Navigated Knee Kinematics After Tear of the ACL and Its Secondary Restraints: Preliminary Results

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In this study we evaluated the role of the anterior cruciate ligament (ACL) and its secondary restraint in controlling knee stability using a navigation system. The purpose of this study was to evaluate the kinematics of the knee in different conditions of instability: ACL intact, after transection of the posterolateral (PL) bundle, after transection of the anteromedial (AM) bundle, and after lesion of the anterolateral femorotibial ligament (ALFTL). Anterior tibial translation and rotation were measured with a computer navigation system in 6 knees in whole fresh-frozen human cadavers by use of a manual maximum load. Anterior translation was evaluated at 30°, 60°, and 90° of flexion; rotation at 0°, 15°, 30°, 45°, 60°, and 90° of flexion. Cutting the PL bundle does not increase anterior translation and rotation of the knee. Cutting the AM bundle significantly increased the anteroposterior (AP) translation at 30° and 60° of flexion (P=.01), but does not increase rotation of the knee. Cutting the ALFTL increased anterior translation at 60° of flexion (P=.04) and rotation at 30°, 45°, and 60° of flexion (P=.03). The PL bundle does not affect anterior translation and rotation of the knee. The AM bundle is the primary restraint of the anterior translation but does not affect rotation of the knee. The lateral compartment becomes the primary restraint of rotation after ACL cut. The primary kinematic effect of an ACL injury is an increase in anterior tibial translation, but there is no significant change in maximum internal or external rotation. The lesion of the ALFTL increases tibial rotation and could be correlated to the pivot shift phenomenon.

The goals of reconstruction of the anterior cruciate ligament (ACL) should be to restore the kinematics of the injured knee to those of a normal knee.1 Although in recent years many studies demonstrated that reconstruction of the ACL restored functional knee stability in most cases, several studies have now shown that normal knee joint kinematics are not restored, with the pivot shift phenomenon remaining in >15% of cases.2-5 To address this problem, anatomic double-bundle ACL reconstruction has been proposed.6

Not all injuries to the ACL result in the same knee instability. Seldom is the ACL injured in isolation. Different degrees of ACL tear combined with damage to other intra- and extra-articular structures of the knee result in different patholaxities.7-9 A detailed understanding of which structures of the knee joint act as secondary restraints to the ACL and how their lesions correlate to clinical tests is necessary so that proper diagnosis can be made. Unrepaired secondary stabilizers have been noted as a cause for reconstruction failure.10

Recent studies have shown that ACL reconstruction is often successful in repairing anterior stability, while rotational instability often persists.1,11-14 The pivot shift test is the most specific test for knee rotational instability and is the only physical examination test that is correlated with the subjective feeling of instability.15 However this test is based on an examiner’s subjective feel of the rotation and translation of the tibia and is clearly subject to intraobserver variability.

Recent advances in navigation systems have provided an additional use for this technology in accurately evaluating the kinematics of the knee. Navigation can be used for better tunnel positioning during ACL arthroscopic reconstruction and to measure the exact displacements between

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the tibia and the femur. Navigation is becoming increasingly useful and, unlike other instruments used to measure knee laxity, it is not subject to the same interference by soft tissue.16,17

The goal of our study was to determine the kinematic changes of the knee after rupture of the ACL and the subsequent kinematic changes that occur with additional injury to the anterolateral structures of the knee, with the ultimate aim being to determine the contribution of the anterolateral structure to the stability of the knee.

A computer navigation system enables precise quantification of the effect of each of these lesions on the knee stability. Systematic cutting of the 2 bundles of the ACL enables measurement of their individual contribution to knee stability.

Whereas previous research has looked at the role of the anterolateral structures and the lesions of the individual bands of the ACL, we have used computer navigation to quantify the effect of lesions in this area.7,16,18-21

**MATERIALS AND METHODS**

**Cadavers**

In this study we tested the kinematics of 6 knees in whole fresh-frozen human cadavers. The cadavers included 4 men and 2 women with an average age at death of 72 years (range, 63-80 years). The cadavers were stored at −20°C and thawed at room temperature for 24 hours before testing. Knees were examined and subsequently excluded from the study if they showed any signs of ligamentous injuries, severe osteoarthritis, bony abnormalities, or previous surgical intervention. The cadavers remained fully intact and no soft tissue was removed from around the knee, so as to most closely match a normal human knee. Saline solution was used to keep the specimens moist throughout testing.

**Computer Navigation System**

The 2.0 OrthoPilot ACL navigation system (B. Braun Aesculap, Tuttingen, Germany) was used to accurately calculate the knee kinematics. This system measured anterior tibial translation (ATT), internal rotation (IR), and external rotation (ER) of the tibia in relation to the femur.

The femoral and tibial transmitters were attached using 2.5-mm K-wires and various extra-articular landmarks were entered into the system using the straight pointer (third transmitter). The extra-articular landmarks registered were the tibial tuberosity, tibial crest, and medial borders of the tibial plateau (Figure 1). Knee flexion and internal and external rotation were also performed to register these movements in the system. The navigation system then generated a 3D image of the cadaveric knee and tracked its movement in space.

Anterior translation was recorded by the navigation system and expressed in millimeters. Values for internal and external rotation were expressed in degrees.

All measurements were recorded under a manual maximum force applied by the same senior surgeon (A.F.), who performed all procedures to minimize the interoperator variability and who made every effort to apply similar loading to the knee.

The manufacturer states that the system has an accuracy of 100% when the landmarks are registered correctly.

**Procedure**

We used the computer navigation system to measure maximum manual ATT, maximum manual IR, and maximum manual ER at 4 stages for each knee: (1) with the ACL and all other ligaments intact, (2) after transection of the PL bundle of the ACL, (3) after transection of the AM bundle of the ACL (complete loss of ACL), and (4) after lesion of the anterolateral portion of the knee joint capsule. These transections were performed consecutively so that each lesion was added to the ones done before.

The PL and AM bundles of the ACL were accessed arthroscopically, separated and excised 1 after the other.

The iliotibial tract was divided along its fibers and the articular capsule exposed. An incision approximately 2 cm long was made through the ALFTL at the level of the lateral joint line, below the lateral meniscus (Figure 2).

Anterior and rotational forces were applied manually by the same surgeon for all cadavers to minimize intraoperator variability. Effort was made to ensure that similar loading was applied to each knee. Maximal anterior translation of the tibia was measured at 30°, 60°, and 90° of knee flexion. (These angles were selected so as to correlate with standard clinical examination tests): the Lachman test, performed at 30° of knee flexion, and the anterior drawer test, performed at 90°. Maximal IR and ER of the tibia were...
measured at 0°, 15°, 30°, 45°, 60°, and 90° of flexion. More angles of knee rotation were measured to reflect the nature of the standard clinical test for rotational instability of the knee, the pivot shift, which is an active test performed through a cycle of flexion.

Statistical Analysis
All values were recorded in a standard Excel spreadsheet (Microsoft Office; Microsoft Corporation, Redmond, Washington). ANOVA 1-way analysis and MANOVA multivariate analysis of variance were used for statistical analysis of the data. The value for statistical significance was set at $P < .05$. We used unpaired Student t tests to determine whether statistically significant differences existed between the mean values for each stage.

RESULTS

Anterior Translation
Cutting the PL bundle alone did not result in any significant increase in anterior translation at any of the flexion angles measured ($P > .05$).

The additional lesion to the AM bundle produced noticeable increases in anterior translation compared with the isolated lesion of the PL bundle, with statistically significant increases seen at 30° and 60° of flexion ($P = .01$).

Comparing the ACL-deficient knee (both AM and PL bundles cut) to the intact ACL showed statistically significant differences at 30° and 60° of flexion ($P = .01$) and 90° of flexion ($P = .047$).

A lesion to the anterolateral structures resulted in a further increase in ATT at 30° and 60° of flexion, with a significant increase recorded at 60° ($P = .04$) (Figure 3).

Internal Rotation
Cutting the PL bundle saw minor increases in IR at all flexion angles except for 0°, but none of these were considered statistically significant ($P > .05$).

Minor increases in IR were seen at all flexion angles except for 15° of flexion when the AM bundle was cut, but these increases were also not deemed statistically significant ($P > .05$).

The anterolateral lesion produced increases in IR between 0° and 60° of flexion, with a significant increase seen at 0° ($P = .05$) (Table).

External Rotation
Cutting the PL bundle showed no significant increase in ER at any of the flexion angles measured ($P > .05$).

Subsequent removal of the AM bundle produced minor increases in ER at all angles except 0°, but none of the increases were statistically significant ($P > .05$).

The lesion to the anterolateral structures showed an increase in ER at all flexion angles, but was only considered statistically significant at 90° ($P = .02$) (Table).

Combined Rotation
No significant change was observed in combined rotation at any of the flexion angles measured when the PL bundle of the ACL was cut ($P > .05$).

Small increases were observed in combined rotation when comparing the intact ACL with the ACL-deficient knee (PL + AM bundle cut); however, none of these were statistically significant ($P > .05$) (Table).

A lesion to the anterolateral structures in the absence of the ACL resulted in an increase in combined rotation at all flexion angles, with statistically significant increases seen at 30°, 45°, and 60° ($P = .03$) (Figure 4).

DISCUSSION
This study measured the kinematic effect of lesions to the AM and PL bundles of the ACL as well as lesions to the anterolateral knee structures. A computer navigation system was used to enable precise evaluation of the effect of each of these lesions.
Although single-bundle ACL reconstruction techniques restore functional knee stability in most cases, several studies have now demonstrated that normal knee joint kinematics are not fully restored in rotational stability and that 14% to 30% of patients may have a residual pivot glide.22-27 It has been well known since Palmer’s27 report in 1938 that the ACL is composed of 2 distinct bundles, the AM and the PL, and recent research has a high focus on comparing double- and single-bundle techniques to determine which is superior, mostly with regard to rotational control.

The reliability of the navigation system in evaluating knee kinematics during ACL reconstruction has been well documented.16,28-30 This system measures the exact displacement between the tibia and the femur. The navigation system transmitters are fixed directly to the tibia and femur by K-wire and unlike other instruments used to measure knee laxity, it is not subject to the same interference by soft tissue (Figure 1).31,32

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<tr>
<th>IR (°)</th>
<th>AM+PL CUT (NO ACL)</th>
<th>ACL</th>
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ER+IR (°)

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Abbreviations: ACL, anterior cruciate ligament; ALFTL, anterolateral femorotibial ligament; AM, anteromedial bundle; ER, external rotation; IR, internal rotation; PL, posterolateral bundle.

ᵃP = comparison with AM+PL cut (NO LCA)
ᵇP = comparison with ACL

Values that are statistically significant are expressed in bold italics.
has an overall accuracy of approximately 1 mm or 1/100. Moreover surgical navigation systems seem to be precise intraoperative tools to quantify knee stability and may help delineate complex rotatory stability patterns of knee motion. More recently, Pearle et al reviewed conventional stability measurements of the knee and compared them with navigated techniques, focusing on the navigated pivot shift examination: they demonstrated that direct intraoperative measurements and quantifications of knee stability, including the pivot shift phenomenon, are now possible with the use of navigation.

Although the Lachman test is the most valid test for ACL insufficiency, the pivot shift examination better correlates with functional instability and patient outcomes; it reproduces the functional combined rotatory and translational instability in the ACL-deficient knee. This test evaluates a special form of lateral compartment instability, which is characterized by anterior subluxation of the tibial plateau out from beneath the lateral femoral condyle.

A better understanding of the pathogenesis of rotational instability could be useful to help surgeons find better surgical solutions.

The anterolateral stabilizing structures of the knee joint include the capsular ligament and the iliotibial tract. The anterior portion of the capsule is reinforced by superior and inferior retinacula and the vastus lateralis muscle; the iliotibial tract is an extension of the fascia lata and attaches at the Gerdy tubercle on the anterolateral surface of the tibia.

The ALFTL refers to an area of capsule thickening at the lateral margin of the tibial plateau, deep to the iliotibial band.

In 1976, Hughston proposed a classification for knee ligament instabilities and divided lateral compartment instability into 6 types (anterolateral rotatory instability; posterolateral rotatory instability; combined anterolateral and posterolateral rotatory instability; combined anterolateral and anteromedial rotatory instability; combined posterolateral, anterolateral and anteromedial rotatory instability; straight lateral instability), pointing out the attention to the difficult about a prompt diagnosis of these lesions. Moreover, the lateral capsular structures are involved in preventing anterior subluxation of tibial plateau as the tibia is internally rotated. The aim of our study was to evaluate kinematic changes in the knee after lesion of the ALFTL associated with ACL tears rather than the injury of the ACL alone.

The results of our study showed that, in combined IR and ER, no significant changes were observed when only the PL bundle of the ACL was cut ($P>0.05$) and only a small and not statistically significant increase was observed when both bundles were sectioned. However, a lesion to the ALFTL in the previously sectioned ACL resulted in an increase in combined rotation with statistically significant increases seen at 30°, 45°, and 60° flexion angles ($P=0.03$).

The entire cadaver was used and all soft tissues remained in place to limit the effect that removal might have (Figure 1).

In previous biomechanical studies, the femur and tibia were cut approximately 20 cm from the joint line, and the surrounding skin and muscles that were 10 cm away from the joint line were removed to expose the bone, showing that the PL bundle was the main structure limiting IR of the knee. In our results, cutting off the PL bundle alone resulted in no significant increase in IR. Using the entire leg in a cadaver rather than using an amputated limb could account for the differences between our results and those of other studies. In the amputated knee, the loss of tension of the peripheral myotendinous structures can result in overestimation of the biomechanical role of the ACL itself.

Previous research has shown the anterolateral structures of the knee to act as secondary stabilizers to the ACL. In their 1993
study, Wrobles et al. found that sectioning the anterolateral structures (iliotibial band and midlateral capsule) in ACL-deficient knees increased anterior translation. They also noted consistent increases in IR when the anterolateral structures were sectioned, with some knees only showing significant increases once the anterolateral structures were cut (not when only the ACL was cut). Samuelson et al. also found that the anterolateral structures contribute as secondary restraints to the ACL. Our results support these findings.

It is well known that injuries of the ACL are frequently associated with mild tears of anterolateral and posterolateral capsular ligaments without or with bony avulsion (Segond fracture) (Figure 5). Moreover, in knees with chronic ACL insufficiency, a progressive stretching of secondary restraints in the lateral structures of the knee often occurs. Based on our results, we believe that repair in acute cases or reconstruction in chronic cases should be considered to restore rotational stability and limit pivot shift.

The advancement of arthroscopic surgical techniques for ACL reconstruction has meant that extra-articular structures are no longer necessarily observed during a routine ACL reconstruction. Thus, the integrity of these structures is not always examined and it is possible that injuries to these areas may be overlooked during a routine ACL reconstruction. George et al. noted that a failure to recognize and treat concomitant injuries to the secondary restraints places increased stress on the reconstructed ACL and can be a reason for failure.

Current research about ACL reconstruction has a high focus on comparing double- and single-bundle techniques to determine which is superior, mostly with respect to rotational control. It is possible that previous research, which suggests that the anterolateral structures are an important secondary restraint to the ACL, is being overlooked.

Our results support this research and confirm the importance of the ALFTL in controlling both anteroposterior and rotational stability of the knee. Our results suggest that treatment be focused on the possible associated lesions rather than the type of ACL reconstruction to control rotational stability. Some authors have found significant improvement in objective knee laxity when the lateral plastic was added to a single-bundle ACL reconstruction. In an in vitro analysis, the extra-articular plastic, associated with intra-articular reconstruction, seems to protect the graft, reducing the stress by 43%. Other authors showed in cadaveric studies that repairing the lateral lesion reduces tibial rotation and the displacement of the lateral compartment with less risk of pivoting of the knee. Recently Ferretti et al. always using a navigation system, showed that a single-bundle plus extra-articular reconstruction is more effective than a double-bundle reconstruction in controlling IR of the knee.

The use of cadaveric specimens has a number of limitations. The age at death of the cadavers ranged from 60 to 80 years, which is much older than the average age of people who suffer ACL injuries. Woo et al. looked at the effect of the age on the ACL and its bony attachments and found that ultimate load and stiffness reduced with age. It is therefore possible that, because these cadaveric knees were much older than the average population age of people who suffer ACL injury, the observed laxity in the cadaveric specimens could be greater than what would be expected in the average patient. However, compared with other cadaveric studies looking at knee kinematics, our comparisons with previous studies are valid.

Our relatively small sample size makes it difficult to draw any major conclusions from these data. It would be worthwhile to continue this research with more specimens to strengthen the evidence and enhance the reliability of this study. Our specimen number, however, was consistent with other cadaveric studies in this field.

The cutting order of the ligaments also created some limitations for our study, because a complex interaction exists between each of the components that contribute to knee stability. Because the cutting order was identical for each cadaver, the effect of each new lesion was only measured in addition to the previous lesions.

To measure the kinematic changes, external loads were applied manually, so it is possible that forces applied may have differed.

The strength of our study is that we used entire cadaveric specimens and all soft tissue remained in place to limit any changes in knee kinematics that may occur with their removal. Previous cadaveric studies have used lower cadaveric specimens and dissected away soft tissue surrounding the knee.

Moreover we used a computer navigation system that allowed precise evaluation of the kinematic changes that occurred after each lesion.

Based on our results, we can assume that the PL bundle seems to be not much involved in controlling AP translation or rotation of the knee. The fact that no significant rotational instability was seen until after the lesion to the ALFTL may suggest that rotational instability may be due to secondary injuries in conjunction with injuries to the ACL.

CONCLUSION

Despite great interest and consensus for more anatomic double-bundle ACL reconstructions, we believe it is more correct and biomechanically valid to repair the lesion associated with the anterolateral structure of the knee at the same time as the ACL reconstruction (suture in acute cases and reconstruction in chronic cases) to prevent the pivot shift phenomenon and the possible need for subsequent revision surgery.

REFERENCES


