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Navigated knee kinematics after cutting of the ACL and its secondary restraint

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Abstract

Purpose The purpose of this study is to evaluate the kinematics changes of the knee after cutting of the ACL with or without injury of the anterolateral structures.

Methods In this study, the role of the ACL and one of the secondary restraints in controlling knee stability using a navigation system was evaluated. The kinematics of the knee was evaluated in different conditions of instability: ACL intact, after dissection of the posterolateral (PL) bundle, after dissection of the anteromedial (AM) bundle, and after lesion of the lateral capsular ligament (LCL). Anterior tibial translation and rotation were measured with a computer navigation system in 10 fresh-frozen cadaveric knees 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°.

Results 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° ($P = 0.01$), but does not increase rotation of the knee. Cutting the LCL increased anterior translation at 60° ($P = 0.04$) and rotation at 30°, 45°, and 60° ($P = 0.03$).

Conclusions Within the testing conditions of this study, 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 while the lesion of the LCL increases tibial rotation and could be related to the pivot shift phenomenon, so it is more correct and biomechanical valid to assess and repair the associated lesion of the antero-lateral structure of the knee at the time of ACL surgery.

Keywords Navigation · Knee kinematics · ACL

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Introduction

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 [39].

Not all injuries to the ACL result in the same knee instability. Seldom is the ACL injured in isolation [40].

Different degrees of ACL tear combined with damage to other intra- and extra-articular structures of the knee result in different patholaxities [8, 19, 22]. 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 [15].

Recent studies have shown that ACL reconstruction is often successful in repairing anterior stability, while rotational instability often persists [1–3, 5, 18, 20, 25, 34, 39]. 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 [24]. However, this test is based on an examiner's subjective feel of the rotation and translation of the tibia and is clearly subject to interobserver variability [25].

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 to measure the exact displacements between 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 [6, 21].

The goal of this study was to determine the kinematic changes of the knee after rupture of the ACL and changes that occurred with additional injury to the anterolateral structures; the ultimate aim being to determine the correlation between the pivot shift phenomenon and injuries to the ACL and anterolateral structures.

Although the role of the peripheral structures and their contribution to clinical knee instability was shown in several studies in the 1980s and 1990s, this is an important point that is sometimes lost in contemporary literature. Moreover, the use of new technology such as the navigation and the use of the entire cadaver specimens it is something different to other recent studies.

Materials and methods

The knee kinematics was tested on 10 whole fresh-frozen cadavers knees. The cadavers included 6 men and 4 women with an average age at death of 72 years (range, 63–80). The cadavers were stored at −20° C and thawed at room temperature for 24 h before testing. Samples were excluded from the study if they showed signs of ligamentous injuries, severe osteoarthritis, bony abnormalities, and previous surgical intervention. The cadavers remained fully intact and no soft tissue was cut or removed from around the knee or adjacent joints to most closely match a normal human knee (Fig. 1). Saline solution was used to keep the specimens moist throughout testing.

Fig. 1 A cadaveric knee during testing

Computer navigation system

The 2.0 OrthoPilot ACL navigation system (B. Braun Aesculap, Tuttlingen, Germany) was used to 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. Different extra-articular landmarks were entered into the system using the straight pointer (third transmitter): tibial tuberosity, tibial crest, and medial borders of the tibial plateau. Knee flexion and internal and external rotation were also performed to register these movements in the system. The system then generated a 3D image of the cadaveric knee and tracked its movement in space. Both anterior translation and internal–external rotation position of the tibia in space were measured continuously by the optical system recorded as the difference in position before/after the load was applied.

Anterior translation was recorded by the navigation system and expressed in millimetres while internal and external rotation were expressed in degrees, with no decimals. The accuracy of the navigation system was stated by the manufacturer as 100% if the landmarks are registered correctly.

All measurements were recorded under a manual maximum force applied by the same senior surgeon. All procedures were performed three times, and the mean value taken as the final result in each case.

Procedure

The computer navigation system was used to measure maximum manual ATT, maximum manual IR, and maximum manual ER at four stages for each knee: (1) with the ACL and all other ligaments intact, (2) after dissection of the PL bundle of the ACL, (3) after dissection of the AM bundle of the ACL (complete loss of ACL), and (4) after lesion of the anterolateral portion of the knee joint capsule (lateral capsular ligament as described by Hugston) [19]. The order of cutting was non-randomized and these dissections were performed consecutively so that each lesion was in addition to those previous.

After the initial kinematic evaluation of the intact knee, intra-articular access was obtained arthroscopically using the standard anterolateral and anteromedial portals. The PL bundle was identified and separated from the AM bundle and then it was excised using an arthroscopic scissors and shaver, and knee kinematic measured. The AM bundle was removed using the same procedures, and knee kinematics measured again. Then the lesion to the anterolateral structure was performed, and knee kinematics measurements were repeated. Anterolateral aspect of the knee was approached through a hockey stick skin incision; the iliotibial tract was divided along its fibres and the articular capsule exposed. An incision approximately 2 cm long was made through the lateral capsular ligament at the level of the lateral joint line, below the lateral meniscus (Fig. 2).

Maximal anterior translation of the tibia was measured at 30°, 60°, and 90° of knee flexion. Maximal IR and ER of the tibia were measured at 0°, 15°, 30°, 45°, 60°, and 90° of flexion.

The pivot shift test was performed by the same senior surgeon at each of the four stage at which knee kinematics were measured to determine any correlation between the test and these lesions. He was blinded to which of the structures were cut. Grade 0 was defined as negative, grade 1+ as a glide, grade 2+ as a clunk, and grade 3+ as a gross clunk and subluxation.

Statistical analysis

All values were recorded in a standard Excel spreadsheet (Microsoft Office, Microsoft Corporation). 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.

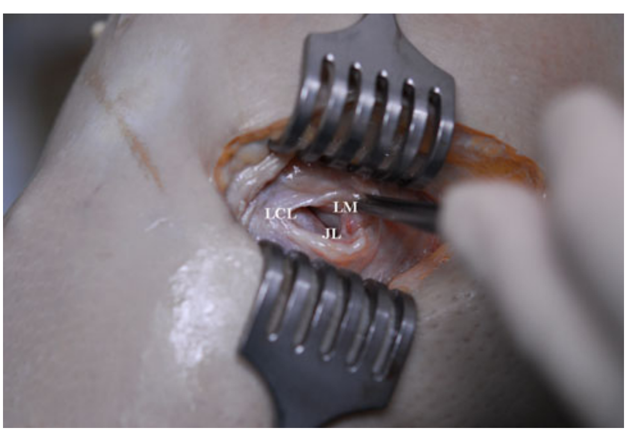

Fig. 2 Lesion of the lateral capsular ligament (*LCL*) in a left knee. An incision approximately 2 cm long was made through the lateral capsular ligament at the level of the lateral joint line (*JL*), below the lateral meniscus (*LM*)

A power analysis was performed to determine the extent to which the proposed sample size would be adequate to detect the hypothesized effects of the subsequent lesions on knee stability.

A priori power analysis is conducted prior to the research study, and it estimated the minimum sufficient sample sizes in $n = 6$ to achieve adequate power.

Post hoc power analysis was conducted after the study, using the obtained sample size and effect size to determine what the power was in the study, assuming the effect size in the sample is equal to the effect size in the population.

With $N = 10$ (given 0.05 alpha, one-tailed test, because after each lesion values are always higher than previous) the study has a power of 0.97 ($\beta = 0.03$).

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 (n.s.).

The additional lesion to the AM bundle produced noticeable increases in anterior translation compared to the isolated lesion of the PL bundle with statistically significant increases seen at all grades of knee flexion ($P < 0.05$).

A lesion to the anterolateral structures resulted in a significant increase in anterior tibial translation recorded at all grades of knee flexion ($P < 0.05$) (Fig. 3).

Internal rotation

Cutting the PL bundle resulted in a minor increase in internal rotation at all flexion angles except for 60° and 90° but none of these were considered significant (n.s.).

Further increases in internal rotation were seen at all grades of knee flexion when the AM bundle was cut, but these were also not deemed significant (n.s.).

The anterolateral lesion produced increases in internal rotation at all grades of knee flexion, with a significant increases seen at 30° ($P = 0.04$) (Fig. 4, Table 1).

External rotation

Cutting the PL bundle showed no significant increase in external rotation at any of the flexion angles measured (n.s.).

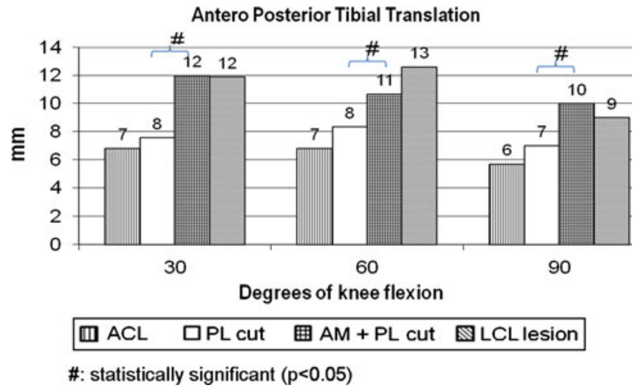

Fig. 3 Values of antero-posterior tibial translation of the knees in different condition

Subsequent removal of the AM bundle produced minor increases in external rotation at all angles, but none of these increases were significant (n.s.).

The lesion to the anterolateral structures showed an increase in external rotation at all flexion angles, but none of these increases were significant (n.s.) (Fig. 4, Table 1).

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 (n.s.).

Small increases were observed in combined rotation when comparing the intact ACL to the ACL-deficient knee (PL + AM bundle cut); however, none of these were significant (n.s.).

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° ($P < 0.05$).

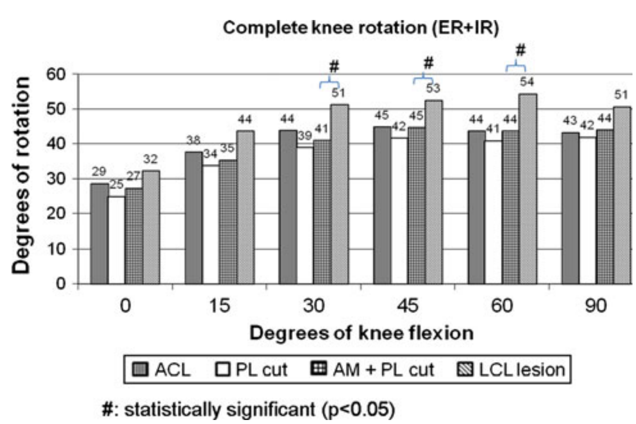

Fig. 4 Values of complete knee rotation in different conditions

Pivot shift

The pivot shift was clinically undetectable (grade 0) in all knees with the ACL intact. Removal of the PL bundle had no change on the pivot shift with all knees continuing to show grade 0. When both the PL and AM bundle were cut, the pivot shift continued to be undetectable (grade 0) in two cases, minor (grade 1+) in seven cases, and only in one case moderate (grade 2+). The additional lesion to the anterolateral area resulted in an increase in the grade of the pivot shift in all cadavers, with a grade 2+ pivot shift seen in 3 cadavers and a grade 3+ in the other 7 cadavers.

Discussion

The most important finding of the present study is that no significant rotational instability was seen until after the lesion to the LCL suggesting that rotational instability of the knee may be due to secondary injuries in conjunction with injuries to the ACL, rather than to injury of only the ACL. Moreover, a high correlation was shown between these lesions of the anterolateral structures and the pivot shift phenomenon.

The aim of this study was to evaluate kinematic changes in the knee after lesion of the lateral capsular ligament associated with ACL tears rather than the injury of the ACL alone especially focusing on the correlation between the pivot shift phenomenon and injuries to the lateral capsular ligament associated with ACL tears.

The results of this study showed that a small and not statistically significant increase was observed when both bundles were sectioned. However, a lesion to the lateral capsular ligament in the previously sectioned ACL resulted in a significant increase in combined rotation at 30°, 45°, and 60° of knee flexion ($P = 0.03$). Moreover, a grade 3+ pivot shift was only seen once the anterolateral lesion was added to the ACL lesion. Moreover, on the basis of the results of this study, the pivot shift phenomenon seems to be more correlated with an increase in total amount of rotation of the tibia (IR + ER) rather than to an increment only of the IR. In fact, the lesion of the lateral capsular ligament results in a significant increase of the IR only at 30° of flexion, while it produced a significant increase in combined rotation (IR + ER) at 30°, 45°, and 60°. In the same time, the tear of the lateral capsular ligament results in a remarkable increase of the pivot shift phenomenon in all knees. These results should suggest a relatively new interpretation of the pivot shift phenomenon, related to an increase of the total amount of tibial rotation rather than to an increase of only the IR.

Although single-bundle ACL reconstruction techniques restore functional knee stability in most cases, several

Table 1 Values of internal, external, and combined rotation in different conditions

AP	Intact ACL	PL cut	*P*	AM + PL cut	*P*	Lateral capsular ligament lesion	*P*
30°	6.8	7.6	n.s.	12.0	***0.01***	11.9	***0.002***
60°	6.8	8.3	n.s.	10.7	***0.04***	12.6	***0.000***
90°	5.7	7.0	n.s.	10.0	***0.03***	9.0	***0.004***
IR							
0°	12.3	13.1	n.s.	16.0	n.s.	19.2	n.s.
15°	14.6	15.9	n.s.	16.0	n.s.	20.4	n.s.
30°	18.0	20.0	n.s.	21.2	n.s.	26.7	***0.04***
45°	21.0	22.3	n.s.	22.4	n.s.	25.6	n.s.
60°	20.8	23.0	n.s.	24.3	n.s.	26.9	n.s.
90°	20.0	25.3	n.s.	25.1	n.s.	26.3	n.s.
ER					n.s.		
0°	10.1	11.8	n.s.	11.2	n.s.	13.0	n.s.
15°	17.3	17.8	n.s.	19.6	n.s.	23.2	n.s.
30°	20.1	18.9	n.s.	19.8	n.s.	24.5	n.s.
45°	20.3	19.3	n.s.	22.2	n.s.	26.9	n.s.
60°	19.6	18.2	n.s.	19.3	n.s.	27.4	n.s.
90°	17.9	16.6	n.s.	19.1	n.s.	24.3	n.s.
IR + ER							
0°	28.6	24.9	n.s.	27.2	n.s.	32.2	n.s.
15°	37.6	33.7	n.s.	35.3	n.s.	43.6	n.s.
30°	43.8	38.9	n.s.	41.0	n.s.	51.2	***0.02***
45°	44.8	41.7	n.s.	44.7	n.s.	52.5	***0.03***
60°	43.6	40.9	n.s.	43.7	n.s.	54.3	***0.01***
90°	43.2	41.9	n.s.	44.0	n.s.	50.6	n.s.

In bold italics values statistically significant

ns not significant

studies have now demonstrated that normal knee joint kinematics are not fully restored in rotational stability and that 14–30% of patients may have a residual glide [7, 16, 23, 27, 37, 41]. It has been well known since Palmer's [30] report in 1938 that the ACL is composed of 2 bundles (AM and PL), and recent research has a high focus on comparing double- and single-bundle techniques mostly with regard to rotational control.

The reliability of the navigation system in evaluating knee kinematics during ACL reconstruction has been well documented [6, 11, 26]. 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 interference by soft tissue [12, 13].

Some researchers in their studies have used a robotic/UFS (universal force sensor) testing system to measure the effect of valgus torque on the kinematics of the intact and ACL-deficient knee and the effectiveness of different grafts for ACL reconstruction in response to anterior tibial load and rotational load [13, 39]. Pearle et al. [32] evaluated the reliability of navigated knee stability examination in a cadaveric study, comparing this system with the robotic/UFS testing system, and found that the surgical navigation system has an overall accuracy of approximately 1 mm or 1°. Moreover, surgical navigation systems seem to be precise intraoperative tools to quantify knee stability and may help delineate complex rotator stability patterns of knee motion. More recently, Pearle et al. [31] 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 rotator and translational instability in the ACL-deficient knee [25]. 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 [14, 36]. This subluxation is graded by the examiner on a subjective evaluation of the amount of instability.

Whilst the pivot shift is used clinically in the diagnosis of the ACL injuries, its precise pathogenesis is not well understood. Most studies agree that the development of the pivot shift dependent on ACL insufficiency; however, various authors have suggested that a secondary lesion to another supporting structure is also a necessary component. In their work on the pathogenesis of the pivot shift, Galway et al. [14] found that isolated lesion to the ACL did not produce a noticeable pivot shift in several of their cadaveric specimens, and it was only after a lesion to the iliotibial band (ITB) that an easily recognisable clunk was observed. Hugston et al. [19] strongly believed that the essential lesion is to the middle one-third of the lateral capsular ligament.

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 [20, 33]. 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 lateral capsular ligament refers to an area of capsule thickening at the lateral margin of the tibial plateau, deep to the iliotibial band.

In this study, the entire cadaver was used and all soft tissues remained in place to limit the effect that removal might have. In fact, 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 more than 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 [13, 39]. In these 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 [13, 39]. 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 [9, 35, 40]. In their 1993 study, Wroble et al. [40] found that sectioning the anterolateral structures (ITB 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. [35] also found that the anterolateral structures contribute as secondary restraints to the ACL. The results of this study support these findings, obtained with use of a more accurate instrumentation as navigator.

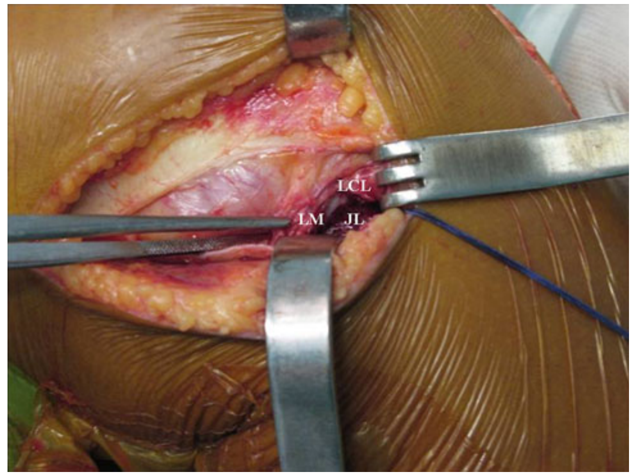

Fig. 5 The lesion of the lateral capsular ligament founded in vivo exploring the lateral compartment of the right knee in association with an acute ACL tear (*JL* joint line, *LM* lateral meniscus, *LCL* lateral capsular ligament)

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) [4] (Fig. 5). Moreover, in knees with chronic ACL insufficiency, a progressive stretching of secondary restraints in the lateral structures of the knee often occurs [12]. 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, these structures are not always examined and it is possible that injuries to these areas may be overlooked during a routine ACL reconstruction. George et al. [15] 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 [35, 36]. It is possible that previous research, which suggests that the anterolateral structures are an important secondary restraint to the ACL, is being overlooked [10, 17, 29]. The results of this study support this research and confirm the importance of the lateral capsular ligament in controlling both anteroposterior and rotational stability of the knee. Moreover, these results suggest that treatment of rotator instability following an

ACL tear should 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 [29]. In an in vitro analysis, the extra-articular plastic, associated with intra-articular reconstruction, seems to protect the graft, reducing the stress by 43% [10]. Recently Monaco et al. [28], 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. [38] 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, the comparisons with previous cadaver studies looking at knee kinematics are valid.

The 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. However, the specimen number 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 and non-randomized, 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, even if the load was always applied by the same experienced author.

Another limitation of the study is that the pivot shift phenomenon was subjectively evaluated and the examiner was not blinded to which of the structures were cut. However, we believe that the pivot shift is the more used test for clinical evaluation of the knee; it is strongly correlated with the clinical outcomes and satisfaction of the patient and is present in all the rating scales concerning ACL reconstruction. In this study, the pivot shift was performed always by the same experienced author in order to ensure the most repeatability to the test.

The strength of this study is that entire cadaver specimens were used and all soft tissues remained in place to limit any change 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, a computer navigation system that allowed precise evaluation of the kinematic changes that occurred after each lesion was used.

Based on these findings, the PL bundle seems to be not much involved in controlling AP translation or rotation of the knee, and no change in knee kinematics was observed after it was removed. The fact that no significant rotational instability was seen until after the lesion to the lateral capsular ligament may suggest that rotational instability may be due to secondary injuries in conjunction with injuries to the ACL. Moreover, a high correlation was shown between the pivot shift and lesions to the anterolateral structure. The significant changes in knee kinematics that occurred following lesions to this area suggest that the integrity of these structure should be assessed when patients present with ACL injuries, so despite the large interest and consensus for more anatomical double-bundle ACL reconstruction, we believe it is more correct and biomechanical valid to repair the lesion of the antero-lateral structure of the knee at the same time we make an ACL reconstruction (suture in acute cases and reconstruction in chronic cases), in order to prevent the pivot shift phenomenon and the possible need for subsequent revision surgery.

Conclusion

Severe rotatory instabilities (pivot shift grade 2+ to 3+) are the result of the tear of the ACL in association with tear of the lateral structures. Therefore, a comprehensive treatment of this type of injury should include identifying and treating these tears. It is our belief that we will never fully understand rotator instability as long as we look only at the ACL.

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