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Ligamentous and Capsular Restraints Preventing Straight Medial and Lateral Laxity in Intact Human Cadaver Knees*†

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ABSTRACT: **In this study, we determined which ligaments and capsular structures resist medial and lateral opening of the joint space in cadaver knees during clinical testing for straight medial and lateral laxity. Restraining function was recorded as the per cent contribution of each structure in resisting the force applied by the examiner. In sixteen cadaver knees tested at 5 and 25 degrees of flexion from full hyperextension, the collateral ligaments provided the primary restraint (greater than one-half of the total) at both flexion angles. At 5 degrees, the posterior part of the capsule and the cruciate ligaments were important secondary restraints. As flexion increased, the posterior part of the capsule became slack, causing a marked decrease in its restraining action. The middle one-third of the medial and lateral halves of the capsule, traditionally considered important, provided little restraining force. The iliotibial tract and the popliteus musculotendinous unit provided little passive restraint. However, a force applied to either the iliotibial band or the biceps tendon, to simulate muscle tension, produced an additional restraint that *in vivo* presumably would protect the lateral ligaments and capsule.**

Using an instrumented kinematic chain to determine the three-dimensional joint motion in six knees during testing for straight varus-valgus laxity by the maneuvers used clinically, we found that axial rotation of the tibia occurred that may be misinterpreted as medial or lateral joint opening. When just the medial or the lateral collateral ligament (the primary restraints) was sectioned, only a three to five-millimeter increase in joint opening occurred. This increase was small because only low forces were applied during the clinical examination and the secondary restraints blocked further opening even though the primary restraint was disrupted. Near full extension, the secondary restraints almost completely blocked opening of the joint after sectioning of the collateral ligaments.

CLINICAL RELEVANCE: **With knowledge of the hierarchy of restraining moments contributed by the medial and lateral ligament and capsular structures and an appreciation of the rotatory movements of the knee that may occur during tests for straight varus-valgus laxity, both diagnosis and treatment can be more precise.**

In the past, most assessments of ligament function have been based on the changes in laxity observed after cutting selected ligaments[3,11,18,32] or else on the injury patterns associated with observed clinical laxities[1,8,13,14,16,20,24,25,28]. As a result, confusion and disagreement persist as to the ligament injuries associated with specific laxities. Often in clinical practice the ligaments that may be involved are just listed. Accurate diagnosis and optimum treatment require that the function of the ligaments in resisting joint opening be understood and ranked in order of importance.

Recently we described a new method for determining the restraining force provided by each ligament and capsular structure[5,6,9]. This method allows the ligaments to be ranked in order of importance based on the per cent of the total restraining force that each provides. In addition, the method yields results that are independent of the order in which the ligaments are cut, and therefore all ligaments can be studied in each knee.

The purpose of this report is to describe how we applied this method to the measurement of the passive restraints to straight medial and lateral opening of human

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cadaver knees at 5 and 25 degrees of flexion, two positions that commonly are tested clinically. Our goals were to document what ligaments resist the forces applied by the clinician when he or she examines the knee for straight medial and lateral laxity; to measure the joint motions that actually occur during the examination; and to determine the biomechanical interactions of the ligaments as they function as stabilizers of the joint.

Materials and Methods

Specimens

We measured the restraining action of the ligaments in sixteen knees (eight right and eight left) obtained from eleven cadavera, eighteen to fifty-five years old (mean age, 36.8 years). Two were female and nine, male. The causes of death included drug overdose, gunshot wound, acute myocardial infarct, stroke, automobile accident, and (in two cadavera that provided three knees) leukemia and septicemia.

Only the medial restraints were determined in three knees and only the lateral restraints, in three. In the remaining ten knees, both medial and lateral restraints were measured. Prior to testing, all knees were placed in plastic bags and frozen at −30 degrees Celsius except for one which was tested in a fresh state. The night before testing, the specimens were placed in a refrigerator to thaw at 4 degrees Celsius. Final dissection of the specimens and their preparation before testing were carried out as previously described[5].

Mounting

The restraints were determined using an Instron model-1321 biaxial testing system. Each knee was mounted horizontally with the lateral side down, as shown in Figure 1. The femur was secured to the load-cell with two grips that allowed adjustment of its position. Prior to testing, the tibia was supported manually while the load-cell was adjusted to read zero when loaded with the weight of the grips and femur. The tibia then was attached to the actuator through a planar hinge mechanism that prevented axial rotation and flexion of the tibia during the tests (Fig. 1).

Once a knee was mounted, its flexion angle was adjusted by rotating the actuator. To do this, the flexion axis of the knee had to be aligned with the long axis of the actuator. This alignment was accomplished in two steps before securing the bones in the clamps. First we verified that knee flexion occurred in a horizontal plane, using a level placed on the tibia. Second, the femur was positioned to minimize tension in the cruciate ligaments over the range of flexion angles studied. The tension was determined from the torsional output of the load-cell and by feeling the tension in the cruciate ligaments with the index finger.

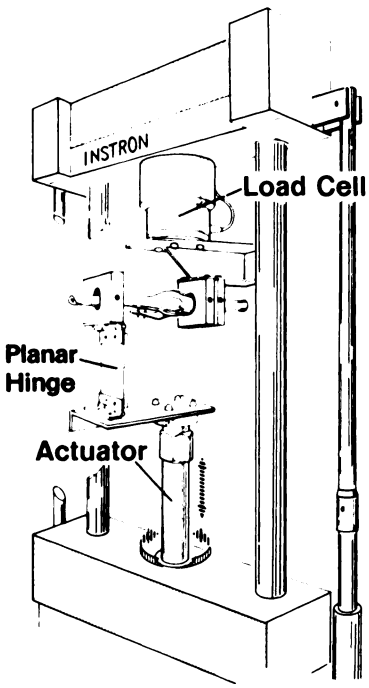

FIG. 1

The knee is mounted horizontally, lateral side down, with the fibula secured to the tibia by two threaded pins. The femur is rigidly attached to the load-cell with two grips that permit its position to be adjusted. The tibia is held by one grip and is attached to the actuator through a planar hinge mechanism. Vertical motion of the actuator produces varus and valgus displacements of the knee. Rotation of the actuator is used to adjust the angle of knee flexion.

Ligament Restraints

First, each knee was placed in the fully extended (hyperextended) position by applying a five-newton-meter extension moment. Then the tests were performed with the knee flexed 5 and 25 degrees from this position. One-plane varus and valgus displacements were produced by causing the actuator, shown in Figure 1, to move up and down but not rotate. The motion of the tibia that was produced was rotation (in a vertical plane) that caused medial opening of the joint when the distal end of the tibia was pulled downward and lateral opening when it was pushed upward. The planar hinge prevented changes in the flexion angle of the knee and internal-external axial rotation of the tibia, but did not restrict varus-valgus rotation, joint distraction, or medial-lateral shift of the tibia with respect to the femur. This arrangement left the knee free to seek its own center of rotation, as it does *in vivo* during the clinical examination for laxity.

The restraining action of each ligament was determined in the following manner. The tests were performed in a fixed order that produced first medial and then lateral opening of the joint. A constant rate was used so that peak opening occurred in one second. Twenty-five conditioning tests producing six millimeters of medial and six millimeters of lateral opening were carried out initially at 5 and 25 degrees of knee flexion. This conditioning procedure minimized stress relaxation during subsequent tests. Typically, the peak force changed less than 0.25 per cent per cycle during the last five conditioning cycles.

After conditioning, baseline tests were conducted at both flexion angles. A ligament then was cut and the test was repeated at each angle. The restraint due to the cut ligament was taken to be the drop that occurred in the joint restraining moment compared with the moment determined in the test just before the cut. This process was repeated after cutting other structures until the restraining moments due to all of the ligamentous and capsular structures had been measured.

Measurements

The joint restraining moment was calculated as the product of the vertical force applied to the tibia through the planar hinge and the moment arm of this force, the horizontal distance to the joint line. The angular displacement of the tibia in radians was calculated as the difference in the vertical displacements of the tibia at the attachment of the planar hinge and at the joint line divided by the moment arm. The movement of the vertical actuator was used as the measurement of tibial displacement at the planar hinge. The vertical displacement at the joint line, due primarily to bending compliance of the femur, was calculated as the product of femoral compliance and the measured moment. The compliance of the femur was determined separately for varus and valgus displacements at the start of each test by applying a known moment and measuring the deflection of the femur at a point two centimeters proximal to the joint line with a dial indicator. No correction was made for either the bending deflections or the medial-lateral shifts of the tibia that also occurred during testing.

Medial and lateral joint-space opening, in millimeters, was calculated by multiplying the tibial rotation, expressed in radians, by the distance from the center of rotation to the joint margin on the opening side. Since the location of each center of rotation was not measured in every knee, we used an approximate average distance to the joint margin of 57.2 millimeters (2.25 inches). Using this value, one millimeter of opening was equivalent to 1 degree of tibial rotation.

The methods employed for the measurement of force and length and the details of data acquisition and reduction were described in an earlier paper on the ligaments that restrain anterior and posterior tibial displacements during the drawer test[5].

Clinical Examination

In six additional cadaver lower limbs, we measured the three-dimensional motion of the knee joint during the clinical examination for medial and lateral laxity (Fig. 2). The motions first were measured in the intact knee, and then one collateral ligament was cut through a small skin incision and the tests were repeated to determine the increase in laxity. The opposite collateral ligament then was cut and the laxity was measured again. Our goal was to determine the actual motions produced in intact knees by a typical clinical examination and to evaluate the change in laxity associated with division of each of the collateral ligaments. We intentionally did not measure the forces applied as we examined these knees, since this would have made it impossible to perform a typical examination.

The motion of the knee during this examination was measured using the instrumented kinematic chain[10,17,29], shown in Figure 2, which was positioned across the knee on the lateral side. One end was attached to the tibia and the other, to the femur, through mounting platforms made of pins measuring one-eighth inch (3.18 millimeters) in diameter. In assembling the platforms, at least three pins were placed through both cortices of each bone to obtain rigid fixation. The six limbs tested provided five measurements of the effect of sectioning each collateral ligament, since just the medial collateral ligament was sectioned in one and just the lateral collateral ligament, in another. To measure the motion of the knee, it was necessary to know the positions of the ends of the instrumented chain with respect

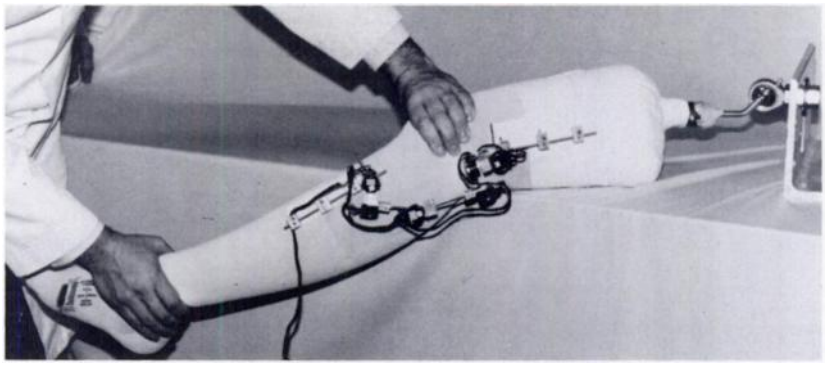

FIG. 2

The instrumented kinematic chain, used to measure three-dimensional joint motion, is shown mounted across the knee on a cadaver lower limb. Each end of the chain is attached to a mounting platform made from pins 3.18 millimeters (one-eighth inch) in diameter. The platforms are attached securely to each bone by three pins which pass through the skin, underlying muscle, and bone. The femur is attached to an angle-plate by means of a rod cemented in the medullary canal and a mobile ball-and-socket joint that simulates the hip. The angle plate is secured to a table with c-clamps.

to the femur and tibia. These positions were established by performing a three-dimensional analysis using biplane radiographs[4].

The six angles between the seven links of the kinematic chain were measured from the output of rotatory potentiometers with a ModComp II computer and an analog-to-digital converter giving a resolution of 0.18 degree. All six angular measurements were made during 100 microseconds, effectively freezing any motion.

The three-dimensional positions of each joint were calculated from these measurements and were expressed in terms of six clinical quantities: flexion-extension, abduction-adduction, and internal-external tibial rotation in degrees, and anterior-posterior displacement, medial-lateral shift, and distraction of the joint surfaces in millimeters[10,26]. Joint motions were described by the changes in joint position that occurred between any two sets of measurements. Verification tests demonstrated that translational and rotational motions could be measured with an accuracy of ±0.5 millimeter and ±0.5 degree, respectively[17].

Ligaments Sectioned

The ligaments and capsular structures studied were the anterior cruciate ligament (ACL), the posterior cruciate ligament (PCL), the superficial parallel fibers of the medial collateral ligament (MCL), the lateral collateral ligament (LCL), the popliteus musculotendinous unit (POP), the medial and lateral halves of the capsule, and the femorotibial portion of the iliotibial band (ITB). The medial and lateral halves of the capsule were subdivided into anterior, middle, and posterior thirds. The middle third of the medial capsule was considered to be the deep fibers of the medial collateral ligament as described by Slocum et al.[28] and by Warren and Marshall[31]. The posterior third was assumed to include the complex of capsular structures described by Hughston and Eilers[12] and by Warren and Marshall[31], as well as the remaining portion of the medial part of the capsule extending to the mid-popliteal region, of which the oblique popliteal ligament is a part. The lateral half of the capsule was divided into the anterior third (from the lateral margin of the patellar tendon to Gerdy's tubercle), the middle third (from Gerdy's tubercle to just anterior to the lateral collateral ligament), and the posterior third (the popliteal arcuate complex and the rest of the capsule extending back to the mid-popliteal region). The ligaments of Humphrey and Wrisberg, when present, were considered to be capsular structures.

Results

The results of a typical test on one intact knee, and on the same knee after sectioning the medial collateral ligament, are shown in Figure 3-A. The vertical axis of this graph is the moment (in newton-meters) that restrains opening of the joint. This moment is due to forces in the ligaments and capsular structures acting through moment arms equivalent to their perpendicular distances from the center of rotation. The horizontal axis of the graph is the joint opening (in millimeters). Medial opening is to the right and lateral opening, to the left. The curve marked INTACT represents behavior after conditioning but before cutting any ligaments. The restraining moment was greater during loading (upper curve) than during unloading (lower curve) due to the viscoelastic properties of the ligaments.

To understand these curves, consider how they may be used to obtain the total medial and lateral laxity of the knee before and after cutting the medial collateral ligament. The laxity is the horizontal distance between the two sides of the curves and depends on the moment applied, which in turn depends on both the location and the amount of force applied. For example, during a clinical test in which varus and valgus forces of forty-five newtons (ten pounds) are applied at the ankle, a moment of approximately eighteen newton-meters is produced at the knee. As seen in Figure 3-A, varus and valgus moments of eighteen newton-meters produced a laxity of 6.5 millimeters (length of the double arrow) in this typical intact knee. This total laxity was nearly equally divided between the medial and lateral joint openings. When the medial collateral ligament was cut (MCL CUT curve), the laxity of the knee increased approximately three millimeters. This increase was only in the medial direction while a valgus moment was applied. Further opening was blocked by the secondary restraints, which were sufficient to resist the small forces that are typical of those applied in a clinical examination.

The restraining moment produced by the medial collateral ligament alone is shown in Figure 3-B. This curve was obtained by subtracting the MCL CUT curve from the INTACT knee curve shown in Figure 3-A. The subtraction was done separately for the loading and unloading portions of the curve at one-tenth-millimeter intervals along the joint-opening axis. The contribution of the ligament, as a per cent of the restraining moment in the intact knee, also was calculated at these intervals. A similar procedure was carried out for each of the other structures. The following results are the average per cent contributions calculated for each ligament and capsular structure.

Medial Restraints

The ligaments and capsular structures resisting five millimeters of medial joint opening are shown for 5 degrees of knee flexion in Figure 4-A and for 25 degrees of flexion in Figure 4-B. The vertical line at the top of each bar and all ± values in the text represent one standard error of the mean.

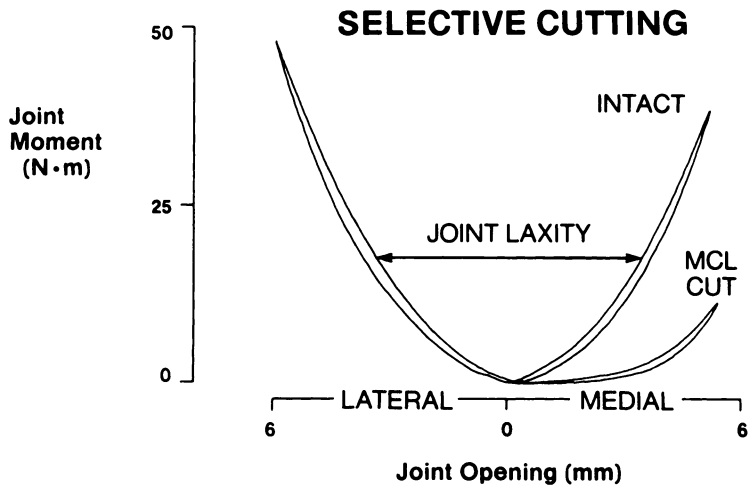

FIG. 3-A

The restraining joint moment, in newton-meters, is shown for a typical intact knee and for the same knee after selective cutting of the medial collateral ligament (MCL). The test starts at the neutral position (0) with the knee intact. Six millimeters of medial opening is produced at a constant rate during one second. The knee then is returned to neutral and the same amount of lateral opening is produced. When the test is repeated after cutting the medial collateral ligament the restraining moment to medial opening is markedly reduced, but there is no change during lateral opening.

Medial Collateral Ligament

The medial collateral ligament (parallel-fibered superficial portion) was the primary restraint at both flexion angles, providing 57.4 ± 3.5 per cent of the total restraining moment at 5 degrees and 78.2 ± 3.7 per cent at 25 degrees of knee flexion. The increased contribution of this ligament with flexion was due primarily to a decrease in the contribution of the posterior medial part of the capsule, which became increasingly slack as flexion occurred. The effect of increasing medial joint opening on the contribution of the medial collateral ligament is shown in Figure 5 for both flexion angles. At 5 degrees, the contribution of the medial collateral ligament decreased from 70.0 per cent at two millimeters to 53.2 per cent at six millimeters of opening. The decline was evaluated by a regression analysis of the per cent contribution at two, three, four, five, and six millimeters of opening for all thirteen specimens. We found a decline of 4.2 per cent per millimeter of joint opening, which was statistically significant ($p < 0.005$; $r = 0.419$; $n = 65$). This decrease was associated with an increase in the contribution of the posterior medial part of the capsule, to be described. At 25 degrees of flexion, when the posterior medial part of the capsule was slack, we found no change in the contribution of the medial collateral ligament associated with increased joint opening.

Cruciate Ligaments

The medial restraint provided by the anterior and posterior cruciate ligaments in combination (Figs. 4-A and 4-B) was 14.8 ± 2.1 per cent of the total at 5 degrees of flexion and 13.4 ± 2.7 per cent at 25 degrees. Their contributions were less than expected and caused us to wonder if they were real or due to the order in which the ligaments were cut. However, when we compared the results of tests

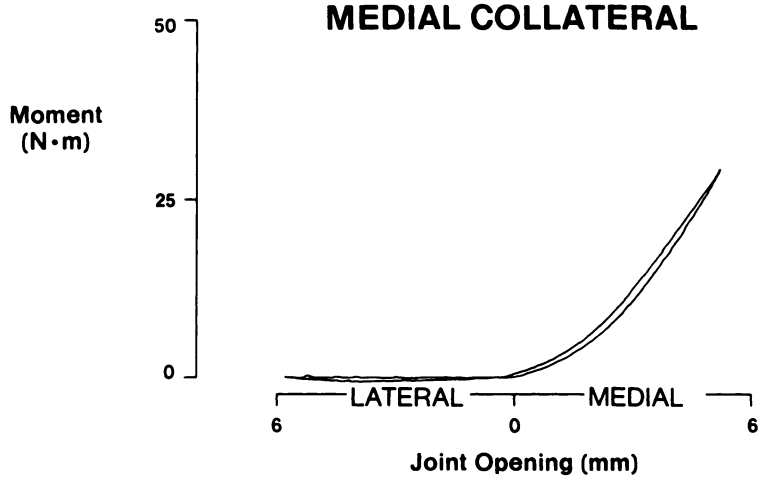

FIG. 3-B

The curve for the restraining moment of the medial collateral ligament alone versus joint opening. This curve was obtained by subtracting the curve after the medial collateral ligament was cut from the curve for the intact knee shown in Fig. 3-A.

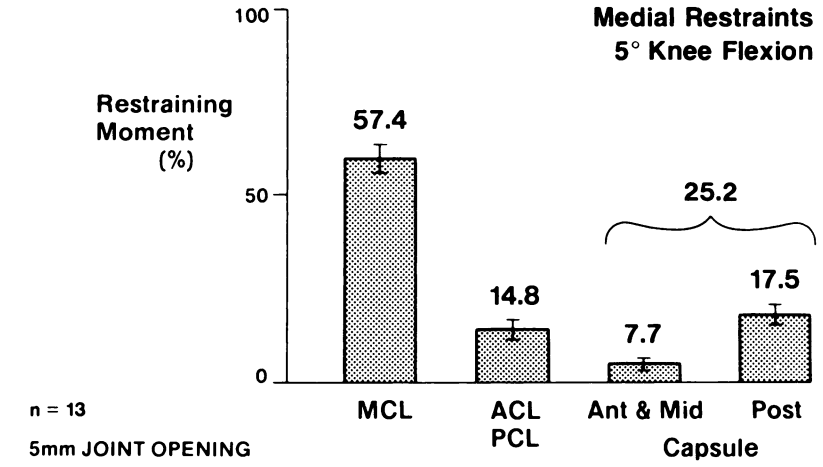

FIG. 4-A

The average per cent contributions to the medial restraints by the ligaments and capsule at five millimeters of medial joint opening and 5 degrees of flexion. The error bars represent ± one standard error of the mean.

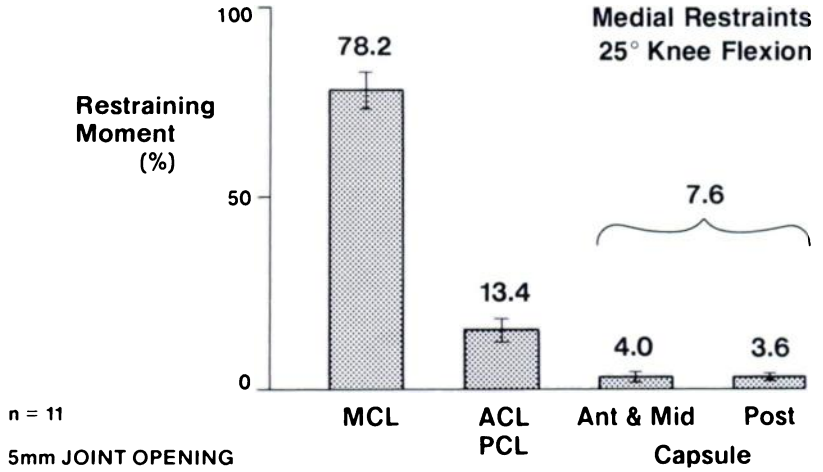

FIG. 4-B

The per cent contributions of these same structures to the restraints at five millimeters of opening and 25 degrees of flexion.

in which the cruciate ligaments were cut first (eight specimens) with the results of tests in which they were cut last (five specimens), we found no statistically significant difference between their combined contributions at the two knee-flexion angles studied.

In nine specimens we were able to separate the contribution of one cruciate ligament from that of the other (Table I). At 25 degrees of flexion, the posterior cruciate ligament accounted for approximately 75 per cent of the combined restraint exerted by the two cruciates to medial opening, while the anterior cruciate ligament accounted for the remaining 25 per cent. This result did not depend on whether the posterior cruciate ligament was cut before or after the anterior cruciate ligament.

At 5 degrees of flexion, on the other hand, the results did depend on whether the posterior cruciate was cut before or after the anterior cruciate ligament. When the posterior cruciate was cut before the anterior cruciate (three knees), we found that it accounted for approximately 70 per cent of their combined restraint. When the posterior cruciate was cut after the anterior cruciate (six knees), its contribution was approximately 20 per cent of their combined restraint. This finding indicates that the cruciates do not function independently of each other when the knee is near full extension.

Anterior and Middle Parts of the Medial Half of the Capsule

Over-all, we found that the anterior and middle parts of the medial half of the capsule provided only a weak secondary restraint limiting medial opening. This restraint was equivalent to 7.7 ± 1.7 per cent of the total restraint at 5 degrees and to 4.0 ± 0.9 per cent of the total at 25 degrees, with five millimeters of opening. However, in two knees from one eighteen-year-old man, the anterior and middle parts of the medial half of the capsule accounted for 18 per cent in one and for 20 per cent in the other at 5 degrees of flexion. In these two knees the parallel-fibered superficial portion of the medial collateral ligament provided the single largest restraining moment of any of the medial restraints, 49 and 40 per cent. However, these contributions were the smallest of any that we recorded for

TABLE I

PER CENT RESTRAINING MOMENT DUE TO THE CRUCIATE LIGAMENTS FOR MEDIAL JOINT OPENING*

Ligament	5 Degrees — Posterior Cruciate Cut before Anterior Cruciate (n = 3)	5 Degrees — Posterior Cruciate Cut after Anterior Cruciate (n = 6)	25 Degrees† (n = 9)
Anterior cruciate	5.0 ± 2.6	12.0 ± 2.9	2.4 ± 0.6
Posterior cruciate	10.2 ± 1.6	2.5 ± 0.8	7.8 ± 2.5
Both	15.2 ± 3.1	14.5 ± 3.0	12.2 ± 2.6

* Mean total medial restraining moment ± one standard error of the mean.

† The data for 25 degrees of flexion are the combined results obtained when the posterior cruciate was cut before the anterior cruciate and when the posterior cruciate was cut after the anterior cruciate ligament. The data were combined because we found no statistically significant difference between the data obtained during the two cutting sequences.

the medial collateral ligament in all of the knees tested. These results suggest that in some knees the medial capsule may provide a larger portion of the restraint. However, the medial collateral ligament was always the single most important restraining ligament.

Posterior Part of the Medial Half of the Capsule

As shown in Figure 4-A, the posterior part of the medial half of the capsule provided 17.5 ± 2.0 per cent of the total restraint at 5 degrees of flexion and five millimeters of medial opening. The contribution of this part of the capsule depended on the amount of medial opening and increased by 2.7 per cent per millimeter of opening. This increase was statistically significant ($p < 0.005$; $r = 0.461$; $n = 65$). At 25 degrees of flexion, however, the restraint due to this part of the capsule dropped to 3.6 ± 0.8 per cent of the total (Fig. 4-B).

Lateral Restraints

The average contributions of the lateral ligaments, lateral half of the capsule, and cruciate ligaments to the restraining moment at five millimeters of lateral joint-space opening are shown in Figures 6-A and 6-B for 5 and 25 degrees of knee flexion. The total lateral restraint, on which the per cent values were based, included the contributions of the passive, ligament-like actions of the femorotibial portion of the iliotibial tract and the popliteus tendon, but not the active effects of these musculotendinous structures. The effect of applying a force to the tract proximal to its femoral attachment, to simulate muscle tension, was studied separately, as will be described.

Lateral Collateral Ligament

The lateral collateral ligament was the primary ligament restraint limiting lateral opening of the joint at both flexion angles. It provided 54.8 ± 3.8 per cent of the total restraint at 5 degrees of flexion and 69.2 ± 5.4 per cent at 25 degrees of flexion. The increased contribution of the lateral collateral ligament with flexion, like the increased contribution of the medial collateral ligament described already, was due to a decrease in the restraint provided by the posterior part of the lateral half of the capsule. The variation in our data for the lateral collateral ligament was large. The contributions of this ligament ranged from 34.6 to 83.7 per cent at 5 degrees and from 40.5 to 94.7 per cent at 25 degrees of knee flexion. In all but one of the thirteen knees tested, however, the lateral collateral ligament provided a restraining moment greater than the combined moments of the cruciate ligaments and the entire lateral half of the capsule.

Lateral Half of the Capsule

As shown in Figures 6-A and 6-B, the entire lateral half of the capsule provided 17.2 per cent of the varus restraint at 5 degrees of flexion and 8.8 per cent of this restraint at 25 degrees of flexion. The anterior and middle one-thirds of the lateral half of the capsule contributed only a small secondary restraint, 4.1 ± 1.5 per cent at 5 degrees and 3.7 ± 1.5 per cent at 25 degrees of knee flex-

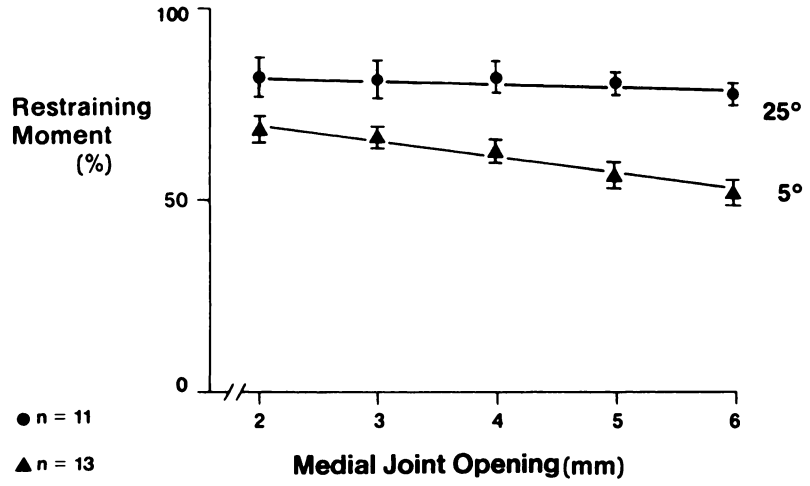

FIG. 5

The per cent contribution of the medial collateral ligament to the restraints limiting medial joint opening in the range of two to six millimeters. The decrease with joint opening at 5 degrees is statistically significant ($p < 0.005$; $r = 0.419$; $n = 65$).

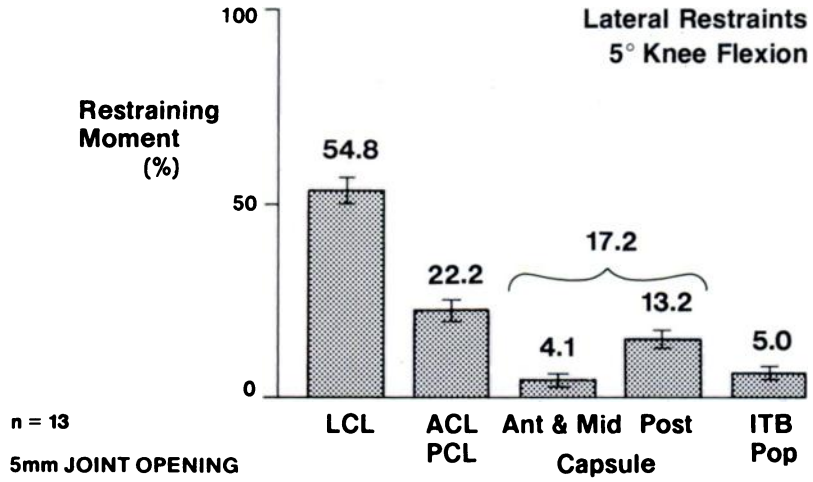

FIG. 6-A

The average per cent contribution to the lateral restraints by the ligaments and capsule at five millimeters of lateral joint opening and 5 degrees of knee flexion. The error bars indicate ± one standard error of the mean. There was no tension on the iliotibial band proximal to the lateral femoral condyle in these preparations.

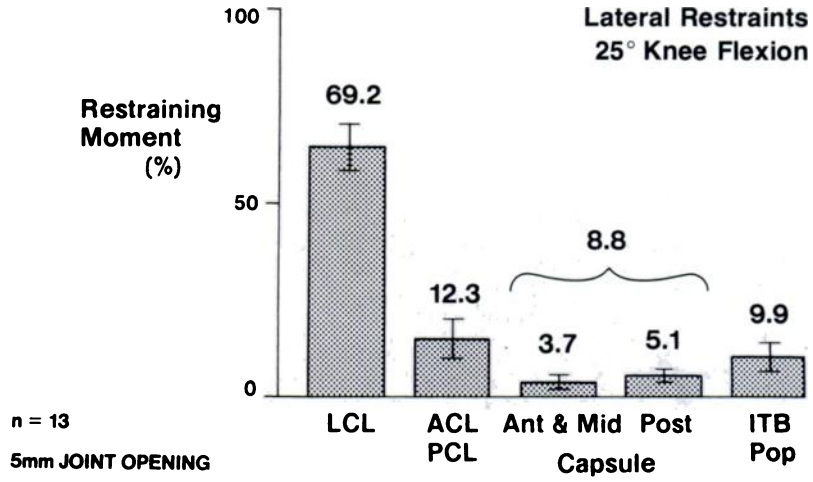

FIG. 6-B

The per cent contribution of these same structures to the restraints at five millimeters of opening and 25 degrees of knee flexion.

ion. The largest contributions that we measured for the capsule were 15.3 per cent at 5 degrees and 13.7 per cent at 25 degrees of flexion.

At 5 degrees of flexion most of the restraint from the lateral half of the capsule was due to the posterior arcuate complex, which provided 13.2 ± 2.4 per cent of the total restraint. With flexion to 25 degrees, the arcuate complex became slack and its contribution decreased to 5.1 ± 1.3 per cent.

Cruciate Ligaments

At five millimeters of joint opening, the cruciate ligaments together provided 22.2 ± 2.6 per cent of the total restraining moment at 5 degrees and 12.3 ± 4.2 per cent at 25 degrees of flexion (Figs. 6-A and 6-B). At these flexion angles we found no statistically significant effect of the order in which the ligaments were cut (cruciate ligaments cut first or last). However, there was a large variation between specimens. At 5 degrees of flexion their combined restraint ranged from 10.7 to 36.7 per cent. At 25 degrees the range was from 1.9 to 45.7 per cent.

We were able to separate the contributions of the anterior and posterior cruciate ligaments to the restraint of varus opening in eleven specimens. The results (Table II) were independent of whether the anterior cruciate was cut before or after the posterior cruciate ligament. The anterior cruciate provided the greater portion of the combined restraining effects of the two cruciate ligaments at both angles of knee flexion.

Iliotibial Tract, Popliteus Tendon, and Biceps Tendon

The restraints limiting lateral opening caused by the ligament-like actions of the popliteus tendon and muscle and of the femorotibial portion of the iliotibial tract were minimum at both angles of flexion studied (Figs. 6-A and 6-B). Therefore, we combined their restraints for this presentation. These results, however, do not reflect the *in vivo*

restraining action of either structure, since both are believed to transmit muscle force across the knee.

In two knees, we studied the effect on lateral opening of tension in the iliotibial tract and in the biceps tendon. A 225-newton (fifty-pound) force was applied to the iliotibial tract with a deadweight and pulley system. A curve of the restraining moment is shown in Figure 7-A for one intact knee before and after the tension was applied. The tension produced a marked increase in the lateral restraining moment. When the effect of the tension alone was analyzed (Fig. 7-B), it was seen that the applied force produced a nearly constant restraining moment, independent of the amount of lateral opening of the joint. A nearly identical result was found at 25 degrees of knee flexion. As expected, when different amounts of force were applied the restraining moment was found to be proportional to the magnitude of the applied force. Similarly, the restraining moment produced when a force was applied to the biceps was proportional to the applied force and was independent of joint opening.

TABLE II

PER CENT RESTRAINING MOMENT DUE TO THE CRUCIATE LIGAMENTS FOR LATERAL JOINT OPENING (N = 11)*

Ligament	Flexion Angle	
	5 Degrees	25 Degrees
Anterior cruciate	19.7 ± 2.7	10.3 ± 4.1
Posterior cruciate	2.7 ± 0.7	4.1 ± 1.1
Both	22.4 ± 3.0	14.4 ± 4.7

* Mean of total lateral restraint ± one standard error of the mean.

Because the restraining moment of the iliotibial tract was nearly constant within the range of lateral joint-space opening tested, the per cent contribution of the tract was greatest at small joint openings, when the action of other ligaments was smallest. As the joint opened farther the restraints due to other ligaments increased, causing the per cent contribution of the iliotibial tract to decrease.

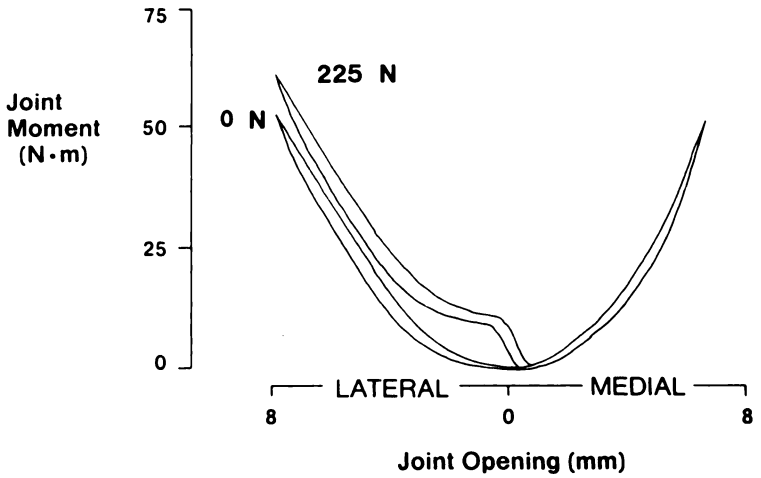

FIG. 7-A

Effect of applying a 225-newton (fifty-pound) force to the iliotibial tract. The force increases the lateral restraint (joint moment) and decreases lateral joint laxity (joint opening).

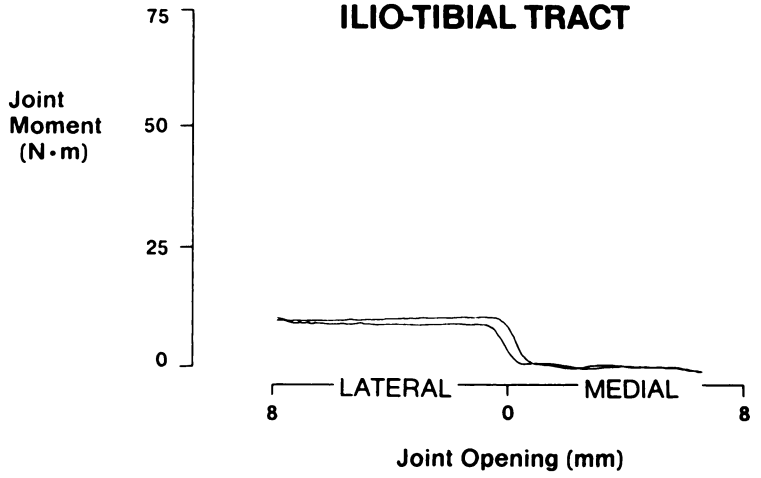

FIG. 7-B

Difference curve showing the isolated lateral restraining effect of the force applied to the iliotibial tract. Note that the restraining action is independent of the amount of joint opening.

Locations of the Rotation Axes

On one specimen we used the instrumented kinematic chain to measure the three-dimensional motion of the knee during tests with the Instron testing system. From these data we calculated the locations of the axes of rotation for varus-valgus planar motion of the knee. This is a compound motion made up of varus-valgus rotation, medial and lateral shift, and joint distraction.

The locations of the axes with respect to the femur for 5 degrees of knee flexion are shown in Figure 8. In this figure the tibia, which moves during the test, is drawn in the neutral position, corresponding to the start of the test. The rotation axes are located above the contact area on the lateral femoral condyle for valgus displacement and above the medial contact area for varus displacement. The lower points locate the rotation axes for the first half of the varus and first half of the valgus test (approximately zero to 2.5 millimeters of joint opening). The upper points locate the axes for the last half of each test (2.5 to five millimeters of opening). For the total varus and total valgus motion, the axes are located near the mid-points of the lines connecting the lower and upper points.

The positions of the axes above the joint line indicate that a sliding motion occurs between the tibia and the femur. During a valgus test, the tibia slides laterally in the same direction as the applied force. During a varus test, the opposite sliding motion occurs and the tibia moves medially. The motion of the instant center upward, away from the joint line, reflects an increase in the amount of medial-lateral shear movement for each degree of varus-valgus rotation as the test progresses. The increase in the amount of shear movement per degree of rotation can only occur if the rotational stiffness of the joint increases more rapidly than its shear stiffness.

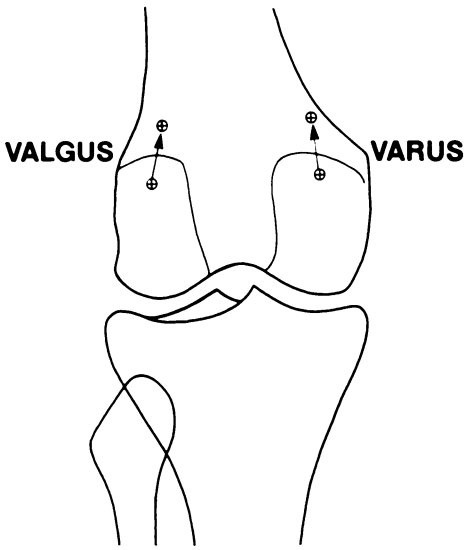

FIG. 8

The instant centers for one-plane varus and valgus displacements of the knee at 5 degrees of knee flexion. The instant centers are above the joint line, indicating that a sliding motion occurs at the contact region. During valgus displacement the instant center is on the lateral side and during varus displacement, on the medial side. The arrows indicate that the instant centers move proximally as the medial and lateral joint openings increase.

In addition to calculating the rotational axes, we used the motion measurements to evaluate our grips. The grips were designed to prevent any changes in the flexion angle or axial rotation of the tibia during varus-valgus testing. In the one specimen studied, we found an average change of flexion of 0.13 degree (standard deviation, 0.55) and an average of −0.09 degree (standard deviation, 0.83) of tibial rotation during the tests. These values were the maximum average movements within the grips that occurred in the intact knee and in this same knee after cutting the cruciate and collateral ligaments.

Joint Motions during Clinical Examination

The actual three-dimensional joint motions and laxities that occurred during the maneuvers performed in a typical clinical examination were measured in six knees using the instrumented kinematic chain described previously. Our objective was to determine how well such an examination can detect complete loss of the collateral ligaments (the primary restraints).

The total laxity (combined varus and valgus laxity) prior to cutting any ligaments in these six knees was 4.4 ± 0.98 millimeters (mean ± standard deviation) at 5 degrees of flexion and 7.5 ± 1.29 millimeters at 30 degrees of flexion. We performed the tests with the leg over the side of the table, palpating the joint line with one hand while applying a force at the ankle with the other hand (Fig. 2). The force applied was not measured with a load-handle because use of the handle would make it impossible to perform the examination in the conventional manner.

To check the data from our clinical examination, we determined the average moments that were required to produce similar laxities in the knee preparations used to measure the ligament restraints. At 5 degrees of knee flexion, a nine-newton-meter moment was required to produce an average laxity of 4.4 millimeters. At 25 degrees, a fifteen-newton-meter moment produced an average laxity of 7.5 millimeters. These moments were approximately equivalent to the moments produced by five and eight pounds (twenty-three and thirty-six newtons) of force applied at the ankle.

The increases in laxity after cutting the collateral ligaments are shown in Table III. During varus testing, the increases after cutting the lateral collateral ligaments were 0.84 ± 0.5 millimeter at 5 degrees of flexion and 2.56 ± 0.8 millimeters at 30 degrees of flexion. The greater laxity in the flexed position was consistent with the loss of the restraint provided by the posterior part of the capsule and the increase in the contribution of the lateral collateral ligament, previously noted. Still, the increases at both flexion angles were small due to the action of the secondary restraints at the low forces applied during a clinical examination. The largest increase in any knee was 3.7 millimeters. This occurred in 30 degrees of flexion, a position in which the knee normally has more laxity.

During valgus testing, after cutting the medial collateral ligament we found larger increases in joint laxity than those observed during varus testing. This difference was consistent with the larger contribution to varus-valgus restraint provided by the medial collateral ligament compared with the contribution of the lateral collateral ligament. As in the varus test, the increase in valgus laxity after sectioning of the medial collateral ligament was greater in the more flexed position. The largest increase in valgus laxity was 5.5 millimeters in one knee at 30 degrees of flexion. By our clinical grading system, this was a borderline Grade-2 laxity (a five to ten-millimeter increase) even though there was complete absence of the primary restraint (the medial collateral ligament).

The increases in varus-valgus laxity at both flexion angles were consistent with those expected from the moment-angle curves measured on the isolated knee preparations. We concluded that large joint openings may not be demonstrated by clinical examination even when the primary restraint is torn.

TABLE III

INCREASE IN LAXITY FOLLOWING LOSS OF THE COLLATERAL LIGAMENT (N = 5)*

	Mean ± Standard Deviation (mm)	Range (mm)	
		Minimum	Maximum
Lateral laxity			
5° of flexion	0.84 ± 0.46	0.3	1.3
30° of flexion	2.56 ± 0.80	1.7	3.7
Medial laxity			
5° of flexion	1.24 ± 0.69	0.4	2.3
30° of flexion	3.90 ± 1.43	2.0	5.5

* All numbers are in millimeters of joint opening. One millimeter is equivalent to approximately 1 degree of tibial angulation.

A particularly important finding was the large amount of out-of-plane tibial rotation that consistently occurred during the clinical examination. Typically, the amount of axial tibial rotation was greater than the total varus-valgus laxity. For example, in one knee the laxity (varus and valgus combined) near full extension was 2.5 millimeters, and this was accompanied by 4.5 degrees of axial tibial rotation. In 30 degrees of flexion, the laxity was 6.5 millimeters, and this was accompanied by 8.2 degrees of axial tibial rotation. This observation was not peculiar to one examiner, but was a general finding.

Discussion

Although we could simulate the clinical examination adequately, there were obvious differences between the knees of patients and the knee preparations that we used. Most obvious were the effects of postmortem tissue lysis, storage by freezing, and changes in the state of tissue hydration. It is impossible to avoid some changes due to all of these factors, particularly when testing human preparations. Our data, however, are reported as percentages of the total restraint in each knee, so that if similar changes occurred in all ligaments, the results should not be affected.

The most significant differences between our preparations and knees *in vivo* were: (1) the absence of all skin and muscles, (2) disruption of the tibiofibular interosseous membrane (Fig. 1), and (3) loss of the proximal attachments of the iliotibial tract, as already noted. The skin is not thought to be a significant passive restraint. Muscles contribute both an active tension and a passive resting tension. During the examination for laxity, the clinician attempts to eliminate all active contribution by the muscles, and local or general anesthesia sometimes may be required. Thus, we do not believe that absence of active muscle tension was a limiting factor in our study. However, at full extension the resting passive tension in the knee flexors and popliteus in living patients may provide reinforcement to the capsular structures that we did not measure.

The final factor is the order in which the ligaments are cut. To eliminate this effect, exactly the same knee motions would have to be reproduced from test to test. This could have been accomplished by fixing the location of the axis of varus-valgus rotation[26,27]. However, no data were available on the correct location of this axis. Furthermore, if the location of the axis was fixed, the results would depend on where we fixed the axis. We therefore left each knee free to rotate around its own axis, just as occurs during a clinical examination. This procedure has the disadvantage that the location of the axis may change after a ligament is cut, making the results dependent on the cutting order. To evaluate this effect, we employed two cutting sequences. In one the cruciate ligaments were cut first, while in the other they were cut last. Although no statistically significant difference was found, this does not mean that there was no effect, only that it was small in comparison to other sources of variability. For this reason, we examined the data to look for any trend indicating dependence on the cutting order, but none was found.

Medial Collateral Ligament

Our finding that the long, parallel-fibered, superficial portion of the medial collateral ligament is the primary restraint limiting medial joint opening agrees with the findings of Warren et al.[32], who reached a similar conclusion by measuring changes in laxity after selective cutting of the ligaments. However, they did not quantitate the true restraining moment contributed by the medial collateral ligament and other structures or the changes in their contributions at different positions of knee flexion.

We found that the per cent contribution of the medial collateral ligament was greater at 25 degrees of knee flexion than at 5 degrees of flexion, due to a decrease in the contribution of other structures, mainly the medial posterior part of the capsule. Clinically, this is appreciated as an increase in laxity as the knee is flexed, and was observed

previously in cadaver knees by Brantigan and Voshell[3], Warren et al.[32], and Markolf et al.[18].

The actual magnitude of the restraining force exerted by the medial collateral ligament changes little with flexion. This finding is in agreement with the observations of other investigators[2,30], who found only small changes in the length of this ligament over the range of flexion that we tested.

The increases in laxity that we measured by clinical examination after cutting the medial collateral ligament were small, averaging less than four millimeters at 25 degrees of flexion. Based on this finding, we believe that a five to eight-millimeter increase, determined clinically after an acute injury, indicates significant collateral ligament injury and impairment of the ligament's restraining effect. A larger joint opening is prevented by the secondary restraints, including the middle part of the medial half of the capsule and the cruciate ligaments, which readily resist the small forces applied during a clinical examination[5,22,23].

The important point is that even though an increase in laxity is small, it indicates significant tearing of the primary restraint and, therefore, the need for treatment. Accordingly, we urge respect for subtle laxities and the need for accurate assessment of medial opening. Protection is required for healing to occur and rehabilitation is needed to restore adequate neuromuscular control.

Capsule

Based on the restraining effects of the ligaments demonstrated in this study, it is our opinion that the mid-medial and mid-lateral parts of the capsule have been assigned major stabilizing roles incorrectly. This concept of their roles is based on the results of failure studies and on analyses of failures seen at the time of surgery. Thus, the middle parts of the medial and lateral halves of the capsule were thought to be the first line of defense, and it was assumed that after these parts of the capsule fail, the collateral ligaments have greater restraining function and fail as joint displacement increases.

We believe that analyses of failure cannot be used to determine the function of a ligament. In the first place, the actual displacement of a knee joint at the time of injury is not known. Secondly, a structure that has failed may have done so not because it was providing a large resisting force, but simply because it was inherently weak. Based on the findings in this study, we concluded that the mid-medial and mid-lateral capsular structures provide important attachments for the menisci but do not have primary roles in limiting straight medial and lateral laxity. However, it would be incorrect to interpret our data as indicating that the capsular complex is not important. The entire medial half of the capsule, together with the long medial collateral fibers, form a functioning unit, as does the lateral capsular complex.

At surgery, meticulous repair of all damaged structures is important to restore the hierarchy of restraining forces that was demonstrated in the studies reported here.

Lateral Collateral Ligament

Our studies showed that the lateral collateral ligament consistently provided a greater restraining moment than the combined moments exerted by the entire lateral half of the capsule, the iliotibial tract, the popliteus tendon, and the cruciate ligaments. Therefore, we believe that the lateral collateral ligament is the primary restraint limiting lateral joint opening.

This finding is contrary to common belief, especially with regard to the flexed knee in which the lateral collateral ligament is thought to be lax. Although the lateral collateral ligament does shorten as flexion occurs, it has not been determined whether most of the shortening occurs during the first part of flexion or later, as the flexion angle approaches 90 degrees. The findings of Edwards et al.[7] and of Wang et al.[30] are in direct conflict on this issue. Our results are consistent with the data of Wang et al.[30], who found only a 4 per cent shortening of the lateral collateral ligament between full extension and 30 degrees of flexion. We performed our tests with the knee in 5 degrees of flexion (just unlocked) and at 25 degrees of flexion, the positions used in clinical testing. Brantigan and Voshell[3] tested knees in 90 degrees of flexion, a position in which the lateral collateral ligament has shortened significantly. Therefore, it is difficult to compare their results with ours. That the lateral collateral ligament carries load during the test for varus laxity may be appreciated by palpation. However, this finding does not indicate its relative importance. When we measured the lateral collateral ligament's contribution, it was considerable.

We cannot say how much the lateral collateral ligament contributes to over-all varus stability of the knee during activity because the active restraints of the iliotibial tract, the popliteus, and the biceps may make major contributions to stability. Furthermore, the insertion of the biceps into the lateral collateral ligament, as noted by Marshall et al.[19], may enable this muscle to tighten the lateral collateral ligament and provide additional restraint resisting joint opening.

Cruciate Ligaments

Our data indicate that in intact knees, the cruciate ligaments act as secondary restraints during medial and lateral opening of as much as five millimeters. If there is a tear of one of the collateral ligaments, however, and ten to fifteen millimeters of opening is demonstrated, then the cruciate ligaments have become primary restraints. The concept that the cruciates have a secondary restraining function in the normal knee is contrary to what is usually taught. This secondary role may be understood if it is recalled that medial and lateral joint opening are produced by rotations of the tibia in the frontal plane and that these rotations are restrained by moments. Figure 8 shows the true centers of rotation in one knee at 5 degrees of flexion. The cruciate ligaments are located in the center of the

knee, close to the center of rotation. Because of this, the moment arms for the cruciate ligaments are about one-third those for the collateral ligaments. Thus, to produce restraining moments equivalent to the ones due to the collateral ligaments, the cruciates would have to provide a force three times larger than that of the collaterals.

We believe that the cruciate ligaments are better evaluated by other tests, such as the anterior-posterior drawer, flexion-rotation drawer, and gravity drawer tests, in which these ligaments act as primary restraints. In the tests for medial and lateral laxity, intact capsular structures may limit the amount of joint-space opening even when there is damage to the collateral and cruciate ligaments. However, large joint openings imply cruciate ligament damage, as Hughston et al. reported[13,14], and we would add that since both cruciates resist medial and lateral opening, partial cruciate-ligament tears may be more common than has been recognized previously.

Iliotibial Tract

Our results indicate that the iliotibial tract acts as a single functional unit. When the tract is removed from its proximal pelvic attachments, the femorotibial portion becomes slack and incapable of restraining lesser amounts of lateral opening. The major function of the fibers of this portion appears to be the transmission of the tension applied by muscle forces and the tautness of the iliotibial tract.

In vivo there are two main sources of tension in the tract[15]: the passive ligament-like tension between the iliac insertions of this structure, and the active muscle forces transmitted by the tract. The passive ligament-like tension should increase when the tract is stretched, as occurs during lateral joint opening. The ilium-to-tibia distance is so long, however, that lateral joint opening of a few millimeters does not produce much additional tension in the tract.

Our results suggest that the restraining function of the tract depends primarily on transmitted active muscle forces. Unfortunately, at present we can only speculate as to the magnitude of these forces and the relative importance of the tract both in restraining laxity during testing and in resisting forces generated during functional activity.

Clinical Examination

Our analysis of three-dimensional motion of the joint during the clinical examination for varus-valgus laxity and our measurements of the ligamentous restraints in cadaver limbs, as well as our clinical observations, have led us to identify the following points that are helpful in arriving at the correct diagnosis of medial and lateral ligament injuries.

First, is accurate estimation of the amount of straight medial or lateral opening during the examination. We recommend holding a finger at the joint line and estimating the laxity in millimeters of opening compared with the opposite knee. This procedure provides a semi-quantitative index of the laxity, which we categorize into four grades of severity: Grade 1 (less than five millimeters of increase), Grade 2 (five to ten millimeters of increase), Grade 3 (ten to fifteen millimeters of increase), and Grade 4 (more than fifteen millimeters of increase).

Second, if axial rotation of the tibia occurs due to inadvertent rotation of the leg during testing for medial or lateral laxity, the examiner may overestimate the amount of true opening. This occurs because associated external or internal tibial rotation can be perceived as additional joint opening. Recognition of the axial rotation is particularly important when assessing medial ligament injuries. Two types of medial-laxity tests have been described: one in which only straight medial laxity is assessed and one in which straight laxity is assessed with external rotation allowed to occur. We believe that the latter test gives an indication of anteromedial rotatory instability instead of straight one-plane medial laxity. This test is performed by abducting and externally rotating the leg with the femur held stationary. We have found that the examiner may not distinguish between these tests and therefore may lose the reliability of both[22].

As the varus-valgus examination is performed, the extremity may either be held in a cradled position or be placed over the side of the table with the thigh resting on the examining table. Often one position shows the laxity better than the other; therefore, we believe that both techniques should be used. In cases of anterior cruciate laxity, the cradled position may cause difficulties. While the leg is being held prior to testing, both straight anterior displacement (a positive drawer test) and anterolateral subluxation can occur[21,23]. In this event the joint is partially subluxated, and a mediolateral rocking motion can be obtained which may be misinterpreted as medial or lateral one-plane laxity. To prevent this, the knee also should be examined with the thigh supported by the examining table and gravity preventing the anterolateral tibial subluxation.

Interpretations

The correct diagnosis of medial and lateral soft-tissue injuries of the knee requires: (1) accurate assessment of small joint laxities, and (2) an understanding of the restraining functions of the various ligament and capsular structures. The clinician must distinguish straight medial and lateral joint opening from any associated tibial rotations. Varus-valgus laxity should be tested first by purposely attempting to block tibial rotation, and then repeated with rotation by applying a torque with the hand. The first test brings out the straight laxity, while the second test displays both straight and rotatory laxities. If the two motions are not distinguished, the findings may be misinterpreted.

The collateral ligaments are the primary restraints that limit straight medial-lateral laxity at 5 and at 25 degrees of flexion. Even a five-millimeter increase in joint opening compared with the opposite knee implies significant col-

lateral ligament injury that requires treatment. The greatest laxity occurs in the flexed position when the posterior part of the capsule is slack. Laxity is greatly reduced with the knee in full extension due to the secondary restraining action of the posterior part of the capsule and the cruciate ligaments. If there is appreciable laxity in extension, injury to the posterior part of the capsule and cruciate ligaments as well as to the collateral ligaments should be expected.

The cruciate ligaments, by themselves, can block joint opening in the fully hyperextended position. However, they are secondary restraints and are at a mechanical disadvantage due to their location in the center of the joint, close to the axis of varus-valgus rotation. Thus, we believe that they are better evaluated by tests for anterior-posterior laxity in which, as we have shown previously, they act as primary restraints[5]. The anterior and middle portions of the medial and lateral halves of the capsule provide only a secondary passive restraint resisting straight medial and lateral opening. There is thus a hierarchy of structures restraining straight medial and lateral laxity. Knowledge of this is required for accurate diagnosis and treatment.

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