscus has firm attachments to the posterior knee capsule, data regarding the role of meniscocapsular lesions on the rotatory stability of the knee are limited. One recent cadaveric study revealed increased anterior translation and external rotation with these lesions (22). Importantly, these injuries may not be detected in preoperative imaging and thus necessitate careful arthroscopic examination (23).

Meniscus Root

The meniscus root plays an especially important role in the normal function of menisci. The integrity of the root allows the menisci to preserve their load-transferring function by converting the axial load to circumferential hoop stress, while preserving proper knee kinematics (24, 25). Injuries to the meniscus root have substantial consequences, as in vitro biomechanical studies showed that outcomes following lesions to the meniscus root are comparable to total meniscectomy (26). Moreover, the stabilizing function of menisci becomes critically important in setting of ACL injury. For instance, lateral meniscus root injuries are reported to be identifiable in 8% of ACL injured patients (27) and have been shown to increase the rotatory laxity of ACL deficient knees during a simulated pivot shift (28). Likewise, lesions of medial meniscus root result in increased instability of ACL deficient knee (29). Thus, surgeons should aim to identify and repair meniscus root tears to restore its load transferring and stabilizing functions.

In summary, ACL surgeons should attempt to preserve the function of the menisci to the greatest degree possible. While many acute meniscal injuries can be repaired, high-grade injuries that require significant resection may necessitate future meniscal allograft

transplantation surgeries. Appropriate treatment of meniscal injuries benefits ACL-injured patients in the short-term by restoring the stabilizing function of the meniscus, and in the long-term by restoring its load transferring properties.

Anterolateral Complex

The anterolateral structures of the knee have long been considered as secondary knee stabilizers (30, 31). Recent reports have suggested that a distinct ligamentous structure in the anterolateral region of the knee, known as the anterolateral ligament (ALL), provides a significant contribution to rotatory knee stability. These recent studies have led to a resurgence of interest in the anterolateral knee structures and their role in rotatory instability of ACL injured patients (32, 33). However, there is great controversy in the current literature regarding the anterolateral structures' anatomy (32-34), prevalence of a distinct ALL (32, 35-38), contribution to joint stability (39-44), and proposed treatment options (23, 45, 46). For standardization purposes and due to the close proximity of multiple contributory anterolateral structures, it is the authors preference to refer to these structures collectively as the anterolateral complex (ALC), which includes the iliotibial band (ITB), the Kaplan fibers, the capsulo-osseous layer of the ITB, and the anterolateral capsule.

Prevalence of a Distinct ALL: While some cadaveric studies reported an identifiable ligamentous ALL to be present in nearly all of the specimens examined, other studies reported to find it in only 30-50% of the specimens (32, 34, 36, 38, 47, 48). In the only study examining pediatric cadaver specimens, the authors reported finding a distinct ALL in only 1 of 8 specimens (49). Interestingly, some authors have enhanced the existence of this structure with their dissection techniques by internally rotating the tibia and removing any surrounding tissue not under tension (40, 50). The lack of consistent dissection techniques, varying specimen preservation techniques, wide ranges in the age of studied specimens, and the lack of standard descriptions of anterolateral knee anatomy all contribute to discrepant reports in the literature (32, 36).

In Vitro Biomechanics: Controversy also exists in the literature regarding the role of ALC on rotatory stability. Sonnery-Cottet et al. demonstrated that sectioning of the ITB increased rotational laxity in an ACL intact knee; moreover, it was demonstrated that sectioning of the ALL further increased rotational laxity after sectioning of the ITB (51). Several in vitro biomechanical studies have shown that resection of the ALL resulted in increased rotational laxity of ACL injured knee, especially in higher flexion angles (39, 41, 46). Other studies revealed that when lesions of the ALL were associated with preserved ITB function in whole lower limb cadavers, no increase in rotatory laxity was observed during pivot shift testing (42). Similarly, studies that distinguished the role of the deep layer of the ITB (capsulo-osseous layer) from the ALL suggested a more important role for the ITB as compared to the ALL (52). More recently, it has been determined that separating the area of the lateral capsule that includes the ALL (to simulate an ALL-sparing injury) has a much greater effect on joint stability as compared to transecting the ALL (53, 54). This suggests that the

anterolateral capsule contributes to joint stability as a whole sheet of tissue, rather than as a traditional ligamentous structure (Figure 3) (53, 54). In fact, the role of the anterolateral capsule was more remarkable in higher flexion angles, whereas the ACL was the primary restraint in lower flexion angles, where most in vivo activities occur (55, 56).

In Vivo Biomechanics: Few studies have evaluated the role of anterolateral complex in patients. Two recent studies suggested that acute injuries to the anterolateral capsular structures, as visible on magnetic resonance imaging (MRI), are associated with greater rotatory instability (18, 19). Using a quantitative methodology, it was demonstrated that MRI findings of anterolateral capsule injury were associated with an approximately 35-40% increase in the amount of lateral compartment translation during pivot shift testing in ACL injured patients (Figures 2) (19). Of note, the distinction of different anterolateral knee structures can be difficult with routine clinical MRIs (57). Hence, the structures observed on MRI often include the entire anterolateral complex. Overall, one can conclude that the anterolateral complex acts as a secondary restraint to rotatory knee stability in an ACL deficient knee; however, this role is likely not attributable to a specific ligamentous structure, but rather multiple components working synergistically.

Clinical Management: The appropriate management of patients with an anterolateral complex injury has yet to be elucidated. A recent case-series reported favorable outcomes for patients undergoing what they described as a combined "anatomic ALL reconstruction" and ACL reconstruction, although no control group was enrolled for comparison (23). In a cadaveric study, Helito et al. defined the radiographic landmarks of the ALL as they pertain to minimally invasive surgical reconstruction (58). In vitro biomechanical studies also supported the role of anatomic ALL reconstruction in the presence of combined ALL injuries (45). However, a separate study reported no added stability with an "anatomic ALL reconstruction" technique, yet supported a previously known extra-articular technique using an ITB tenodesis (46). On the other hand, extra-articular techniques that utilize the ITB as a graft have the potential risk of over-constraining the knee due to the stiffer tensile properties of the graft as compared to the native anterolateral structures (37, 59, 60). Moreover, the ITB functions as an ACL agonist, and using an ITB graft for an extra-articular reconstruction may impair its native contribution to knee stability (61). In fact, it is still unknown if injuries to the anterolateral complex need reconstruction surgery or if they could potentially heal on their own. Of note, several studies demonstrated that combined intra- and extra-articular ACL reconstruction results in over-constraining the internal rotation of the knee during in vivo activities (62). These findings underline the need for cautious evaluation before enhancing lateral side restraints of the knee by an additional reconstruction surgery.

Based on current evidence, routinely performing additional extra-articular reconstruction surgeries in conjunction with ACL reconstruction is not recommended. However, these procedures may be useful in a select subset of patients with significant rotatory instability due to ACL injury. Future prospective studies with long-term follow-up are needed to determine the appropriate indications (63).

Other Soft Tissue Stabilizers

As previously noted, several structures contribute to the stability of the knee joint. Injuries to the posterolateral corner (PLC) structures (lateral collateral ligament, popliteus complex) are often associated with cruciate ligament injuries (64, 65). Sectioning of PLC structures results in increased internal and external tibial rotation in ACL-deficient knees, as well as increased graft forces (potentially leading to increased graft failure rates) in ACL-reconstructed knees (11, 12, 66). In fact, in the presence of PLC injury, isolated ACL reconstruction does not restore the rotatory stability of the knee at 30° and 90° of flexion (67).

The medial collateral ligament (MCL) not only functions as the primary restraint to valgus deformity of the knee, (68) but also as a secondary restraint to anterior translation, (69, 70) internal rotation, (70) and external rotation of the tibia (71). Sectioning of the MCL has been shown to result in increased internal and external rotation laxity (72). MCL injuries are also important to consider in the context of pivot shift testing. As the MCL plays a significant role in the pivot shift mechanism by restraining the motion of the medial compartment when valgus force is applied, MCL insufficiency could result in a diminished pivot shift response (73).

Injuries to MCL and PLC need to be adequately addressed to achieve optimal outcomes. While no single treatment algorithm is universally agreed upon, there is a tendency to perform repair or reconstruction of higher-grade injuries. The timing and staging of these procedures is not standardized and often left to surgeon preference.

Additional Factors to Consider

There are other factors that need to be considered in the management of ACL injured patients. In addition to the soft tissue restraints, bony morphology (such as the tibial slope), biodynamic factors (such as the functional joint space, joint contact path, and muscle function), proprioceptive factors (such as neuromuscular control, knee abduction moments, and landing patterns), and biologic factors (such as genetic disorders and generalized joint hypermobility) all affect the rotatory stability of the knee (74). Consideration of each of these factors is crucial to individualizing treatment and improving patient outcomes.

Ideally, objective and quantitative assessment of rotatory knee stability (such as pivot shift testing) would be performed preoperatively, intra-operatively, and postoperatively. Preoperatively, this assessment could help identify high-risk patients with excessive rotatory instability. Intra-operatively, it could help to confirm the restoration of normal joint stability, and potentially determine the need for secondary procedures. Post-operatively, it could help to verify the graft and secondary restraint healing process and assess return to play readiness (63). However, this type of objective assessment necessitates reliable and valid non-invasive technologies that can be used in everyday clinical practice (75). Future studies will be needed to further refine these quantitative assessment methods and to develop treatment algorithms based on the quantitative testing.

Conclusion

Joint stability in the setting of ACL injury is multifactorial. Methodical and objective assessment of each of these contributing factors is critical to ACL reconstruction success. While the primary goal of ACL reconstruction should be to recreate the native ACL anatomy and function, additional procedures will sometimes be needed. However, treatment plans should be individualized for each patient, and caution should be exercised to avoid over constraint. Future studies will be needed to further refine quantitative joint stability testing and to develop evidence-based treatment algorithms based on individual patient pathology.

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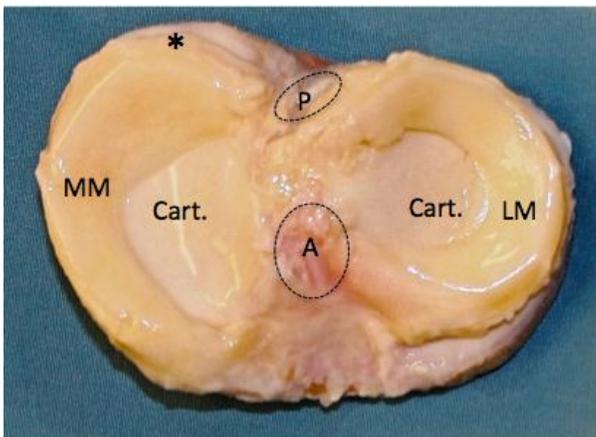
Figure 1: Axial view of the Right Proximal Tibia Demonstrating its Anatomical Structures. Both lateral and medial menisci play important role in stability of the knee joint as well as transferring the compressive loads. The posterior attachments of MM to knee capsule have role in rotational stability of the knee. Medial meniscus (MM), lateral meniscus (LM) articular cartilage (Cart.), ACL insertion site (A), PCL insertion site (P), and posterior meniscocapsular junction (*).
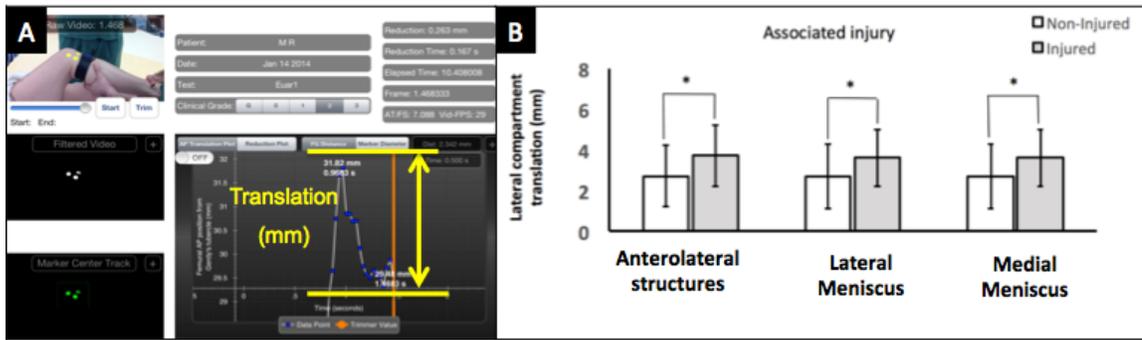
Figure 2: Quantitative Pivot Shift Test Results. A) Screen shot the computer tablet demonstrating the reduction plot during pivot

shift test. The difference between the maximum and minimum points of the reduction plot represents the anterior translation of the

tibia during pivot shift test.

B) Injury to the anterolateral structures, lateral meniscus or medial meniscus, as determined on MRI, was associated with an increased

amount of lateral compartment translation in anterior cruciate ligament injured patients.
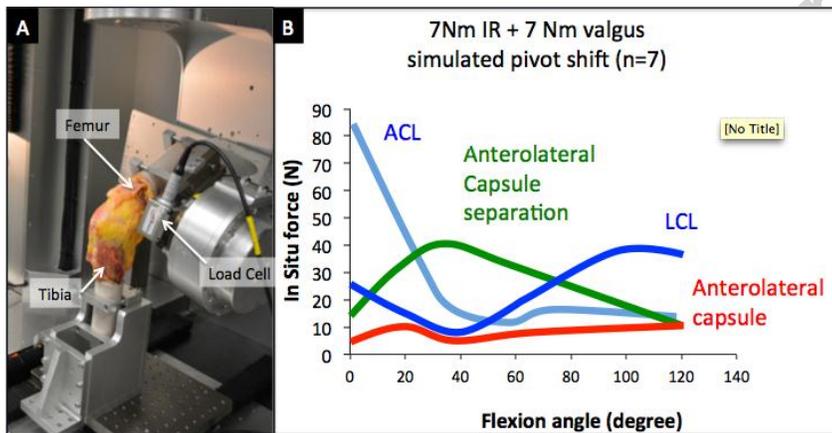
Figure 3: Robotic Pivot Shift Testing. A) Testing set up for simulation of the pivot shift test of a right knee joint by a robotic system.

B) In situ forces of the knee structure in response to simulated pivot shift test (7 N-m of Internal rotation + 7 N-m of valgus torque)

performed by the robotic system. The anterolateral capsule experiences negligible forces in the proximal-distal direction, indicating it

does not function like a ligament.