■ KNEE: RESEARCH

The contribution of each anterior cruciate ligament bundle to the Lachman test

A CADAVER INVESTIGATION

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The clinical diagnosis of a partial tear of the anterior cruciate ligament (ACL) is still subject to debate. Little is known about the contribution of each ACL bundle during the Lachman test. We investigated this using six fresh-frozen cadaveric lower limbs. Screws were placed in the femora and tibiae as fixed landmarks for digitisation of the bone positions. The femur was secured horizontally in a clamp. A metal hook was screwed to the tibial tubercle and used to apply a load of 150 N directed anteroposteriorly to the tibia to simulate the Lachman test. The knees then received constant axial compression and 3D knee kinematic data were collected by digitising the screw head positions in 30° flexion under each test condition. Measurements of tibial translation and rotation were made, first with the ACL intact, then after sequential cutting of the ACL bundles, and finally after complete division of the ACL. Two-way analysis of variance analysis was performed.

During the Lachman test, in all knees and in all test conditions, lateral tibial translation exceeded that on the medial side. With an intact ACL, both anterior and lateral tibial landmarks translated significantly more than those on the medial side ($p < 0.001$). With sequential division of the ACL bundles, selective cutting of the posterolateral bundle (PLB) did not increase translation of any landmark compared with when the ACL remained intact. Cutting the anteromedial bundle (AMB) resulted in an increased anterior translation of all landmarks. Compared to the intact ACL, when the ACL was fully transected a significant increase in anterior translation of all landmarks occurred ($p < 0.001$). However, anterior tibial translation was almost identical after AMB or complete ACL division.

We found that the AMB confers its most significant contribution to tibial translation during the Lachman test, whereas the PLB has a negligible effect on anterior translation. Section of the PLB had a greater effect on increasing the internal rotation of the tibia than the AMB. However, its contribution of a mean of 2.8° amplitude remains low. The clinical relevance of our investigation suggests that, based on anterior tibial translation only, one cannot distinguish between a full ACL and an isolated AMB tear. Isolated PLB tears cannot be detected solely by the Lachman test, as this bundle probably contributes more resistance to the pivot shift.

Since the concept of double-bundle anterior cruciate ligament (ACL) reconstruction emerged,[1-5] partial ruptures of the ACL have led to new interest in the so-called ACL augmentation technique, in which only the torn bundle is reconstructed. Accurate diagnosis of a partial tear of the ACL is not always easy[6,7] and relies on a combination of the history of the mechanism of injury, clinical examination, stress tests[8,9] MR scanning[10] and arthroscopic evaluation of the ACL. DeFranco and Bach[11] stated that a partial tear of the ACL is characterised by an asymmetric Lachman test[12] result (manual anterior tibial displacement in 20° of flexion), a negative pivot shift test, a low-grade KT-1000 arthrometer measurement (evaluation of anterior tibial displacement revealing only a slight increase), as well as arthroscopic evidence of ACL injury. The Lachman test has been shown to be the most sensitive for diagnosis of a complete rupture,[11-18] but little is known about its value in patients with a partially torn ACL.[6]

It is generally accepted the ACL consists of two functional bundles, the anteromedial bundle (AMB) and the posterolateral bundle (PLB);[19,20] an intermediate bundle has also been described.[21] The AMB primarily limits anterior translation of the tibia on the femur with the knee in flexion.[22] It also contributes to stability in both internal and external rotation.[23,24] The PLB limits anterior translation, hyperextension and rotation.[24-26] The oblique

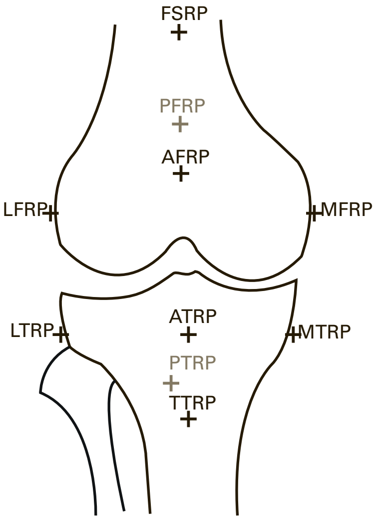

Fig. 1

Diagram showing the position of the cancellous screws that were used as reference points on the femur and tibia: FSRP, femoral shaft; PFRP, posterior femur; AFRP, anterior femur; LFRP, lateral femur; MFRP, medial femur; ATRP, anterior tibia; LTRP, lateral tibia; MTRP, medial tibia; PTRP, posterior tibia; TTRP, tibial tubercle.

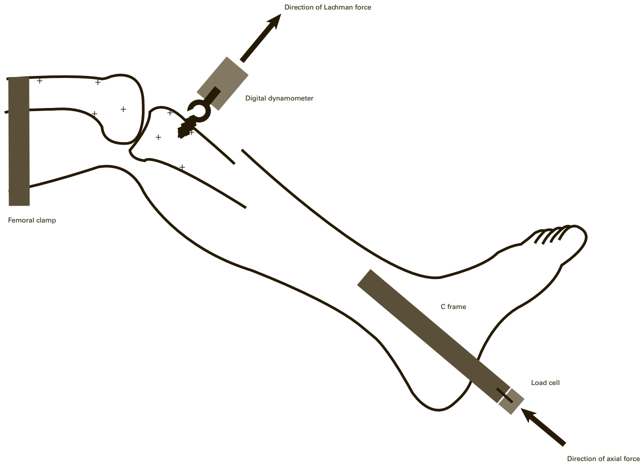

Fig. 2

Illustration of the experimental set-up for the simulated Lachman test with axial loading. A digital dynamometer attached to the metal hook was used to adjust the desired Lachman force. A load cell mounted under the C frame aligned with the tibial shaft was used to monitor the axial compression force.

position of the PLB provides more rotational control than the AMB, which is in a more axial position.[27-29]

In order to investigate the relative contributions of each functional bundle we performed simulated Lachman tests on cadaver knees with sequential division of the bundles. The tibial displacement on the femur was measured by three-dimensional (3D) digitisation of fixed bony landmarks. This allows calculation of both the anterior translation of medial and lateral aspects of the tibia and tibial rotation. We hypothesised that during the Lachman test, in contrast to the PLB, isolated sectioning of the AMB should significantly increase tibial translation, whereas isolated sectioning of the PLB should significantly increase tibial internal rotation.

Materials and Methods

We used six fresh-frozen unembalmed cadaver lower limb specimens from five males and one female with a mean age of 37 years (30 to 45). Specimens were screened before harvesting to verify that there was a normal range of knee movement, no previous evidence of surgery, and to exclude the presence of knee laxity. Specimens were harvested after hip disarticulation, and the leg and foot were saved intact. After thawing they were maintained at room temperature for 24 hours before use.

The femur of each specimen was cleaned of all soft tissue to enable firm fixation in a vice secured to a table-top clamp, maintaining the mid-shaft in a horizontal position. The collateral ligaments were left intact. Taking care not to disturb the menisci, the patella, patellar ligament and quadriceps were excised in order to obtain unobstructed access to the ACL. It has been reported that this dissection does not significantly affect passive anteroposterior stability of the knee.[30] Tissues were kept moist throughout the duration of the measurements.

A total of five 6.5 mm fully threaded cancellous screws were inserted into the distal femur and five into the proximal tibia, with their heads resting against the cortex. On the femoral side screws were inserted into each epicondyle, immediately above the trochlear groove on the anterior aspect, on the posterior aspect, and 10 cm proximal to the previous screw on the anterior aspect of the femur. On the tibial side three screws were inserted 1 cm below the joint line: one anterior in the middle of the epiphysis, one medial and one lateral. Two additional screws were inserted 4 cm below the previous screws, one through the anterior aspect of the tibia and one through the posterior aspect. These screws were used as fixed landmarks for digitisation of the bones' positions (Fig. 1).

A metal hook was screwed into the centre of the tibial tubercle at a mean distance of 49 mm (41 to 55) from the joint line. This hook was later used to apply a 150 N load to the tibia, directed from posterior to anterior, aimed at simulating the Lachman test. With the femur and tibia parallel to the floor, complete knee extension was defined as 0°. The knee then received manual axial compression with 6.35 kg of force via a handheld dynamometer (SBA-50L S-Type Compression/Tension Load Cell, maximum capacity 50 lb (full bridge); CAS Corporation, Seoul, Korea) to load and centre the joint during data collection as recommended by Belisle et al.[31] The dynamometer was linked to the tibia via a metal stirrup frame made of hard steel, 1.5 × 1.5 cm thick, 20 cm in length and 17 cm wide, fixed through the tibia with two parallel 5 mm diameter Steinmann pins.

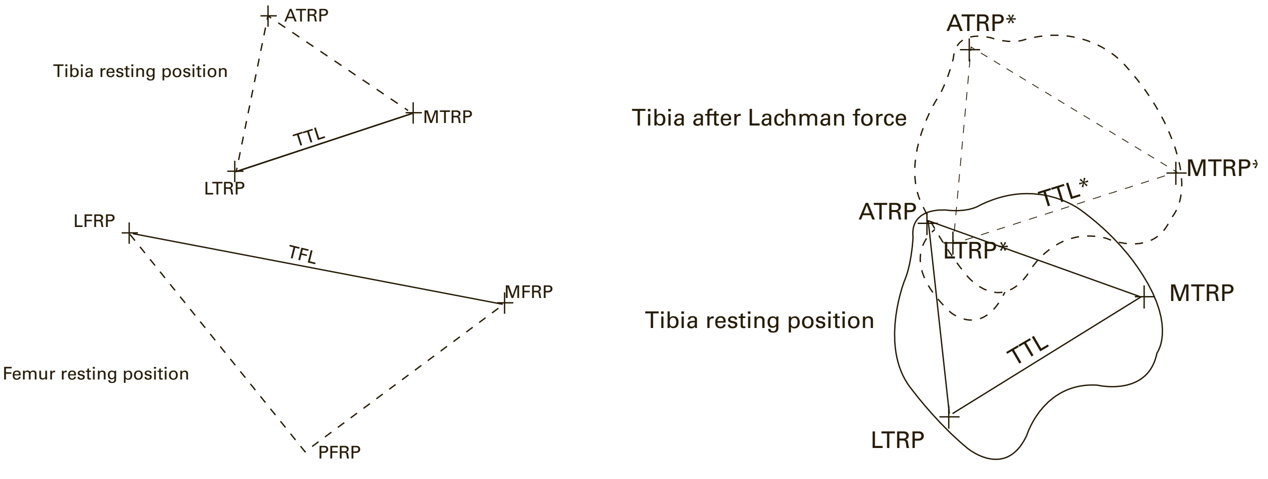

Fig. 3a

Fig. 3b

Figure 3a – axial image obtained from the MicroScribe G2X digitiser during full extension. The transverse femoral line (TFL) was drawn between the reference points on the medial (MFRP) and lateral femur (LFRP). The transverse tibial line (TTL) was drawn between the reference points on the medial (MTRP) and lateral tibia (LTRP). The angle between these lines was used to measure the 'resting angle of the tibia' (RAT) (ATRP, anterior tibia; PFRP, posterior femur). Figure 3b – axial images obtained from the MicroScribe G2X digitiser before and during the Lachman test. Dashed lines show the position of the tibia after applying the Lachman force (with asterisks denoting the new reference positions). The change in the measurements between MTRP and MTRP*, ATRP and ATRP* and LTRP and LTRP* defined tibial translation. The angle between TTL and TTL* was measured and described as 'absolute tibial rotation' (ATR) for the calculation of tibial rotation during the Lachman test.

With this dynamometer it was also possible to monitor the torque applied to the stirrup. The tibia was free to rotate during this experiment, as no torque was applied (Fig. 2). One of the investigators monitored the dynamometer computer screen throughout testing to ensure that constant axial compression was maintained throughout the data collection.

The Lachman test. The 3D knee kinematic data were collected with a MicroScribe G2X digitiser (Emicroscribe Co., Ahmerst, Virginia). This digitiser has five degrees of freedom; it is accurate to 0.20 mm and its workspace size is 1.27 m.[32] Kinematic data points were manually recorded at a sampling speed of up to 1000 Hz. First, under constant axial loading with the knee in extension at 0°, the femoral screw heads were used to define reference lines and planes on the femur, and the 3D positions of the tibial screw heads were recorded with the MicroScribe G2X. Secondly, under constant axial loading, the knee was manually flexed to 30° under direct vision of the MicroScribe computer screen, the angle of flexion of the knee was recorded and the positions of the tibial screw heads were again digitised. Finally, a 150 N load was applied to the tibial tubercle with a second dynamometer simulating the Lachman test. Again, the angle of flexion was recorded and the positions of the screw heads were digitised. For each specimen the measurements were repeated four times for each position of the knee and loading condition. All the measurements were performed initially with the ACL intact, then with sequential division of the ACL bundles, and finally after complete division of the ligament.

Sequential cutting of the ACL. With the ACL intact the knee was set between 60° and 90° of flexion and an anterior drawer was manually applied to the tibia. In this loading condition the fibres of the AMB are predominantly tensed and it becomes easy to indentify each of the two bundles. In half of the specimens the AMB was divided first (specimens 2, 4 and 6) and in the other half the PLB was divided first (specimens 1, 3 and 5). The same measurements as described above were repeated; finally the remaining bundle was divided and the measurements were repeated again.

Data recording. The recorded data were transferred to commercially available Surfcam V5 software (Surfware Inc., Camarillo, California) for editing the digitised 3D data. Three femoral and three tibial landmarks were used to complete the measurements of rotation and translation; other landmarks were used for cross-checking. A total of ten reference points were used as landmarks: the femoral shaft (FSRP), the anterior (AFRP), medial (MFRP), lateral (LFRP) and posterior femoral (PFRP) reference points; the anterior tibial (ATRP), tibial tubercle (TTRP), medial (MTRP), lateral (LTRP) and posterior tibial (PTRP) reference points. Using four of these landmarks, two lines were created as the transverse femoral (TFL) and the transverse tibial line (TTL) (Fig. 3). As the femur was fixed, femoral reference points did not move during the Lachman test; changes in the positions of tibial reference points and the TTL were described by adding an asterisk (e.g. MTRP*, TTL* etc.) for further identification. Before each set of measurements the digitiser was calibrated and screw head positions were digitised with regard to a fixed reference point on the table where the experimental set-up was installed. This was done to verify the absence of movement

Table I. Mean (SD) tibial displacement during the Lachman test for the intact anterior cruciate ligament (ACL) and after dividing the posterolateral bundle (PLB) with axial loading applied to the tibia (specimens 1, 3 and 5). In both situations the lateral tibial plateau and the anterior tibial tubercle translate more than the medial tibial plateau. The internal rotation of the tibia increases by a mean of 2° after dividing the PLB

Test condition	Medial tibial plateau (mm)	Anterior tibial tubercle (mm)	Lateral tibial plateau (mm)	ΔRot (°)
Intact ACL	13.5 (6.0)	17.4 (5.3)	20 (4.2)	9.3 (1.7)
PLB divided	11 (2.9)	19.3 (4.6)	20.1 (6.6)	11.3 (7.9)
Variation PLB divided – ACL intact	-2.5	1.4	0.1	2

Table II. Mean (SD) tibial displacement during the Lachman test for the intact anterior cruciate ligament (ACL) and after dividing the anteromedial bundle (AMB) with axial loading applied to the tibia (specimens 2, 4 and 6). In both situations the lateral tibial plateau and the anterior tibial tubercle translate more than the medial tibial plateau. Only the tibial translation is increased after dividing the AMB. There is no effect on the tibial rotation

Test condition	Medial tibial plateau (mm)	Anterior tibial tubercle (mm)	Lateral tibial plateau (mm)	ΔRot (°)
Intact ACL	11.6 (3.2)	15.6 (4.3)	15.8 (3.7)	5.9 (2.1)
AMB divided	24.6 (8.7)	29 (9)	31.1 (9.8)	6.0 (4.2)
Variation AMB divided – ACL intact	13	13.4	15.3	0.1

Table III. Mean (SD) tibial displacement during the Lachman test for the intact anterior cruciate ligament (ACL) and after dividing both bundles, with axial loading applied to the tibia (all six specimens). In both situations the lateral tibial plateau and the anterior tibial tubercle translate more than the medial tibial plateau. After complete division of the ACL there is a significantly increased translation of all measurement points. However, after division of the ACL tibial rotation does not significantly change

Test condition	Medial tibial plateau (mm)	Anterior tibial tubercle (mm)	Lateral tibial plateau (mm)	ΔRot (°)
Intact ACL	11.5 (3.9)	15.9 (4.6)	17 (4.1)	6.6 (2.3)
ACL divided	25.9 (10.7)	30.3 (10.3)	31.8 (10.7)	7.4 (3.2)
Variation divided – intact (axial load)	14.4	14.4	14.4	0.8

of the femur, the vice or the table that could modify the reference points of the coordinate system.

Rotation measurements. Before performing the Lachman test, the angle formed between TFL and TTL was measured and named as the resting angle of the tibia (RAT) (Fig. 3a). This angle was used to measure the natural rotation of the tibia with regard to the femur in each specimen. In order to calculate the differential rotation of the tibia during the Lachman test, angular changes between TTL and TTL* were measured and referred to as the absolute tibial rotation (ATR) (Fig. 3b).

Translation measurements. Before and after the Lachman test the absolute distances between MTRP and MTRP*, ATRP and ATRP*, LTRP and LTRP* were measured and referred to respectively as anterior translation of the medial tibia, anterior translation of the anterior tibia, and anterior translation of the lateral tibia (Fig. 3b).

Statistical analysis. The digital kinematic data were imported to an Excel spreadsheet (Microsoft, Redmond, Washington) on a personal computer for analysis. All displacement and rotation angles recorded for each testing condition through the four separate measures were used separately. Two-way analysis of variance (ANOVA) repeated measures were performed. Bonferroni *post-hoc* tests were used to locate significant differences, and $p < 0.05$ was considered significant.

Results

The mean flexion angle of the resting knee position was 33.5° (standard deviation (SD) 4.7) and after application of the 150 N Lachman load was 32.0° (SD 6.1) ($p = 0.1$). In all knees the tibia was always externally rotated in the resting position. The mean RAT was 12.3° (SD 4.2). The values of tibial translation and rotation according to test condition are listed in Tables I to III.

Tibial translation during the Lachman test. During the Lachman test in all knees and under all test conditions, greater lateral than medial translation was observed; all tibiae rotated internally, which was consistent with dominant lateral translation.

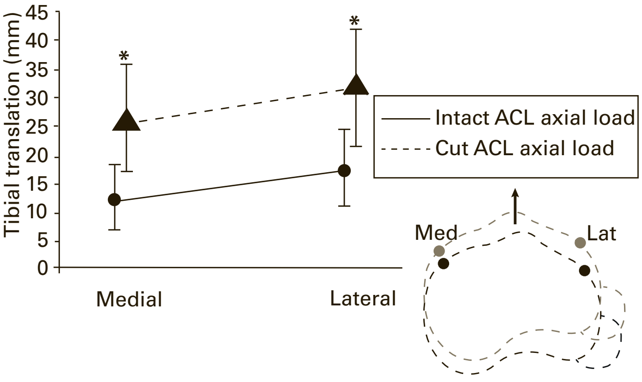

FIg. 4

Graph and diagram showing the mean tibial translation with an intact (solid line and circles) or fully divided anterior cruciate ligament (ACL) (dotted line and triangles) for the six specimens. The error bars denote standard deviation. The lateral (Lat) translation is higher than the medial (Med) in both situations. Lines are parallel owing to the absence of induced rotation after complete division of the ACL. Compared with the resting position, there is a significant increase in both medial and lateral translation (*both p < 0.001). However, there is no statistical difference between the lateral and the medial translation (p = 0.065).

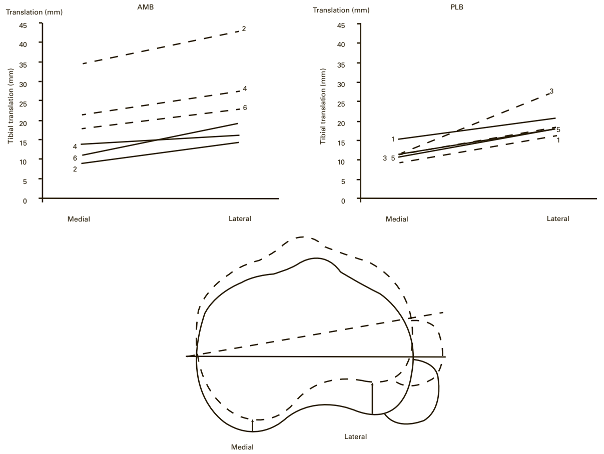

Fig. 5

Graphs showing the individual tibial translation of the six specimens after division of either the anteromedial bundle (AMB) (specimens 2, 4 and 6) or the posterolateral bundle (PLB) in isolation (specimens 1, 3 and 5). Solid lines correspond to resting tibial translation, dotted lines to one-bundle division. After isolated division of the AMB the tibial translation is always larger than that after division of the PLB.

Intact ACL. Both the anterior and lateral tibial points translated significantly more than the medial tibial reference point ($p < 0.001$). No significant difference was found between the lateral and anterior point translations ($p = 0.074$). Compared with the resting position, translation of all points increased significantly during the Lachman test ($p < 0.001$). (Fig 4).

ACL sequential division of the bundles. Compared with the intact ACL, selectively dividing the PLB did not increase translation of any points (Table I, Fig. 5). The mean translation of the anterior point was 1.4 mm (-4.8 to 9.8), whereas the medial point moved backwards by a mean of 2.5 mm (-1.2 (ie. 1.2 mm forwards) to 5.7). Dividing the AMB always increased anterior translation of all points (Table II, Fig. 5). The mean anterior translation of the medial tibia was 13.2 mm (6.1 to 27.7), of the tibial tubercle 15.3 mm (4.6 to 31.4) and of the lateral tibia 15.3 mm (5.8 to 28.7). Dividing the PLB made no additional change in the translation. In both conditions, isolated PLB or isolated AMB division resulted in more lateral tibial translation than occurred medially.

ACL complete division. Compared with the intact ACL, complete division of the ligament significantly increased the anterior translation of all measurement points. The translation for the measurement points were as followed: medial 14.4 mm ($p < 0.001$), anterior 14.4 mm ($p < 0.001$) and lateral 14.8 mm ($p < 0.001$) (Table III, Fig. 4). Thus, there was no significant difference between the extent of the translation of the medial, anterior and lateral tibial reference points ($p = 0.94$).

Tibial rotation during the Lachman test. Division of the AMB or PLB did not influence tibial rotation (Tables I and II), although no statistical analysis could be undertaken due to insufficient numbers of specimens. PLB division induced a mean of 2° internal rotation (4° internal to 5° external rotation) compared with a mean of 0.1° (5° internal to 9° external rotation) after AMB division. In addition, complete division of the ACL did not influence tibial rotation at all with a 0.8° variation ($p = 0.09$). Complete division of the ACL resulted in almost pure tibial translation.

Discussion

Our most important findings were that the AMB provides the greatest contribution to tibial translation during the Lachman test and the PLB has a negligible effect on anterior translation. Dividing the PLB tends to increase internal rotation of the tibia, but the mean amplitude of 2° did not reach statistical significance. This may have been due to a type II error owing to an insufficient number of samples. Complete division of the bundles results in an increase in pure tibial translation with no significant change in tibial rotation.

The 3D movements of the knee have been described in various ways.[33] There are six degrees of freedom, for which Grood and Suntay[34] described a system where joint position is independent of the order in which the translations and rotation are performed. In the method we used, fixing the femur resulted in a single centre of rotation in the femur. So, measuring the anterior translation and rotation of the tibia at a fixed angle of knee flexion is a reasonable option. Axial loading was a key to maintaining the centring of the knee joint when the femur was secured, otherwise unwanted abduction or adduction of the tibia might have arisen. In order to avoid any bias on performance and interpretation of the Lachman test,[35,36] the 150 N tibial translation load was always applied at the level of the tibial tuberosity. The measurements were made in the plane of tibial displacement corresponding to pure translation in the plane of the tibial plateau surface.

Although most attention has been focused on anterior tibial translation, it has been shown by several authors that the tibial displacement that occurs during the Lachman test combines translation and rotation.[10,37,38] There have been mixed reports on the contribution of the ACL to tibial rotational stability. However, following a complete ACL tear it is generally accepted that the lateral compartment of the knee translates more than the medial one, resulting in internal rotation of the tibia.[39-43] There are controversies in the literature regarding the relative contributions of the ACL bundles and the ability to detect their insufficiency. According to Hole et al,[23] partial injuries cannot be reliably identified during clinical examination even when as much as 75% of the ligament is torn. In six cadavers, they found significant increases ($p < 0.05$) in translation only after dividing both the PLB and half of the AMB, and after complete division of the ACL. In the same study, only two of 18 examinations led to the correct identification of a partially divided ACL when the PLB had been divided. They were unable to differentiate a divided PLB from an intact ACL.

In another cadaver study, Lintner et al[6] found that it was not possible to detect differences between an ACL in which the AMB had been divided and an intact ACL by clinical examination and testing with a KT-1000 arthrometer. However, even if arthrometric testing is a useful in the assessment of sagittal laxity of the knee, it may not be sensitive enough to identify partial tears of the ACL unless there is substantial damage to the ligament. In clinical practice, < 3 mm side-to-side difference does not definitely correlate with a partial tear of the ACL and does not give any meaningful information regarding the quality or functional capacity of the intact tissue.[11] Markolf, Graff-Radford and Amstutz measured changes in anteroposterior laxity and graft forces after dividing the PLB in cadavers. With 100 N of anterior tibial force, 100 N of quadriceps force, and 5 Nm of internal tibial torque, they found that dividing the PLB significantly increased the mean laxity by 0.5 mm in 30° of flexion, whereas we found a mean of 1.5 mm with different loading condition. When the knee was passively extended, dividing the PLB significantly reduced mean ACL force at 0° for all loading modes. The authors concluded that the decreases in ACL force at 0° due to dividing the PLB are consistent with the commonly accepted view that the PLB tightens with extension of the knee. They found that division of the taut PLB significantly increased AP laxity between 0° and 30°, but the increases were relatively small (0.5 mm). They concluded that the PLB bundle plays a relatively minor role in controlling anterior tibial translation, which is in agreement with our observations. Wu et al,[44] using a robotic testing system, measured the *in situ* forces in each bundle under various loading conditions and flexion of the knee. At 30° they found that the AMB was significantly more loaded than the PLB in response to a 134 N anteriorly directed tibial load. This is in agreement with our findings, which show that the AMB controls more of the anterior tibial translation at 30° of flexion than does the PLB. However, when combining 10 Nm valgus with 5 Nm of internal torque they also found that the AMB was sharing significantly higher forces than the PLB. This is in disagreement with our results, but the loading conditions of the studies were different.

Bull et al[43] performed intra-operative Lachman test measurements, computing combined tibial translation and rotation with an electromagnetic device, before and after ACL reconstruction. Prior to reconstruction they found a mean anterior tibial translation of 16 mm (SD 4) coupled with an internal rotation of 3.8° (SD 3.3). After complete division of both bundles we found a mean of 14.4 mm and 0.8°, respectively (Table III). Like Bull et al,[43] we observed only small and inconsistent rotational effects during the Lachman test. Tibial rotation is also strongly influenced by peripheral damage, and we could not be sure that the secondary restraints of the specimens were always strictly intact.

Our findings that during the Lachman test the lateral tibiofemoral compartment translates more than the medial is consistent with those in the literature,[38-42] whether the ACL is intact or fully or partially divided. At 30° of flexion most of the anterior tibial translation is under the control of the AMB.[23,43] Compared with the AMB, division of the PLB alone tends to increase internal rotation, but with only six specimens statistical significance was not demonstrated. The number of specimens allowed a valid statistical analysis only between the intact specimens and the fully divided ACLs. Nevertheless, the pattern of tibial displacement was the same for each sequence of ACL division: PLB only divided or AMB only divided.

In conclusion, the results of this study are partially in accordance with the initial hypothesis: dividing the AMB predominantly increases tibial translation during the Lachman test. However, division of the PLB did not contribute significantly to internal rotation, which may have been due to a type II error owing to insufficient numbers of samples. As far as clinical significance is concerned, based on anterior tibial translation only, one cannot distinguish between complete ACL rupture and an isolated AMB tear. An isolated PLB tear cannot be detected solely by the Lachman test, as this bundle may contribute more to pivot shift resistance. Further studies should be performed to confirm these findings.

No benefits in any form have been received or will be received from a commercial party related directly or indirectly to the subject of this article.

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