Departments of Orthopedics and Traumatology, [1]Tiefenauspital der Stadt Bern and [2]Regionspital, Interlaken; and [3]Orthopedic Clinic, Inselspital, University of Bern, Switzerland

Stressradiography of the knee

Cruciate ligament function studied in 138 patients

Hans-U. Stäubli[1], Bruno Noesberger[2] and Roland P. Jakob[3]

Correspondence: Dr. Hans-U. Stäubli, Department of Orthopedics and Traumatology,
Tiefenauspital der Stadt Bern, CH- 3004 Bern, Switzerland
Tel +41–31 230473 Fax –31 243529

ACTA ORTHOPAEDICA SCANDINAVICA SUPPLEMENTUM NO. 249, VOL. 63. 1992

MUNKSGAARD · COPENHAGEN

Printed in Sweden
Wallin & Dalholm
1992

Anterior is anterior
  posterior is posterior
    the anatomic zero position...

      that is the question

Table of contents

Foreword

Evaluation of knee instability resulting from cruciate ligament damage is difficult. We used stressradiography in the near extended position to document final knee positions in patients with intact and deficient cruciate ligaments. Methods to measure anterior-posterior knee motion include using anatomic investigations, mechanical testing, clinical examination, and instrumented knee evaluation. Stressradiography at various knee positions is used to assess normal and abnormal motion limits in vitro and in vivo. Stereophotogrammetry, cineradiography, cinecomputer tomography, and integrated cinemagnetic resonance imaging may complement knee motion analyses.

When we compare normal joint play with abnormal knee motion in cruciate ligament-deficient knees, several questions arise:

1) What is the patient's position in respect to gravity—supine, prone, right lateral, left lateral?

2) What is the starting position of the tibia relative to the femur before performing any instability test?

3) Where is the anatomic zero femorotibial compartmental alignment?

4) What is the magnitude of the anterior and posterior knee motion segments in respect to the anatomic zero position?

5) Where is the limit of central, and where are the limits of femorotibial compartmental anterior and posterior displacements with respect to the anatomic zero position?

6) Do the limits of anterior-posterior knee motion represent the viscoelastic properties and mechanical competence of the intact cruciate ligaments? And conversely, does abnormal knee motion prove structural damage/mechanical incompetence of deficient cruciate ligaments?

7) Does stressradiography document normal and abnormal, central and compartmental displacement limits of the tibia with respect to the femur?

Multiple factors affect in vitro and in vivo knee instability testing. The factors are patient position, knee position, muscular tone or muscle relaxation, gravity, and the testing procedure. The induced central or compartmental displacement limits depend on orientation, magnitude, direction, or sense of applied forces and moments. Stability testing is affected by preloading cycles, loading mode, and application site of forces and moments. Constitutional factors, functional competence, and viscoelastic properties of primary and secondary ligamentous restraints, and properties of meniscocapsular restraints influence knee motion. The measurement device, measurement principle, location of measurement points, and the accuracy and reproducibility of measurement technique—in respect to the anatomic zero position or in respect to the clinical reference position—influence data acquisition. Based on this knowledge, a simple, noninvasive, universally applicable, reproducible, examiner-independent stressradiographic method was introduced to assess and document the limits of compartmental knee motion in vivo under standard conditions.

In this work, we present our experiences in studying knee motions stressradiographically in the near extended position. The text is organized in five parts. In the first, we describe the evolution of the stressradiographic measurement technique to evaluate the knee in the near extended position. In the next, we state the concepts of knee motion and knee position on which our thesis and practice are based. In the third part, we present stressradiographic results obtained at manual maximum loads in a clinical study involving 138 patients. In the forth, we describe the stressradiographic technique, device, and measurement template. The final part consists of our analysis of a decade of work and the works of others in an effort to attain the optimum method for assessing compartmental motion limits in ligament-intact and ligament-deficient knees.

July 1992

Hans-U. Stäubli
Bruno Noesberger
Roland P. Jakob

Evolution of stressradiography

To measure and document sagittal knee instability in flexion, several authors have advocated stressradiography of the knee at 90 degrees of flexion (Nyga 1970, Kennedy and Fowler 1971, Jacobsen 1976, Levén 1977, Jacobsen 1981, Torzilli et al. 1981, Stedtfeld and Strobel 1983). With the introduction of drawer testing at 15 degrees of flexion, examiners were able to demonstrate, with stressradiography, the advantages of assessing anterior knee motion (Jakob et al. 1987) and posterior knee motion (Stäubli and Jakob 1990b) in the near extended position.

In an in vivo, mechanical evaluation of anterior-posterior motion of the knee, Torzilli et al. (1981) modified the method of Jacobsen (1976) by including five additional measurements to analyze coupled knee motions at 90 degrees of flexion. They found large errors if rotational motions were not accounted for in the analyses. The coupled rotations that occurred with anterior-posterior knee motion were considered important. In subsequent studies of anterior-posterior knee motion in cadaver knees, Fukubayashi et al. (1982) used a specially designed knee testing apparatus to measure tibial displacement, rotation, and torque. In knees with cruciate ligament insufficiency, the greatest increase in anterior displacement occurred at 30 degrees of flexion. The greatest increase in posterior displacement occurred at 70 degrees of flexion. They concluded that, when performing any quantitative measurement of anterior-posterior knee motion, rotational constraint of the femorotibial motion should be used. Gollehon et al. (1987) analyzed coupled internal/external rotation of the tibia. When anterior force was applied to the tibia of ligament-intact knees, the tibia rotated internally. When posterior force was applied, external rotation of the tibia occurred. These coupled rotations with anterior and posterior forces were higher in flexion than near extension. Thus, a method to measure physiologic joint play and increased coupled knee motions in near extension evolved.

Clinical assessment and instrumented testing in the near extended position has become a part of the knee surgeon's armamentarium. To evaluate clinically anterior knee motion in anterior-cruciate-ligament deficiency, Torg et al. (1976) introduced the Lachman test—the anterior drawer sign with the knee tested at 15 degrees of flexion. Following the introduction of the Lachman test, arthrometric devices have been advocated by several authors (Markolf et al. 1978, Daniel et al. 1985, Edixhoven 1986, Edixhoven et al. 1987, Shino et al. 1987, Edixhoven et al. 1989). To document clinical anterior-posterior drawer testing under anesthesia, a stressradiographic measurement technique was introduced by Stäubli et al. (1983). Subsequently, this method was refined to document coupled anterior knee motion in anterior-cruciate-ligament-intact and anterior-cruciate-ligament-deficient knees. Based on these studies, the technique of compartmental stressradiographic knee motion analysis in the near extended position has evolved.

To measure three-dimensional instability of the anterior-cruciate-ligament-deficient knee, Kärrholm et al. (1988) used roentgen stereophotogrammetry (Selvik 1974/1989). They inserted tantalum balls and assessed the knee in a calibration cage. All anterior cruciate ligament-deficient knees displayed an increased anterior-posterior motion. With anterior traction, they recorded anterior-translation/internal-rotation/abduction-rotation. The tests were performed at an anterior force level of 150 N without anesthesia.

Jakob et al. (1987) applied the technique of compartmental stressradiographic analysis of anterior knee motion to grade and document the pivot-shift-phenomena in anterior-cruciate-ligament-deficient knees. From these measurements, Jakob et al. (1987) deduced treatment implications and treatment modalities. In a subsequent prospective study on anterior knee motion, we compared arthrometry and simultaneous radiography in chronic anterior-cruciate-ligament-deficient knees (Stäubli and Jakob 1991). To evaluate posterior knee motion, we measured stressradiographic anterior-posterior motion limits in 24 acute posterior-cruciate-ligament-disrupted knees. We recorded posterior translation, coupled posterior-translation/external-rotation and coupled posterior-translation/internal-rotation (Stäubli and Jakob 1990b).

The technique of stressradiography at maximum manual loads was modified and supplemented (in 1987) by the introduction of the Telos® stress testing device (Telos® GmbH, Unter den Linden 26, 6303 Hungen/Obbornhofen, Germany; Stäubli 1990). Knee supports of varying diameters to maintain constant knee flexion angle, constant anterior-posterior force level, consistent preloading cycles, and a constant loading mode were used. Subsequently, with the introduction of the KMT-20 Template©, tests for accuracy and reproducibility verified the precision we could obtain in measuring knee motion and position on stressradiographic images.

The concepts of knee motion and position

Current concepts of knee motion principles are based on the work of Chao (1980), Andrews (1984), and Grood and Noyes (1988). The results of their studies provide a description and an interpretation of the six degrees-of-freedom and the twelve limits-of-motion.

The principle of motion with *six degrees-of-freedom* consists of three translations—anterior/posterior, medial/lateral, and proximal/distal, i.e. compression/distraction; and three rotations—internal/external, abduction/adduction, and flexion/extension (Figure 1). The principle implies that for each degree of freedom, there are two limits of motion in opposing directions, e.g. for anterior-posterior translation—an anterior and a posterior motion limit. Hence, there are *twelve limits-of-motion.*

The definitions of terms to describe knee motions, in the Glossary, are based on the work of Noyes et al. (1989a).

The knee positions on which we will concentrate are the a) anatomic zero position, b) starting position, and c) final position.

The *anatomic zero position* is a position of relative compartmental alignment of the knee in all planes and around all axes. Stressradiographically, the anatomic zero position is the unstressed knee position in the sagittal plane in which the posterior compartmental tangents coincide. These posterior tangents run parallel to the tibial shaft cortex at the midshaft level touching the most posterior aspects of the medial and lateral femoral and tibial condyles (Figure 2).

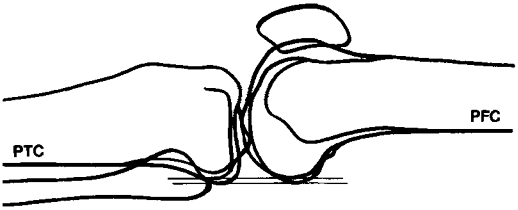


Figure 2. *The zero anatomic position.* With the knee in the extended position the posterior tibial cortex (PTC) and posterior femoral cortex (PFC) form an angle of 0°. Posterior condylar tangents are drawn parallel to PTC. In the zero anatomic position, these tangents are superimposed.

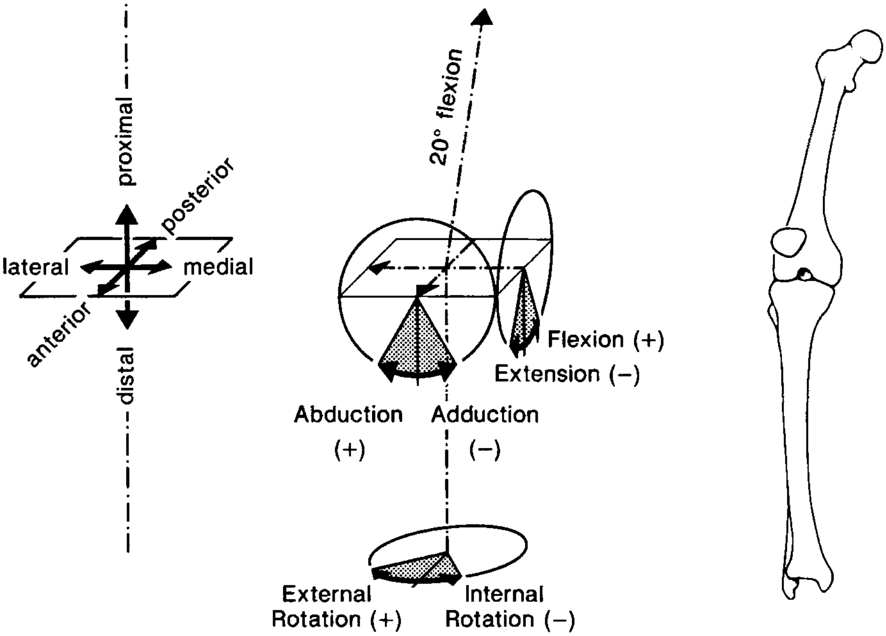


Figure 1. The *six degrees-of-freedom* motion of the knee (Grood and Suntay 1983). The three translation planes (left) and the three rotation axes (center). The joint coordinate system is illustrated for the right knee at 20 degrees of flexion.

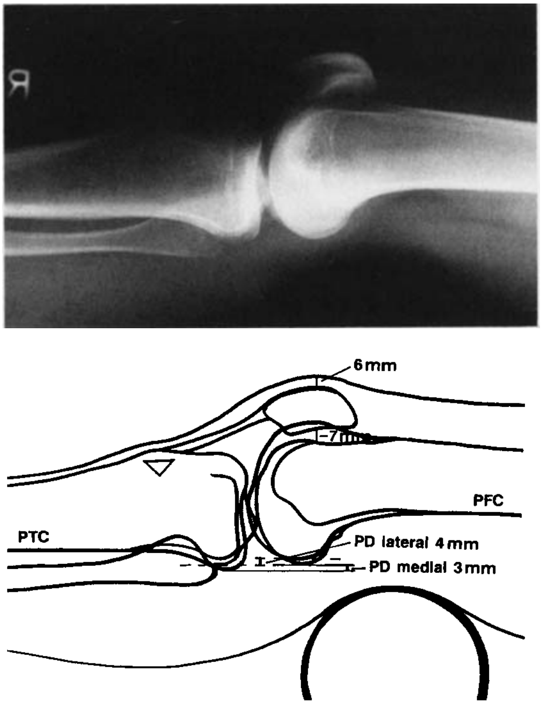


Figure 3. *Starting position.* In the supine position, with the distal thigh supported and the quadriceps muscles relaxed (knee in 15 to 20 degrees of flexion), a minimal amount of bicompartmental posterior displacement (PD), measuring 4 mm for the lateral and 3 mm for the medial compartment, can be documented by a nonstressed unconstrained lateral radiograph in the sagittal plane. This represents gravity-induced laxity-dependent posterior joint play for that individual patient. The soft tissue anterior to the patella is 6 mm; the distance between the patella and trochlea is 7 mm. Arrowhead on the anterior tibia indicates direction of gravity.

In the *starting position,* the patient lies supine, the distal thigh is supported, and the quadriceps is relaxed (Figure 3). With the knee in the near extended position, gravity displaces the tibia posteriorly before the examiner begins to evaluate the knee. If the quadriceps muscle is completely relaxed, gravity is the main displacing factor in the position of 20 to 25 degrees of knee flexion according to the restraining capacity of the intact posterior cruciate ligament, and the intact posteromedial and posterolateral structures. With innervation of the quadriceps muscle, an anterior force vector is created at the proximal tibia. This anterior force reduces the posterior displacement beyond the neutral position into an anterior final position according to the intact restraining capacity of the anterior cruciate ligament, the anteromedial, and anterolateral structures. With innervation of the biceps femoris, a posterior force vector is created at the proximal tibia. This force increases the gravity-induced posterior displacement.

The *final position* is the position of the knee at the end of a motion segment. The induced forces are balanced by the residual restraining capacity of the uninjured functionally competent ligamentous and meniscocapsular restraints. This final position is force dependent. The higher the induced forces, the larger the resultant displacements. Due to the viscoelastic properties of the involved structures (Woo et al. 1990), a hysteresis curve results when a complete anterior-posterior motion cycle is applied and released (Edixhoven et al. 1989).

Motion segments and limits

Terms applicable to describe motion segments and motion limits (sagittal plane) are:

- Anterior final position = limit of anterior motion.
- Anterior motion segment.
- Anatomic zero position = compartmental anatomic alignment.
- Posterior motion segment.
- Posterior final position = limit of posterior motion.

In anterior-posterior translation in the sagittal plane, an anterior motion segment and a posterior motion segment are defined. The *anterior motion segment* describes the displacement between the *anatomic zero position* and the *final anterior position.* The *posterior motion segment* describes the displacement between the *anatomic zero position* and the *posterior final position.* The anterior and posterior final positions represent the limits of anterior and posterior knee motion, respectively. When an anterior force is applied to the tibia (constrained in neutral rotation), an anterior knee motion is induced. The anterior motion comes to a halt when the anterior final position at the anterior limit of knee motion is reached. Conversely, when a posterior force is applied to the tibia (constrained in neutral rotation), a posterior knee motion is induced. At the end of the posterior knee motion segment, the posterior final position at the limit of posterior knee motion is reached.

Terms applicable to describe *central versus compartmental* knee motion are illustrated in Figure 4. The selection of translation reference points is important (Grood and Suntay 1983). The limit of *central* anterior knee motion in respect to the central anatomic position is the motion segment defined by the displacement of a central measurement point located at 50 percent of the total knee width.

The limit of *compartmental* knee motion is defined by two measurement points on each motion segment. At stressradiography, the measurement points are located at 15 percent of the total femoral width for the

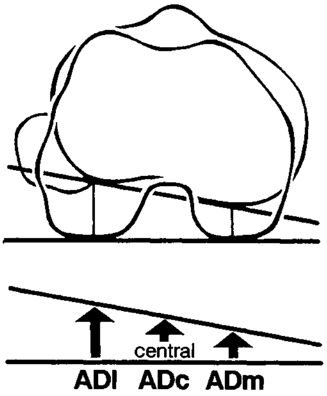


Figure 4. Central versus compartmental motion. The arithmetic mean of the medial and lateral displacements (measured at 15 percent and 85 percent of total knee width) defines the central displacement. ADl anterior displacement, lateral compartment; ADc anterior displacement, center of the knee; ADm anterior displacement, medial compartment.

medial compartment and at 85 percent of the total femoral width for the lateral compartment (Figure 4).

Factors influencing the accuracy and reproducibility of the knee motion analysis in patients are:

- Patient position—supine, prone, left or right lateral.
- Knee position—starting, anatomic zero, final.
- Knee flexion-rotation angle.
- Gravity and gravitational forces.
- Muscular tone and/or muscle relaxation.
- Active or passive knee motion analysis.
- Constrained or unconstrained testing conditions.
- Constitutional factors—ligament quality, constitutional laxity, individual anatomic joint configuration.
- Functional competence and structural and mechanical properties of primary and secondary ligamentous and meniscocapsular restraints.
- Functional competence and structural integrity of secondary restraints.
- Trauma-induced factors—ipsilateral intra- and extra-articular fractures.
- Previous knee surgery or arthroscopy.
- Deficits of active and passive knee motion; interposed large fragment buckethandle tears; degenerative joint disease with terminal motion deficits and altered terminal compliance.

Radiographic landmarks and contour characteristics of femur and tibia

The terms for radiographic measurement lines used in this Supplement are reference lines, posterior femoral cortex (PFC), posterior tibial cortex (PTC), and posterior compartment tangents.

Reference lines are the tangents at the posterior subchondral level of medial and lateral femorotibial compartments. The definition of a reference line is critical when applying a coordinate system for the three-dimensional knee motion (Grood and Suntay 1983).

Posterior femoral cortex (PFC) is used as a reference line at the distal third of the femoral shaft.

Posterior tibial cortex (PTC) is used as a reference line at the midshaft level of the tibia.

Posterior compartmental tangents are measurement tangents to the subchondral aspects of medial and lateral femoral and tibial condyles drawn parallel to the PTC. If measurement tangents are parallel to PTC, then the stressradiographic measurement tangents are parallel to the fixed tibial body axis.

To assess compartmental knee motion, we selected two points on each motion segment. The distal measurement points are the most posterior aspects at the subchondral level of the medial and lateral tibial plateaus. The proximal measurement points are the most posterior aspects at the subchondral level of the medial and lateral femoral condyles. These measurement points represent the center of the corresponding compartments. In stressradiography measurement technique, the PTC at the midshaft level is the tibial reference line and the PFC is the femoral reference line. The anatomic femorotibial flexion angle is the angle formed by the PTC and the PFC. The relative compartmental position of the tibia with respect to the femur is used during motion analysis. Thus the posterior measurement tangents to the femoral condyles (running parallel to the posterior tibial cortex) are used as the anatomic reference in stressradiography.

Definitions of osseous landmarks and reference lines require a thorough knowledge of the normal radiographic compartmental anatomy of the knee joint (Danzig et al. 1981). Rauschning (1979) studied human knee specimens by serial cryosectioning. He provided transparencies of sections through the middle of the medial and lateral compartments (Figure 5). Reflected-light photography of an overview of the knee in extension shows in detail the normal anatomic and subchondral relationships of both compartments. His studies of compartmental anatomy complement our stressradiographic studies of the knee. Independently, we both have arrived at the same definition of the anatomic zero position.

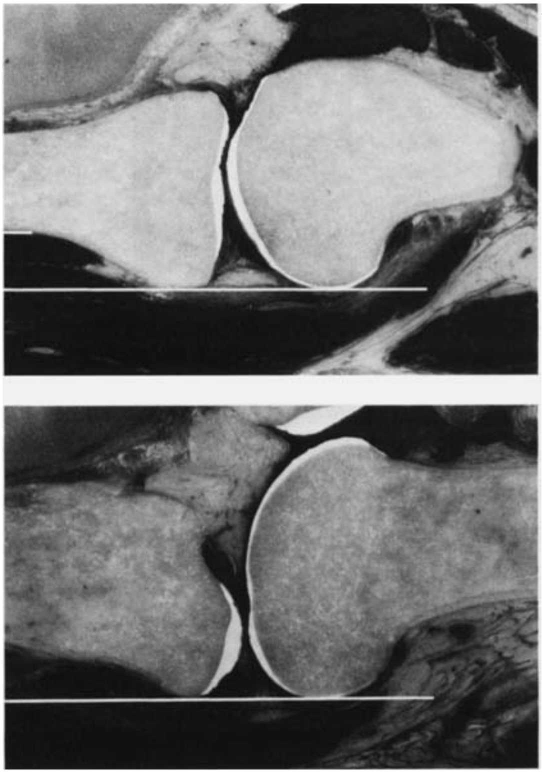


Figure 5. Cryosectional anatomy of the knee (photographs printed from transparencies). The white line, demonstrating the neutral (zero) position was superimposed on the photographs. (Photographs are reproduced by permission from the private collection of Professor Wolfgang Rauschning, Department of Orthopedics, University Hospital, Uppsala, Sweden. Financial support was provided by the Swedish Medical Research Council 8611 and 07474.)

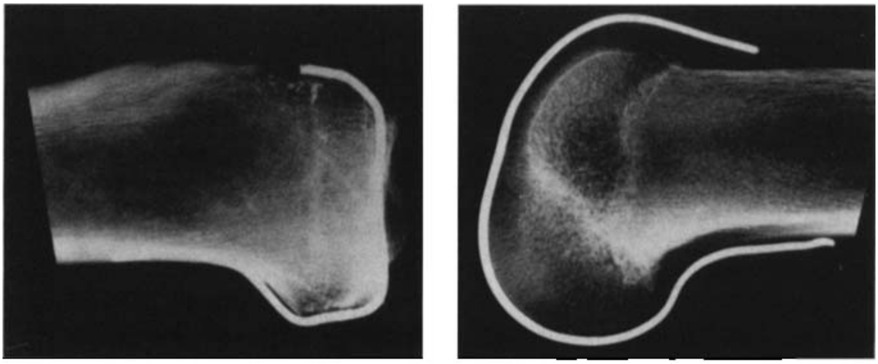
To define knee contours, we outlined compartmental osseous landmarks and reference lines by lead markers in 5 cadaveric knee joints. Lateral radiograms were obtained to evaluate compartmental anatomy and compartmental alignment in the anatomic zero position. Lead wires were placed at 15 percent and 85 percent of the total tibial/femoral width posteriorly at the centers of the medial and lateral compartments. Contour characteristics of compartmental radiographic anatomy with respect to the sagittal projections were defined (Table 1, Figure 6)

The anteroposterior sagittal diameter of the medial femoral condyle is smaller than the diameter of the lateral femoral condyle (Figure 6). The radius of posterior curvature of the medial condyle is smaller than the radius of the lateral condyle. At times, the adductor tubercle (medial condyle) and the fabella (adjacent to lateral condyle) may help to differentiate the femoral compartments. Normally, the terminal sulcus or groove is shallow or flat and located anteriorly on the medial femoral condyle, whereas the triangular-shaped terminal sulcus is located in the projection of the intercondylar roof tangent creating a biconvex distal contour of the lateral condyle. The configuration of the terminal sulcus may be altered by constitutional laxity and incompetence of the cruciate ligaments.

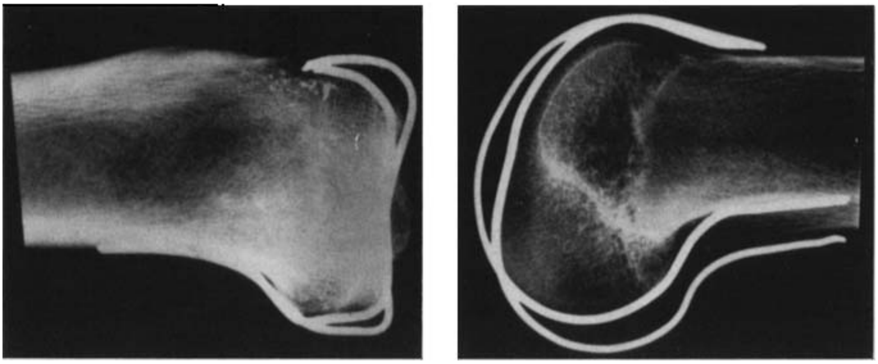
The anterior-posterior sagittal diameter of the medial tibial plateau is greater than that of the lateral tibial plateau. The proximal contour is concave medially and flat or convex laterally. The posterior contour of the medial tibial plateau is squared off while the posterior contour of the lateral tibial plateau slopes downward from the lateral tubercle of the intercondylar eminence to terminate near the proximal tibiofibular joint (Figure 6).

Table 1. Subchondral osseous landmarks and contour characteristics of tibia and femur. Definition of compartmental anatomy in the sagittal plane

	Femoral condyle		Tibial plateau	
Landmark	Medial	Lateral	Medial	Lateral
Sagittal antero-posterior diameter	smaller	greater	greater	smaller
Radius of posterior curvature	smaller	greater	. . .	. . .
Posterior contour	. . .	. . .	squared off	downward slope
Distal contour	convex	biconvex	. . .	. . .
Proximal contour	. . .	. . .	concave	flat or convex
Terminal sulcus location	anterior	in projection of intercondylar roof tangent	. . .	. . .
depths	flat	triangular-shaped	. . .	. . .
Characteristics	adductor tubercle	fabella (8 to 15 percent)	. . .	proximal tibiofibular joint



The lateral tibial plateau. **The lateral femoral condyle.**



The medial and lateral tibial plateaus. The medial and lateral femoral condyles.

Figure 6. Sagittal contours of the condyles shown by lead wires.

Table 2. Clinical anterior-posterior motion tests in the near extended position

Supine Lachman; supine anterior drawer in near extension	
passive	Torg et al. 1976, Gurtler et al. 1990
active	de Montmollin and Pol le Coeur 1983 Cross et al. 1987
Trillat-Lachman sign; combined anterior-posterior drawer testing near extension	Trillat et al. 1978
Posterior drawer sign in the near extended position	
passive	Stäubli and Jakob 1990b
active	Stäubli and Jakob 1990b
Coupled anterior-posterior subluxation/reduction tests	Lemaire 1967, Galway et al. 1972 Hughston et al. 1976 Parts 1 and 2 Losee et al. 1978 Galway and MacIntosh 1980 Jakob et al. 1981 Clancy et al. 1983 Noyes et al. 1989a and b

Clinical and radiographic assessment of knee positions

Before evaluating the knees stressradiographically, the examiner should evaluate both the noninvolved knee and the involved knee clinically. To assess increased anterior-posterior knee motion with the patient in the supine position, several tests have been advocated. A synopsis of the clinical tests with the knee in the near extended position is represented in Table 2. With the knees resting on the thigh support (11.5 cm in diameter), tuberosity position or depth is measured with a ruler to assess gravity-induced posterior sagging or dropback before testing (Stäubli and Jakob 1990b). On an unstressed lateral radiograph and on a diagram (Figure 7), the gravity-induced posterolateral starting position is illustrated. Active and passive drawer signs are then tested. The uninvolved and the involved knees are clinically evaluated according to the OAK knee documentation form (Müller et al. 1988). Subsequent to induction of peridural anesthesia and after complete muscular relaxation, both knees are evaluated for compartmental instabilities. The obtained clinically judged displacement values are recorded in millimeters on the OAK or IKDC (International Knee Documentation Committee) documentation form (Müller et al. 1988).

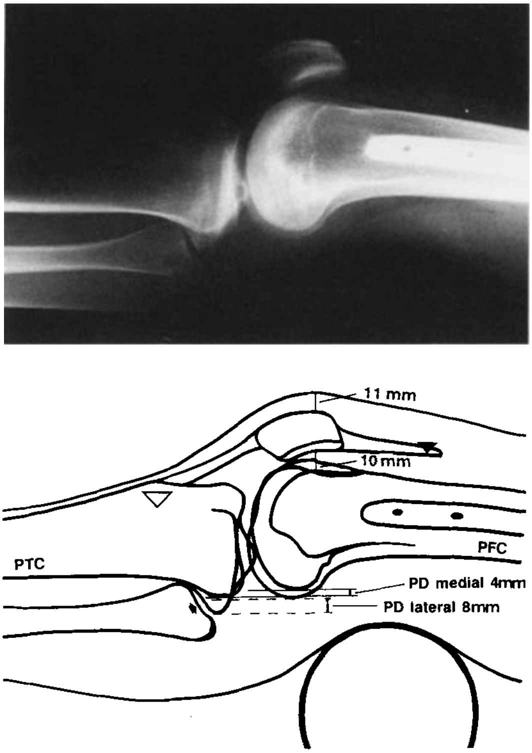


Figure 7. Gravity-induced posterolateral dropback in a posterior-cruciate-ligament-deficient knee. Gravity displaces the tibia posterolaterally. The distal thigh is supported and the quadriceps is relaxed. The leg had sustained a direct impact that required closed intramedullary nailing of a subtrochanteric femoral shaft fracture. The diagram of the radiograph illustrates the 8-mm posterior displacement (PD) of the lateral compartment and a 4-mm posterior displacement of the medial compartment. PTC posterior tibial cortex; PFC posterior femoral cortex. The soft tissue anterior to the patella is 11 mm; the distance between the patella and trochlea is 10 mm. The arrowhead on the anterior tibia indicates the posterior direction of gravity on the tibia; the solid arrow on the fibula points to the proximal tibiofibular joint. If the proximal tibiofibular joint can be seen on the lateral radiograph of the knee, the examiner knows that the tibia is externally rotated if the femoral condyles are superimposed.

Stressradiography at manual maximum loads

Cruciate ligament function in 138 patients

Methods

In the 1980s, we obtained anterior and posterior stress radiograms of the knee under anesthesia at manual maximal loads. On the stressradiographs, we measured the limits of compartmental displacements at the final positions in the sagittal plane in respect to the anatomic zero position. During surgery or arthroscopy, we assessed with a probe the status of the cruciate ligaments in the injured knee.

Exclusion and inclusion criteria

Initially stressradiograms were obtained in 219 knees. A summary of the inclusion criteria appear in Table 3. The study patient population was divided into four groups according to the probed status of the cruciate ligaments (the primary restraints according to Butler et al. 1980). The limits of central anterior-posterior knee motion were determined for these four groups. A Venn diagram shows the status of the cruciate ligaments (Figure 8). Of the 138 patients, anterior stressradiographs were obtained from 53 anterior-cruciate-ligament-intact and 85 anterior-cruciate-ligament-deficient knees; and 138 posterior stressradiographs were obtained from 114 posterior-cruciate-ligament-intact and 24 posterior-cruciate-ligament-deficient knees. We defined "deficient" as a partial tear of the cruciate ligament, a bony avulsion from the tibial attachment, and a complete intraligamentous tear at the midsubstance level.

Procedure

In the routine clinical examination under anesthesia, the uninvolved knee was compared with the involved knee. The involved knee was positioned in the stressradiographic measuring device. In the early 1980s, when this study was begun, the anesthetized patient lay supine on the examining table. We obtained two lateral stressradiograms—one in the anterior-loaded position and one in the posterior-loaded position—to analyze the limits of anterior and posterior knee motion in the involved knee (Figure 9). The final anterior position and the final posterior position of the tibia relative to the femur are illustrated diagrammatically (Figure 9).

To obtain an anterior stressradiogram of the knee in the near extended position, a manual maximum posterior force (estimated 200–300 N) was applied to the anterior aspect of the distal femur (leg support 7.5 cm in diameter under proximal tibia 10 cm below joint line, heel against examining table, film cassette (20 x 40 cm) placed vertically adjacent to medial side of the knee at a tube-to-film distance of 120 cm. To obtain a posterior stress radiogram of the knee in the near extended position, a manual maximum posterior force was applied to the proximal tibia with thigh supported (support 11.5 cm in diameter) 10 cm above joint line. At times, it was necessary to use fluoroscopy to orient the condyles properly.

Anterior and posterior stressradiograms of the noninvolved knee were not obtained because the status of its cruciate ligaments was neither visually assessed nor functionally probed.

Table 3. Summary of inclusion criteria

Adult patients between aged 17 to 50 with closed physes
No previous knee surgery or arthroscopy
Clinical examination and stressradiography under anesthesia
Adequate quality of lateral views of anterior and posterior stressradiographs
No interposed large fragment buckethandle tears
Adequate assessment of cruciate ligament by using a probe at arthroscopy or surgery

The original population totaled 219 knees; 81 knees were eliminated from the study. Patients with ligament injuries and concomitant fractures of the ipsilateral femur or tibia, as well as complete knee dislocations, were excluded from the study.

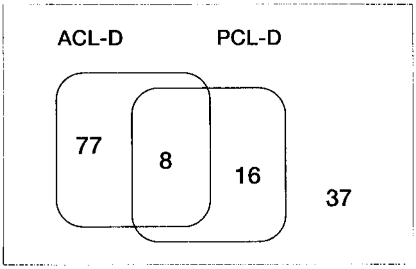


Figure 8. Distribution of the patient population (n 138) according to the status (D deficient) of the anterior cruciate ligament (ACL) and the posterior cruciate ligament (PCL).

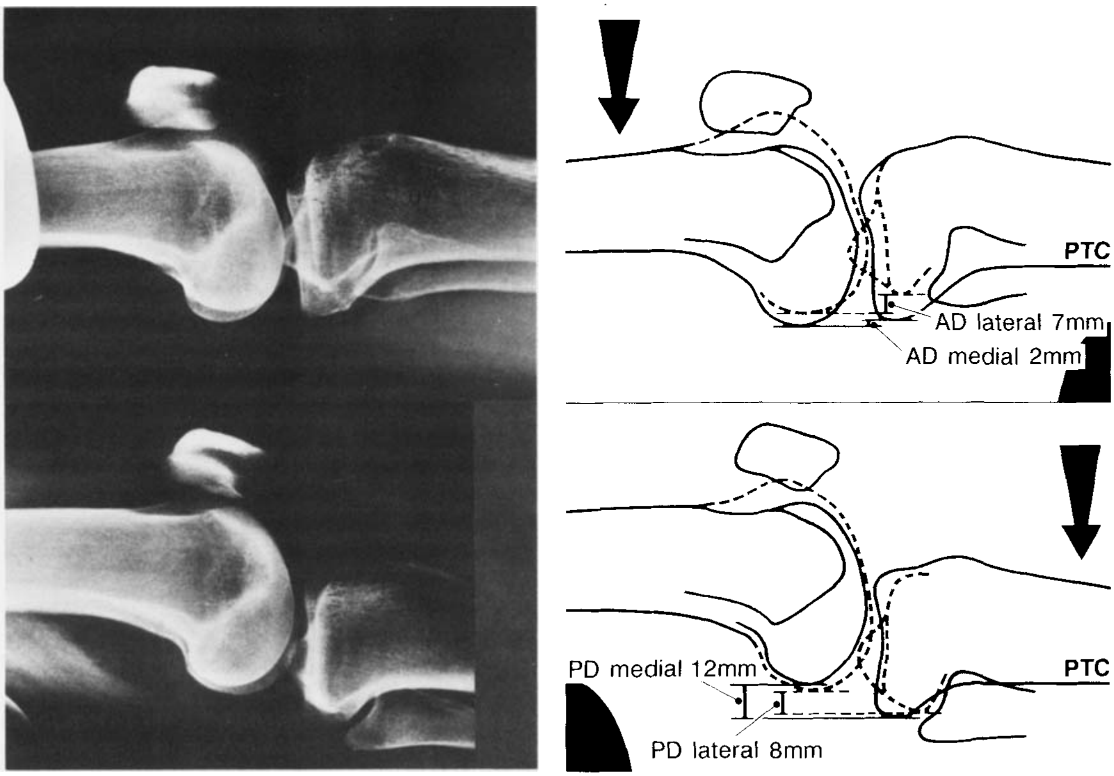


Figure 9. Stressradiographs of a knee with combined ruptures of the posterior cruciate ligament, posterior oblique ligament, tibial collateral ligament, and a capsular tear of the medial meniscus. The anterior cruciate ligament was intact. Diagram (top) of the anterior stressradiograph which illustrates anterior displacements (AD) of the lateral compartment (7 mm) and of the medial compartment (2 mm). PTC posterior tibial cortex. Diagram (bottom) of the posterior stressradiograph which illustrates posterior displacements (PD) of the medial compartment (12 mm) and of the lateral compartment (8 mm).

The means of compartmental anterior and posterior displacement limits, standard errors, and standard deviations of the mean were calculated for the different knee populations illustrated in the Venn diagram (Figure 8). Student's *t*-test was used for paired values if applicable. The central knee displacement was calculated as mean of the medial and lateral compartmental displacements.

Results

Limits of central knee motion (Figure 10)

The limits of anterior-posterior central knee motion in 37 cruciate-ligament-intact knees measured 3.4 ± 1.5 mm for anterior and 4.5 ± 2.1 mm for posterior displacement. In 77 anterior-cruciate-ligament-deficient knees with an intact posterior cruciate ligament, the limits were 13 ± 3.4 mm for anterior and 3.5 ± 2.1 mm for posterior displacement. In 16 posterior-cruciate-ligament-deficient knees with an intact anterior cruciate ligament, the limits were 3.5 ± 1.7 mm for the anterior displacement and 11 ± 2.5 mm for the posterior displacement. The limits of anterior-posterior central knee motion in 8 knees with combined anterior cruciate ligament and posterior cruciate ligament deficiencies measured 9.2 ± 2.4 mm for anterior displacement and 11 ± 1.5 mm for posterior displacement.

Limits of compartmental knee motion (Figure 11)

Using anterior stressradiography, the limits of anterior knee motion were 2.8 ± 2.3 mm for the medial and 4.0 ± 3.2 mm for the lateral compartment in 53 anterior-cruciate-ligament-intact knees; and 9.9 ± 5.3 mm for the medial and 16 ± 4.6 mm for the lateral compartments in 85 anterior-cruciate-ligament-deficient knees ($p < 0.001$).

Using posterior stressradiography, the limits of posterior knee motion were 4.0 ± 3.0 mm for the medial

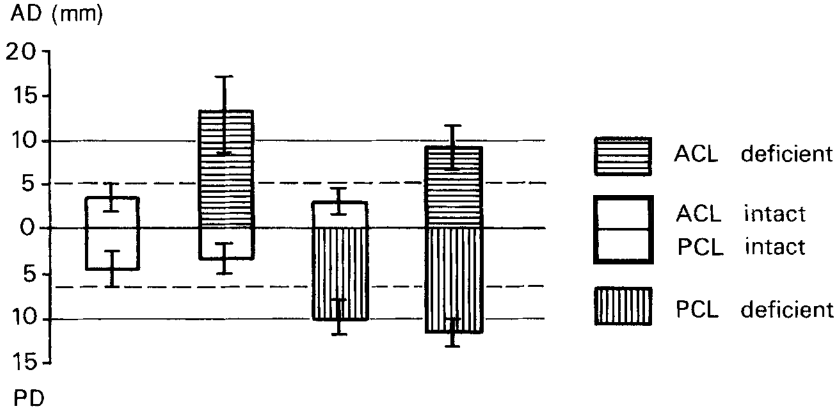


Figure 10. *Central motion limits.* The central anterior (AD; above zero line) and the posterior (PD; below zero line) displacements are given for the groups specified in the Venn diagram (Figure 8).

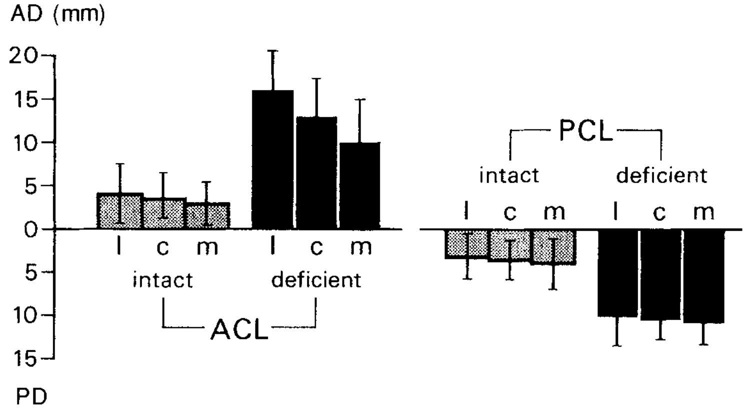


Figure 11. *Compartmental motion limits.* The graph represents lateral (l), central (c), and medial (m) displacement measurements in 53 anterior-cruciate-ligament-intact, 85 anterior-cruciate-ligament-deficient, 114 posterior-cruciate-ligament-intact, and 24 posterior-cruciate-ligament-deficient knees in respect to the zero line. AD anterior and PD posterior displacement.

and 3.3 ± 2.6 mm for the lateral compartments in 114 posterior-cruciate-ligament-intact knees; and 11 ± 2.4 mm for the medial and 10 ± 3.9 mm for the lateral compartment in 24 posterior-cruciate-ligament-deficient knees ($p < 0.001$; Stäubli and Jakob 1990b).

Limits of coupled compartmental anterior-posterior knee motion

In the anterior-cruciate-ligament-intact group, coupled anterior-translation/internal-rotation of the tibia in respect to the femur was demonstrated stressradiographically with the knee in the near extended position. In the anterior-cruciate-ligament-deficient group, an increase ($p < 0.001$) of coupled anterior translation and an increase ($p < 0.01$) of internal rotation were found. In the posterior-cruciate-ligament-intact group, coupled posterior-translation/internal-rotation of the tibia in respect to the femur was demonstrated stressradiographically with the knee in the near extended position. In the posterior-cruciate-ligament-deficient group, an increase of posterior translation of the tibia in respect to the femur was found in 6 cases. In 3 cases, an increase of posterior translation/external rotation was present. Another 9 cases had an increase of posterior-translation/internal-rotation when compared with the anatomic sagittal alignment.

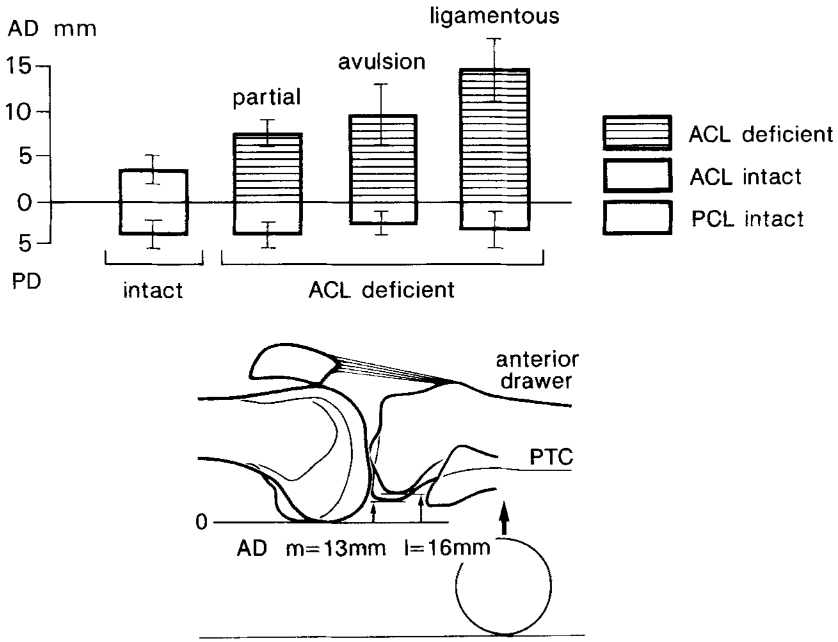


Figure 12. In the anterior-cruciate-ligament-deficient subgroups, increasing anterior displacement (AD) in anterior cruciate ligament partial tears, anterior cruciate ligament bony avulsions, and complete intraligamentous tears were documented stressradiographically in comparison with the normal anterior joint play. Posterior joint play remained within the posterior-cruciate-ligament-intact control values in all subgroups.

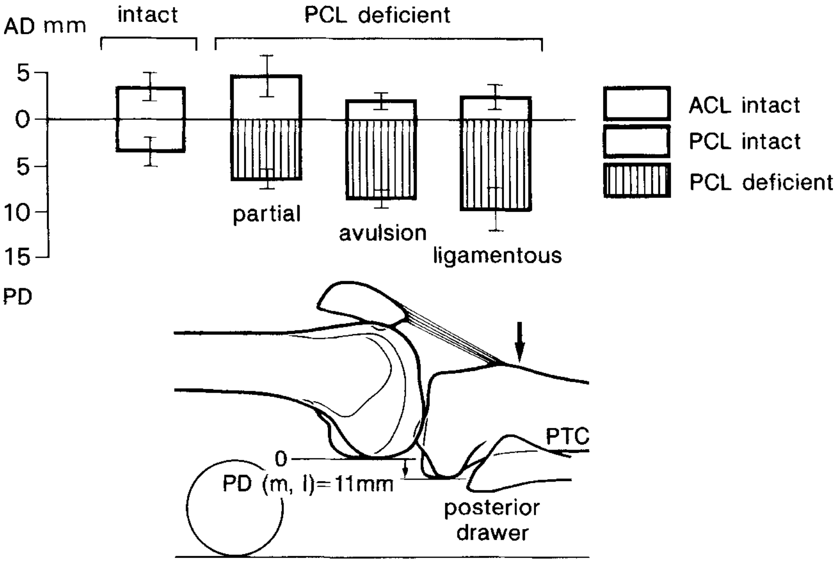


Figure 13. In comparison with the normal posterior joint play, increasing posterior tibial displacement (PD) was demonstrated in posterior-cruciate-ligament partial tears, posterior-cruciate-ligament bony avulsions from the tibia, and in complete intraligamentous tears of the posterior cruciate ligament. Anterior joint play remained within the anterior-cruciate-ligament-intact control values in all subgroups.

The limits of central anterior-posterior knee motion in cruciate-ligament-intact knees were compared with the limits of subgroups of cruciate-ligament-deficient knees. With increasing structural damage of either cruciate ligament, an increasing amount of central anterior or posterior tibial displacement was found (Figures 12 and 13).

Stressradiographic measurements of knee motion limits

Stressradiographic measurement principle

According to the definitions of the reference line, posterior tangents, and contour characteristics of the medial and lateral femorotibial compartments, a stressradiographic measurement principle was formulated.

The femorotibial flexion angle is the angle formed by the PFC and PTC, which are the reference lines (Figures 2 and 14). In Figure 14, FTm and FTl represent posterior tangents to the medial femoral condyle and to the lateral femoral condyle and the TTm and TTl represent posterior tibial tangents at the posteriormost contour of the medial and lateral tibial plateaus in respect to PTC, which runs parallel to the body of the fixed tibial axis. The PFC is used only for documentation of knee flexion angle.

Measurement device

The stressradiographic device (Figure 15) consists of a ground plate (36 x 82 x 2 cm) with a metallic frame (Inselspital, Bern), which allows free exposure of the film cassette (20 x 40 cm, –gradual+). The film cassette is fixed to the ground plate by means of two adjustable clamps mounted on two parallel railings. The Telos® arm is fixed to the metallic frame. The arm can be shifted proximally and distally on the metallic frame. The height of the fulcrum of the Telos® arm is adjustable. Integrated in the Telos® arm is a load system with instant digital display of applied forces. The thigh support is 11.5 cm in diameter, and the leg support is 7.5 cm in diameter. These supports are used at posterior and anterior stressradiography. A tape measure guarantees 120 cm of tube-to-film distance.

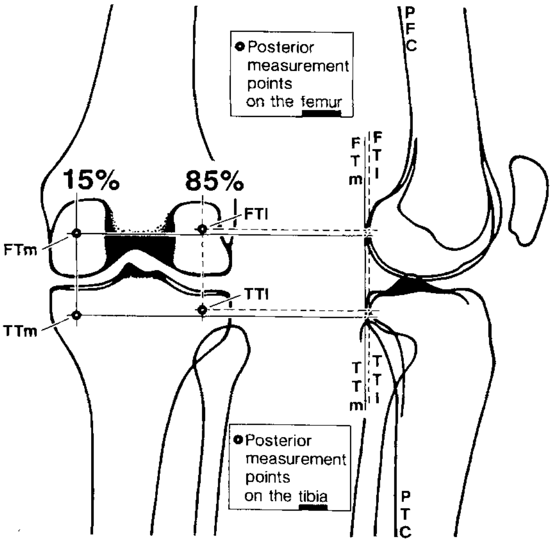


Figure 14. Stressradiographic measurement principle. The posterior corresponding measurement points on the femur and on the tibia are illustrated in the frontal plane (left) and in the sagittal plane (right). If the compartmental medial (FTm/TTm) and lateral (FTl/TTl) tangents coincide, the knee is said to be in neutral anatomic alignment.

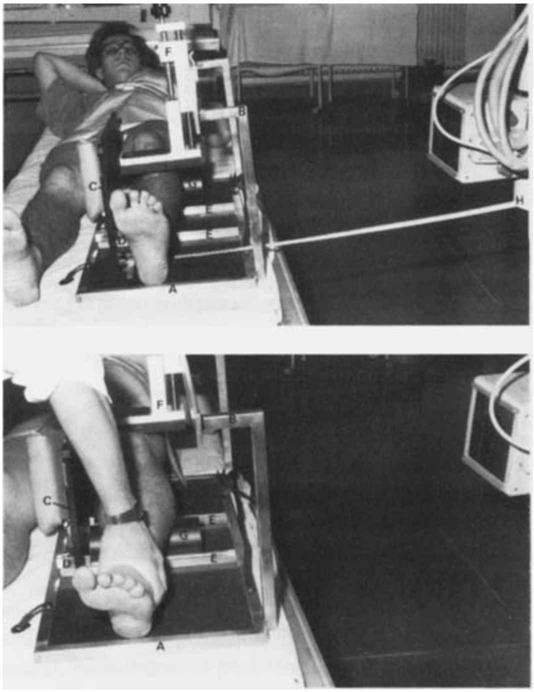


Figure 15. Stressradiographic measurement device. A ground plate; B metallic frame; C film cassette; D adjustable clamps mounted on two parallel railings (E); F Telos® arm fixed to metallic frame (B); G thigh and leg supports; H tape measure to verify that the film-to-tube distance is 120 cm. (Inselpital, Bern, Switzerland).

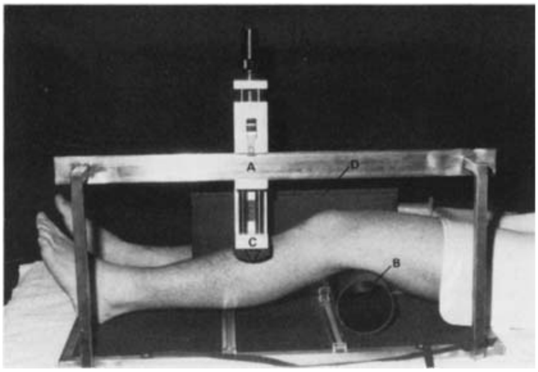


Figure 16. Testing apparatus for *posterior* stressradiography. A testing device; B thigh support (11.5 cm in diameter); C Telos® arm; D film cassette (20 x 40 cm) placed vertically adjacent to the medial side of knee and fixed by two clamps to the ground plate.

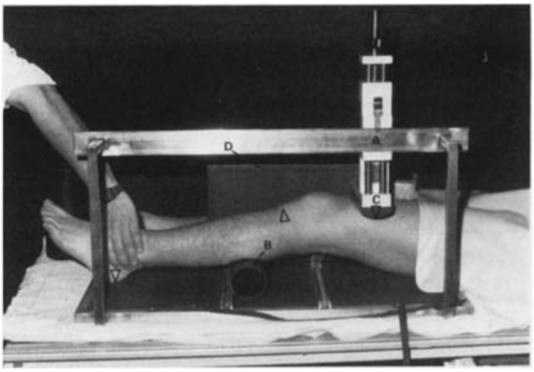


Figure 17. Testing apparatus for *anterior* stressradiography. A testing device; B leg support (7.5 cm in diameter); C Telos® arm; D film cassette (20 x 40 cm, -gradual+).

Testing conditions

The involved knee is placed in the stressradiographic device. Two full anterior-posterior preloading cycles to the opposite motion limits are performed at 223 N over a period of 10 seconds (preloading cycle). Then two stressradiograms in opposite directions are obtained under peridural anesthesia at 178 N.

For *posterior stressradiography*, the patient lies supine (Figure 16). The beam of the x-ray tube is directed horizontally, parallel to the table, and is centered over the posterior contours of the femoral condyles. The distal femur is supported 10 cm above the lateral joint line at the level of proximal railing. The Telos® is applied anteriorly 10 cm distal to the lateral joint line below the tibial tuberosity. A posteriorly directed force is applied. The heel rests on the rigid support of the stressradiographic ground plate. An analysis of unconstrained knee motion is made. The film cassette is placed vertically, adjacent to the medial side of knee, and fixed by two clamps to the ground plate. The tube-to-film distance is 120 cm. The x-ray tube is oriented horizontally from 6 to 8 degrees craniolateral to caudomedial and the x-ray beam is oriented parallel to the posterior contours of the superimposed femoral condyles. To guarantee orthogonal orientation in the sagittal plane, the anterior contour of the lateral femoral condyle must be anterior to the anterior contour of the medial femoral condyle. A 5-degree internal rotation of the femur assures superimposition of the posterior femoral condyles. To assure adequate orthogonal orientation of the femur, the anterior lateral femoral condyle can be palpated slightly anterior to the medial femoral condyle. The sagittal diameter of the lateral condyle can be seen as greater in size than the sagittal diameter of the medial condyle. The anterior surface of the patella serves as reference plane for condylar orientation.

For *anterior stressradiography* (Figure 17), the beam of the x-ray tube is oriented horizontally, parallel to the table, and is centered over the posterior contours of the femoral condyles. The leg support is placed under the midshaft of the tibia at the level of the distal railing. The heel is pressed against the rigid ground plate to guarantee the knee flexion angle and rotational alignment. The Telos® arm is applied anterior to the distal thigh 3 cm above the level of the base of the patella. A posteriorly directed force is applied. An analysis of unconstrained motion (unclamped femur rotates freely) is made.

Measurement technique

PTC (Figure 18) which runs parallel to the fixed tibial axis (Grood and Suntay 1983, Blankevoort et al.

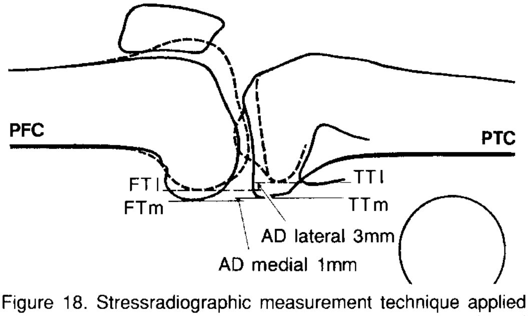


Figure 18. Stressradiographic measurement technique applied to anterior displacement (AD). FTl femoral tangent lateral condyle; FTm femoral tangent medial condyle; TTl tibial tangent lateral plateau; TTm tibial tangent medial plateau. PFC posterior femoral cortex; PTC posterior tibial cortex.

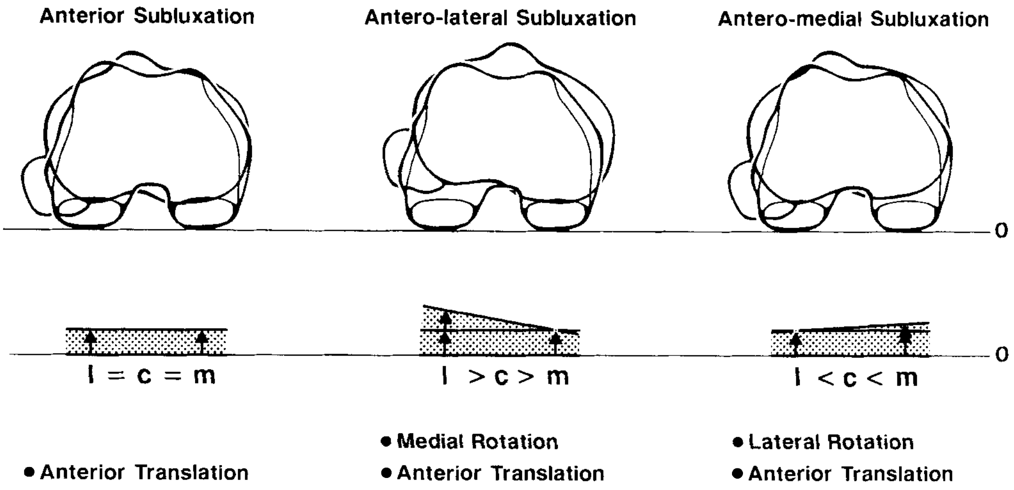


Figure 19. Direct comparison of the translations and rotations of *anterior* displacement (AD). l = lateral, c = central, m = medial.

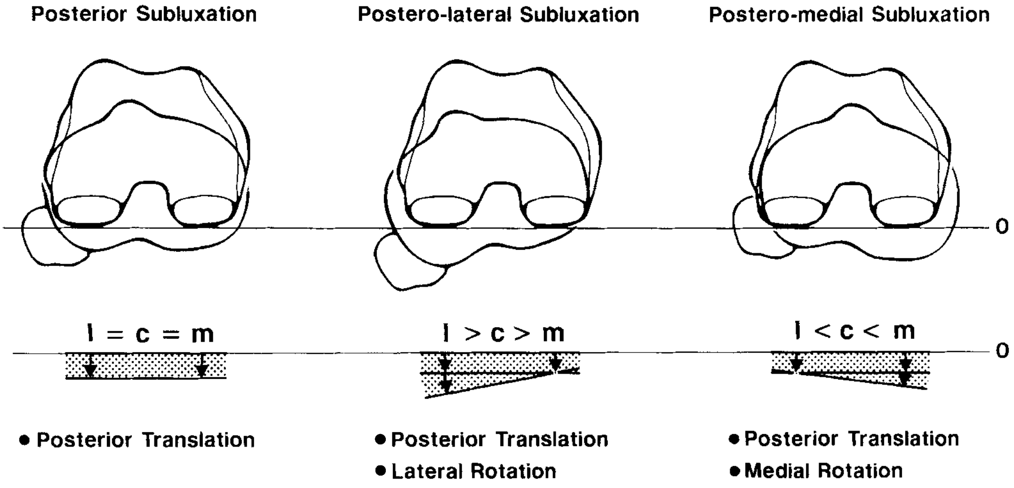


Figure 20. Direct comparison of translations and rotations of posterior displacement (PD). l = lateral, c = central, m = medial.

1988), and PFC form the anatomic femorotibial flexion angle. The PTC provides the basis for the definition of the anatomic zero compartmental alignment in the sagittal plane, irrespective of the flexion angle tested.

One way to measure anterior and posterior displacement of the tibia on a stressradiograph is by constructing two posterior tangent lines parallel PTC—one to each of the most posterior contours of the femoral condyles (FTl and FTm) and one to each of the most posterior contours of the tibial plateaus (TTl and TTm). To determine the compartmental displacements, measure the distances between the corresponding tangents of each compartment (Figure 18). On the anterior stressradiograph, the anterior displacements (AD) for the medial (ADm) and for the lateral (ADl) compartments in respect to the reference line (PTC) can be determined. On the posterior stressradiograph, the posterior displacements (PD) for the medial (PDm) and for the lateral (PDl) compartments in respect to the reference line (PTC) are determined. The arithmetic mean of the medial and of the lateral displacement is the central tibial displacement (ADc/PDc; Figure 4). The abbreviations are listed in Table 4. For direct comparisons, the translations and rotations of AD are shown in Figure 19 and for PD in Figure 20.

A simpler way to measure compartmental displacement on stressradiographs is by superimposing the

Table 4. Measurements obtained at stressradiography

Abbreviation	Meaning of Abbreviation
D	displacement
AD	anterior displacement
ADm	anterior displacement medial compartment
ADl	anterior displacement lateral compartment
ADc	anterior displacement central compartment
PD	posterior displacement
PDm	posterior displacement medial compartment
PDl	posterior displacement lateral compartment
PDc	posterior displacement central compartment

KMT-20 Template©, a measurement tool for determining compartmental displacements of the tibia in respect to the femur. The KMT-20 Template© is a clear plastic sheet with parallel bold lines drawn 1.0 cm apart. Fine parallel lines every millimeter span the 80 mm range (40 mm above and 40 mm below the zero line or anatomic zero position). The dimensions of the KMT-20 Template© are 18 x 14.3 cm including the numerical scale and directional labels on the left-hand side. The KMT-20 Template© has a magnification of 1:1.15 adapted to the corresponding stressradiographic magnification ratio. The details of the technique for measuring anterior-posterior compartmental displacement with the KMT-20 Template© superimposed on the stressradiograph (Figures 21 and 22) appear in the Appendix. The anterior and posterior final positions at 178 N posterior force level define anterior-posterior motion segments for the medial and lateral compartments with respect to the anatomic zero position.

Evidence of reproducibility

To evaluate the intraobserver and interobserver independent reproducibility of stressradiography and measurement technique, the KMT-20 Template© was used to determine measurement accuracy in a prospective study. Two series of anterior and posterior stress-

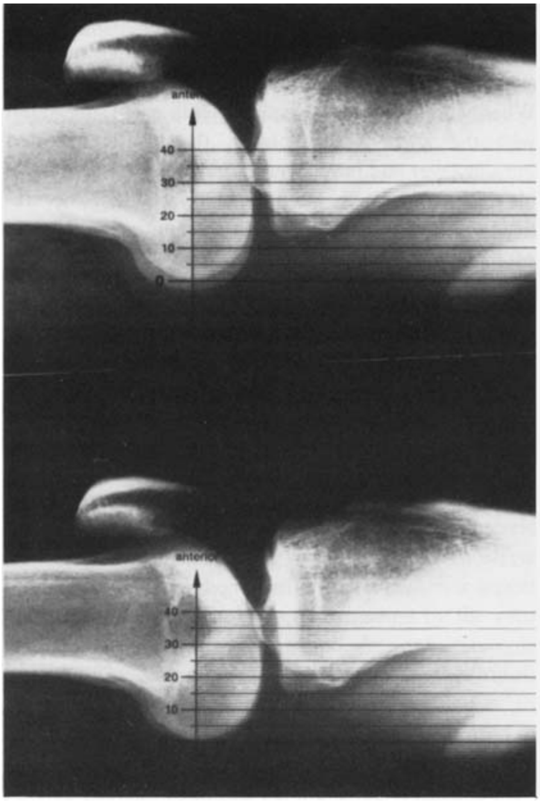


Figure 21. The KMT-20 Template© superimposed on *anterior* stressradiograph. The anterior displacement of the medial compartment (ADm) was 13 mm (top) and of the lateral compartment (ADl) 17 mm.

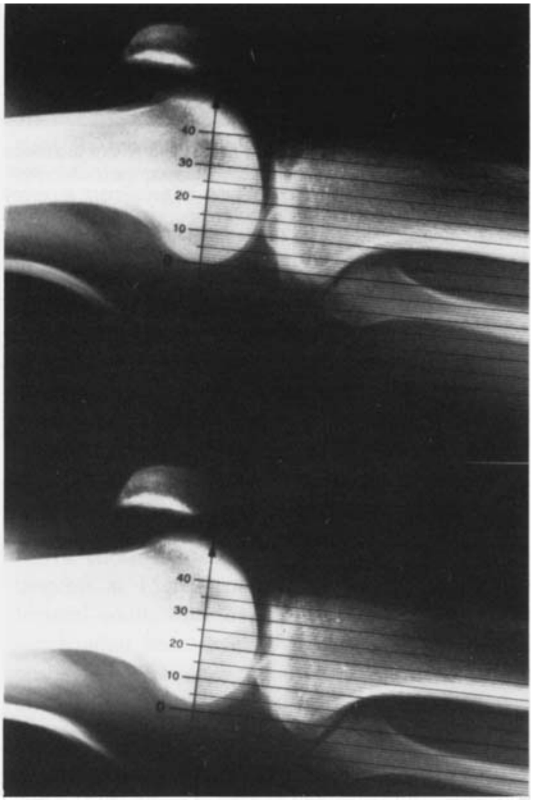


Figure 22. The KMT-20 Template© superimposed on *posterior* stressradiograph. The posterior displacement of the lateral compartment (PDl) was 4 mm (top); and the posterior displacement of the medial compartment (PDm) was 6 mm (bottom).

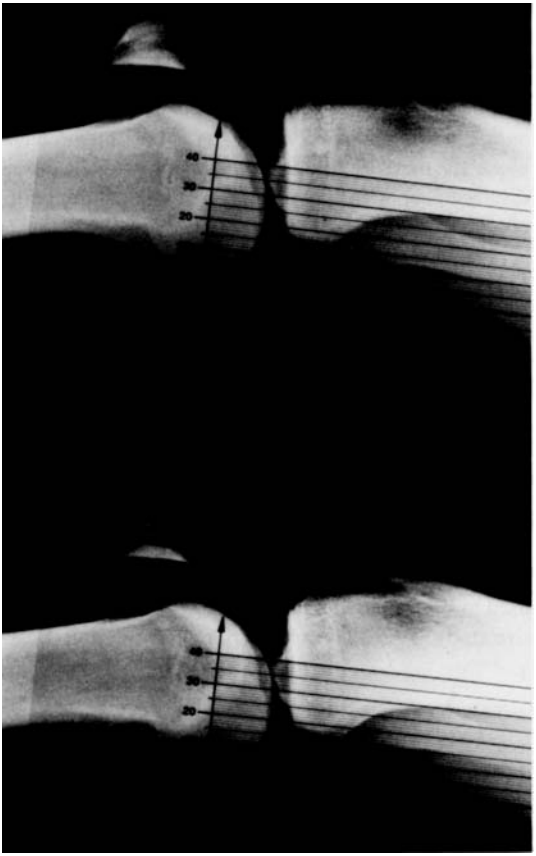


Figure 23. A study to determine if the measurement technique with the KMT-20 Template© was interexaminer and intraexaminer reproducible showed that the measurement accuracy was ±0.5 mm. Measurements of the anterior displacement of the medial compartment (ADm) showed a difference of 1 mm. Examiner One (top), ADm 13 mm. Examiner Two (bottom), ADm 12 mm.

radiograms of knees with acute disruption or chronic anterior-cruciate-ligament deficiency were obtained by two different skilled stressradiographic examiners. Subsequent to two full preloading cycles, the first series of anterior and posterior stress radiograms was obtained by one examiner. The stressradiographic measurement device was then removed and replaced by the second examiner. In both series, the patient position (supine), the femorotibial flexion angle, the magnitude of anterior-posterior forces, the preloading cycle, the force application mode (Telos® arm), and the force direction were identical.

Three observers using the KMT-20 Template© measured the compartmental displacement according to instructions given in the Appendix. The examiners measured the anterior displacement (Figure 23) of the medial and lateral compartment independently on both anterior stressradiographs. Then they superimposed the KMT-20 Template© on both posterior stressradiographs to determine the posterior displacement of the medial and the lateral compartment. Identification data, structural properties of the probed cruciate ligaments, and concomitant meniscocapsular pathology were unknown to the observers. The measurement data were recorded separately. No marks were made on the stressradiographs during the measurement procedure. Each observer examined all stressradiographs on three subsequent days to determine intraobserver variation. When compartmental displacements were measured with the KMT-20 Template©, the results revealed intraobserver and interobserver independent reproducible data acquisitions. Interobserver variability was statistically insignificant; the measurement accuracy was ±0.5 mm.

Discussion

In 1980, we initiated the stressradiographic study to document our clinical observations from testing knees in the near extended position with the patient lying supine. Gravity had a distinct effect upon posterior compartmental displacement in both posterior-cruciate-ligament-deficient and combined anterior-posterior-cruciate-ligament-incompetent knees. In the first report (Stäubli et al. 1983) on stressradiographic determination of physiologic (normal) joint play and pathologic (abnormal) central knee motion, clinical drawer tests in the near extended position were compared with stressradiographically determined anterior-posterior tibiofemoral displacements. A complete disruption of the anterior cruciate ligament resulted in a significant anterior tibial subluxation with a normal posterior joint play. A complete disruption of the posterior cruciate ligament resulted in an abnormal posterior knee motion with a physiologic anterior joint play in respect to the anatomic zero position. In 1980, our technique was limited to manual maximum applied force of an estimated 200–300 N as compared to our current procedures a decade later in which we apply a force of 178 N by an instrumented device (Telos®) with a gauge on which we read the exact amount of force.

To resolve the problem of assessing objectively anterior-posterior knee motion limits, definitions of the starting position and the *zero* position (anatomic alignment) had to be obtained.

To describe accurately the motion segments and the motion limits, the *anatomic zero position* had to be defined irrespective of the flexion angle tested. The anatomic zero position is the unstressed knee position—the position in which the three translational planes intersect with the center of the three translational axes.

We chose the PTC as the reference line. Posterior femoral tangents, running parallel to the posterior tibial cortex—and then parallel to the posterior aspects of both tibial plateaus—were designated by the value zero if the two pairs of corresponding tangents coincided. The compartmental alignment in the sagittal plane at zero degrees of flexion was defined as the anatomical zero position. Moyen et al. (1990) used the coincidence of the medial compartmental tangents to define the zero anatomic position. We defined the anatomic zero position in the sagittal plane at stressradiography as superimposition of posterior measurement tangents constructed at the subchondral bone level of each femorotibial compartment. Our definition of the anatomic zero position is supported by Rauschning's (1979) cryosectional anatomy slices in the sagittal plane (Figure 5). However, the anatomic zero position differs from the starting reference position used at clinical evaluation (Gurtler et al. 1990, Müller et al. 1988, Torg et al. 1976), at instrumented clinical testing (Edixhoven et al. 1989, Markolf et al. 1978), and at arthrometric measurement (Daniel et al. 1985, Daniel and Stone 1990) because the weight force of the leg and the anteriorly superimposed weight of the instrumented testing device alter the starting reference position in the posterior sense (patient supine, thigh supported, quadriceps relaxed).

In a previous stressradiographic analysis of acute injuries of the posterior cruciate ligament, we compared posterior stressradiographs obtained at 10 degrees and 20 degrees of knee flexion to similar testing at constant posterior load at 60 degrees and 80 degrees of knee flexion. We found an increase of posterior subluxation of the tibia with increasing flexion (Stäubli and Jakob 1990b). The maintenance of constant flexion angles therefore is critical during any knee testing procedure. The two greatest sources of measurement error with the arthrometric systems and with the instrumented clinical drawer testing devices using patella sensor pads are 1) lack of muscle relaxation due to pain, hemarthrosis or femoral clamping, and 2) inability to center the patella in the trochlear groove and thus to stabilize the patella sensor pad (Daniel and Stone 1990, Edixhoven et al. 1989). To avoid inadvertent muscle contraction, we induced peridural anesthesia. To reduce inaccuracy of patella-trochlear stabilization and soft tissue interference with anterior measurement systems, we introduced posterior measurement tangents.

We chose to define the posterior compartmental tangents at 15 percent and 85 percent of the total femoral width with the two measuring points at the subchondral bone level of the posterior medial and posterior lateral femorotibial compartments. Noyes et al. (1989) advocate using the six degrees-of-freedom instrument spatial linkage and one central measurement point on the tibia and one on the femur to obtain data.

By using the stressradiographic measurement technique with the reference line and parallel posterior measuring tangents, we were able to define the anatomic zero position and compartmental motion limits in the near extended position. Based upon a posterior measuring system in line with the fixed tibial shaft axis—thus parallel to the three-dimensional coordinate system applied by Grood and Suntay (1983)—data concerning the limits of compartmental knee motion were recorded. The total anterior-posterior compartmental knee motion analysis revealed coupled anterior-posterior translational and rotational motion patterns in respect to the anatomic zero compartmental alignment. Our data on central limits of anterior- posterior knee motion measurements can be compared with anterior-posterior ligamentous restraint measurements reported by Butler et al. (1980) who recorded data from cadavers. In biomechanical anterior drawer testing, the anterior cruciate ligament was the primary restraint. It provided 87 percent of the total resisting force at 30 degrees of flexion. In posterior drawer testing, the posterior cruciate ligament was the primary restraint providing 56 percent of the total restraining force at 30 degrees of flexion (Butler et al. 1980).

In our study of the 138 knees, those knees with intact cruciate ligaments had physiologic coupled anterior-posterior joint play. In anterior-cruciate-ligament-intact knees, we detected anterior translation coupled with internal rotation. This finding is in accordance with physiologic (normal) anterolateral joint play and supports the findings of Gollehon et al. (1987) who reported that, when anterior force was applied to the tibia of an intact knee, the tibia rotated internally. In posterior-cruciate-ligament-intact knees, we detected coupled posterior translation/internal rotation. Our finding of posteromedial joint play is not in accordance with the physiologic posterolateral joint play as reported by Gollehon et al. (1987). These authors reported that, when posterior force was applied to the tibia of the intact knee, the tibia rotated externally. Moyen et al. (1990) confirmed our findings by stressradiography in their study at a lower force level (80 N). They found coupled posterior translation/internal rotation when posterior force was applied to a cruciate ligament intact knee. The report of Moyen et al. (1990) and our findings of coupled posterior translation/internal rotation of the tibia with respect to the femur may be due to damage of the posteromedial capsuloligamentous structures.

In anterior-cruciate-ligament-deficient knees, there was increased anterolateral subluxation of the tibia in respect to the femur. This finding supports the concepts of dynamic subluxation/reduction testing with coupled anterior translational forces and internal rotational moments being applied to the tibia while clinically testing an anterior-cruciate-ligament-incompetent knee (Bach et al. 1988, Jakob et al. 1987).

In posterior-cruciate-ligament-deficient knees, there was increased posterior translation in respect to the anatomic zero position. The posterior tibial subluxation in posterior cruciate ligament incompetence is in accordance with restraint measurements reported by Butler et al. (1980) who found increased posterior subluxation subsequent to dividing the posterior cruciate ligament, the primary resisting force at 30 degrees of knee flexion. Our findings support the measurements of Fukubayashi et al. (1982) who reported increased posterior knee motion following transection of the posterior cruciate ligament irrespective of the flexion angle tested. Stressradiographically determined posterior tibial subluxation in posterior cruciate ligament incompetence supports the concept of clinically assessing posterior subluxation/reduction phenomena—the reverse pivot shift (Jakob et al. 1981)—and the active and passive posterior drawer tests in the near extended position (Stäubli and Jakob 1990b).

Determining the anatomic zero position as compartmental femorotibial alignment in the unstressed position explains the fact that, with the patient supine, a physiologic posterior joint play occurs at the starting position before clinical evaluation. Edixhoven et al. (1989) reported a 3.5 mm posterior starting position in a posterior cruciate ligament deficient knee population. This posterior starting position can be determined clinically by measuring the tuberosity position or depth with a ruler before assessing posterior cruciate ligament disruption or insufficiency. A complete disruption of the posterior cruciate ligament associated with a posterolateral ligamentocapsular injury resulted in coupled posterior translation/external rotation. This posterolateral subluxation was associated with structural deficits and functional incompetence of the posterior cruciate ligament, popliteal tendon and its fascicles (Stäubli and Birrer 1990), of the lateral collateral ligament, and of the arcuate popliteal ligament (Stäubli and Jakob 1990b). These data confirm the increase of coupled posterior translation/external rotation (Grood et al. 1988). A simulated isolated rupture of the posterior cruciate ligament produced an abnormal limit for posterior translation of the tibia with increasing flexion angles tested. The popliteus-arcuate complex and the posterior cruciate ligament limited the amount of coupled posterior translation/external rotation of the tibia with respect to the femur. Our stressradiographic findings are in accordance with the role of the posterolateral and cruciate ligaments, as reported by Gollehon et al. (1987). Their results demonstrated the importance of the posterolateral structures in the prevention of posterior translation, varus rotation, and external rotation of the tibia.

A complete posterior-cruciate-ligament disruption associated with a posteromedial ligamentous capsular injury resulted in a coupled posterior translation/internal rotation of the tibia with respect to the femur. In this respect, our data support the concept of unconstrained clinical testing of posterior subluxation/reduction phenomena and the concept of unconstrained posterior knee motion analysis.

There is no substitute for the clinician's eyes and fingers—he has those to evaluate a patient's knee when measurement tools are not available. In arthrometry, there is interexaminer and intraexaminer variation (Forster et al. 1989, Daniel and Stone 1990); the measurements are examiner-dependent. Soft tissue is a variable. In stressradiography, there is intraexaminer and interexaminer independent motion analysis. If the stressradiographic technique is standardized, if preloading cycles at higher force levels than the actual measurement loads are applied over an interval of ten seconds under anesthesia, the effect of stress relaxation (Woo et al. 1990) may be minimized and stressradiographic displacement measurements are reproducible. Stressradiograms provide objective documentation of compartmental knee motion limits which can be stored/retrieved and analyzed by different unbiased examiners.

The assessment of the limits of motion is force dependent. The higher the applied manual or external forces and moments, the greater the magnitude of displacement (Fukubayashi et al. 1982). Dahlstedt and Dalén (1989) examined 41 patients without and 10 with anesthesia and found significant increases in translation when the patient was under anaesthesia. Therefore we chose a testing procedure under anesthesia at manual maximum loads. The total anterior-posterior knee motion depends upon the knee flexion angle tested. In the near extended position, between zero and 20 degrees of flexion, there is less coupled anterior-posterior translation/rotation than in flexion between 70 and 90 degrees (Torzilli et al. 1984, Gollehon et al. 1987, Blankevoort 1991). The reduction of rotational play in the near extended position is due to the articular cartilage configuration, the screw-home mechanism, and the progressive tightening of the meniscocapsular structures and cruciate ligaments as the knee reaches full extension. At 5 degrees of flexion, the posterior part of the capsule and the cruciate ligaments are important secondary restraints in preventing abduction/adduction rotation (Grood et al. 1981), motions inadvertently associated with coupled translations/rotations.

According to the stressradiography results, unconstrained clinical drawer testing and unconstrained assessment of anterior subluxation/reduction phenomena with the knee in the near extended position document coupled anterior translation/internal rotation of the tibia with respect to the femur (in anterior-cruciate-ligament-deficient knees). The compartmental displacements described in the stressradiographic study are compatible with an analysis of the pivot shift phenomena (performed by members of the International Knee Documentation Committee, 1989). In our stressradiographic in vivo analysis of 85 anterior cruciate ligament-incompetent knees under anesthesia, a similar anterolateral subluxation of the tibia with respect to the femur occurred. The anterior displacement at manual maximum loads measured 16 ± 4.6 mm for the lateral compartment and 9.9 ± 5.3 mm for the medial compartment. This coupled anterior translation-internal rotation of the tibia with respect to the femur supports the concept that the anterior cruciate ligament is an important primary restraint to anterior displacement and a major secondary restraint to internal rotation (Shoemaker and Daniel 1990). Our stressradiographic findings of coupled anterior translation/internal rotation in anterior-cruciate-ligament-deficient knees tested under anesthesia are similar to the findings reported by Kärrholm et al. (1988). Using Selvik's method (1974/1989) of roentgen stereophotogrammetry, they recorded coupled anterior translations/internal rotation/abduction rotation at a 150 N anterior force level without anesthesia. Granberry et al. (1990) used an electrogoniometric instrument to measure anterior-posterior laxity in two positions before and after transsection of the anterior cruciate ligament in 8 cadaver knees. They compared electrogoniometric and radiographic measurements of tibiofemoral translation and determined the accuracy of the radiographic technique to be ± 0.4 mm (95 percent confidence limit) measuring anterior-posterior translation of the tibia with respect to the femur. For the knee tested in 30 degrees of flexion and neutral rotation the average anterior translation as determined radiographically was 9.8 ± 4.2 millimeters in the intact knees, and this increased to 13 ± 11 mm after transsection of the anterior cruciate ligament at 140 N anterior force. However, the initial or zero anatomic position was not defined in their critical analysis of the electrogoniometric measurement which tended to overestimate femorotibial translation by 5.7 mm when compared with the radiographic method.

Definitions of the anatomic zero position, reference points, measuring tangents, and the measurement of the knee flexion angle are prerequisites to assessing compartmental anterior-posterior knee motion limits. Using stressradiographic measurement techniques at maximum anterior-posterior loads under defined test conditions, the examiner can measure the direction, magnitude, and type of knee motion. The limits of compartmental anterior-posterior knee motion can be measured stressradiographically and thus the surgeon can evaluate the intact and deficient primary and secondary restraints in acute disruption or chronic cruciate-ligament deficiency. In addition, the femorotibial anatomic flexion angle can be determined. Compartmental position analysis based on stressradiography yields data on anterior-posterior translation, internal/external rotation, and flexion/extension rotation. Stressradiography objectively documents three relevant motions out of six possible degrees-of-freedom described by Grood and Noyes (1988).

Stressradiography in the near extended position documents the normal and abnormal motion limits in a given knee injury. In complementing arthroscopic findings, stressradiography determines the grade of subluxation. Stressradiographic determination of increased anterior position of the tibia with respect to the femur is evident with increasing structural damage to the anterior cruciate ligament (Figure 12); this evidence supports the concept of a clinical grading system of the Lachman test as proposed by Gurtler et al. (1990). In addition to clinical and arthrometric measurements of total anterior-posterior subluxation at the center of the knee, stressradiography allows compartmental final position analysis in the anterior and in the posterior directions with respect to the anatomic zero position. Under standard conditions, stressradiography documents functional incompetence resulting from a structural damage to primary and secondary restraints subsequent to a knee injury. One major source of error at stressradiography is the inaccuracy of differentiating the exact subchondral compartmental osseous landmarks on radiographs due to malrotation and or superposition of bony contours. Although tube-to-film distance is standardized, the film-object distance varies for the medial and lateral compartments with soft tissue mantle (effect of radiographic magnification and parallax). Nevertheless, stressradiography provides documented information in femorotibial subluxation. Thus, the knee surgeon's task—to select and perform the most appropriate treatment so as to correct the structural damage and to restore functional competence of deficient ligaments—can be based on objective data, a valuable adjunct in assessing combined anterior-posterior knee instabilities.

Stressradiography was our choice of technique to verify clinical diagnoses in the 1980s, and, with the advances in our technique and knowledge, we will use it in the 1990s until we attain the optimum combination for assessing compartmental motion limits in ligament-intact and ligament-deficient knees. Standardized stressradiography of the knee in the near extended position demonstrated that the examiner can measure the direction, magnitude, type, and limits of compartmental anterior-posterior knee motion by determination of final compartmental positions. Thus the effect of intact and deficient primary and secondary restraints upon knee motion and final knee positions can be evaluated in respect to the zero anatomic position.

Acknowledgements

H. Holzherr and C. Langenegger, Abteilung für Unterrichtsmedien, Universität Bern und Inselspital, Bern, Switzerland, prepared the KTM-20 Template© based on our suggestions. H. Holzherr made numerous refinements to the KTM-20 Template© during the testing process.

Rolf Zehnder, formerly at the AO Documentation Centre, Bern (Maurice E. Müller Foundation), statistically examined the results of the clinical study.

Lottie Blanton Applewhite, author's editor, Chapel Hill, North Carolina, USA, provided medical editing services.

Our work was supported in part by a grant from the Swiss Orthopedic Society (Stipendium von der SGO), and it has been endorsed by Orthopädische Arbeitsgruppe Knie (OAK), the Orthopedic Study Group of the Swiss Orthopedic Society.

Glossary

Knee motions

Motion. The act or process of changing position.

Six degrees-of-freedom. Motion principle consisting of three translations and three rotations.

Limits of motion. Final positions at end of motion.

Twelve limits-of-motion. Final positions of tibia with respect to femur at end of motion path in opposite directions starting from zero anatomic alignment.

Limits of central knee motion. Final location of tibia with respect to femur as determined on center of knee at 50 percent of total knee width (Jakob and Stäubli 1990).

Limits of compartmental knee motion. Final compartmental location of tibia with respect to femur as determined at center of medial and lateral compartment at 15 percent and 85 percent of total tibial width using posterior measurement tangents. Compartment is defined as 1) a separate division or section; and 2) one of the parts into which an enclosed space is divided. Medial compartment of the knee is the medial part of the knee when divided in midsagittal plane; lateral compartment is the lateral part of knee when divided in midsagittal plane.

Motion of the knee is termed "constrained," "unconstrained," or "coupled." Constrained motion restricts the motion of a (mechanical) body in a particular mode; unconstrained knee motion is unrestricted motion of the tibia with respect to the femur; coupled motion is a displacement (or motion) in one or more degrees-of-freedom.

Translation. Equidistant, uniplanar, unidirectional bicompartmental displacement (Stäubli and Jakob 1990a); a type of motion or displacement of a rigid body in which all lines attached to it remain parallel to their original orientation (Noyes et al. 1989a).

Rotation. A type of motion or displacement in which all points on a body move around an axis as a center or a motion in which one point is fixed. The axis is commonly termed the axis of rotation (Noyes et al. 1989).

Displacement. The net effect of a motion. The change of position of a body or particle between two points along its path without regard to the path followed (Noyes et al. 1989a).

Subluxation. Partial loss of compartmental contact of opposing articulating surfaces (Stäubli and Jakob 1990a). A partial dislocation in which there is an abnormal position of the osseous structures forming the joint; however, a portion of the opposing articulating surfaces are still in contact (Noyes et al. 1989a).

Dislocation. Complete loss of contact of normally opposing articulating surfaces (Stäubli and Jakob 1990).

Physiologic joint play. Range of motion in between physiologic motion limits.

Pathologic joint play. Range of motion beyond physiologic motion limits.

Instability. A condition of a joint characterized by an abnormally increased range of motion (mobility) due to ligamentous injury, or injury to the capsule, menisci, cartilage, or bone (Noyes et al. 1989).

Laxity. Lack of tension (characteristic of a ligament).

Stiffness. Ligament quality referring to progressive fiber recruitment as tension is applied to the ligament. The slope of the load deformation curve for a specimen with a linear load deformation relationship.

Ligamentous restraint. Characteristic of particular ligament to restrict imposed forces and moments. The ACL is the primary ligamentous restraint to anterior knee motion irrespective of the flexion angle tested. The PCL is the primary ligamentous restraint to posterior knee motion irrespective of the flexion angle tested (Butler et al. 1982).

Knee positions

Position. Of the human body: bodily posture or the arrangement of parts of the body (body segments) for a particular examination or surgical procedure. Of a point: location of a point with respect to a reference system. Of a rigid body: position of a point or particle in the body and the orientation of the body (Noyes et al. 1989a).

Patient position. Location of the human body with respect to gravity.

Knee position. Relative location of the knee with respect to gravity; and relative location of the tibia with respect to the femur.

Compartmental knee position. Relative location of the medial and lateral tibial plateau with respect to the femoral condyles.

Anatomic zero position. Relative medial and lateral compartmental alignment of tibia with respect to femur in all planes and about all axes. At stressradiography (sagittal plane), the anatomic zero position is the unstressed knee position in which posterior compartmental tangents (constructed at subchondral level) coincide (Stäubli et al. 1992).

Starting knee position. Relative location of tibia with respect to femur at the start of clinical examination, arthrometric, or radiographic measurement.

Starting reference position. Relative location of tibia with respect to femur at start of arthrometric measurement (Daniel et al. 1985).

Final knee position. Relative location of tibia with respect to femur at limit of motion.

Orientation. Body rotation relative to other segments (Hoyes et al. 1989a).

Orientation of tibia. Rotation of tibia with respect to femur defined by the three angles of flexion- extension rotation, abduction-adduction rotation, internal-external rotation.

Structural and mechanical properties of ligaments (Woo et al. 1990)

Biomechanics. The study of the mechanics of biological materials.

Creep. A viscoelastic behavior characterized by a change in strain or deformation of a specimenwith time under a constant applied stress.

Deformation. The change in a dimension of a specimen under external loading. For example, the increase in length of a bone-ligament-bone complex under tensile loading.

Hysteresis. A path-dependent characteristic of viscoelastic materials, such that the load-deformation or stress-strain curve obtained during loading differs from that obtained during loading-unloading due to internal energy losses. For a single loading-unloading cycle, these loading and unloading curves form a closed loop (hysteresis loop).

Linear stiffness. For a load-deformation curve with a curvilinear shape, the slope of the curve over a range of deformation where the curve is most nearly linear.

Load. The external force applied to a specimen (ligament). Loads may be further characterized as tensile, compressive, shear, bending, or torsional.

Load-deformation curve. The relationship between the applied load and the corresponding deformation of a specimen obtained during testing (e.g., tensile testing of a bone-ligament-bone complex).

Mechanical (material) properties. The tensile properties of the ligament substance as a material represent by the stress-strain curve. Properties such as tangent modulus, tensile strength, and ultimate strain can be determined from the stress-strain curve.

Mechanics. The study of the force, motion, deformation, and strength of materials in response to externally applied loads.

QLV theory. Quasi-linear viscoelastic theory. A mechanical model to describe the nonlinear viscoelastic behavior of soft connective tissues, first developed by Fung (1972).

Stiffness. The slope of the load-deformation curve for a specimen with a linear load-deformation relationship.

Strain. The change in specimen dimension under external loading divided by the initial reference dimension of the specimen, expressed as a percentage. For example, the change in length with respect to initial length of a ligament during tensile testing.

Strain rate. The rate at which a specimen is deformed, expressed in terms of strain per unit time.

Stress relaxation. A viscoelastic behavior characterized by a decrease in stress in a specimen with time under a constant applied strain or deformation.

Stress-strain curve. The relationship between the applied stress and corresponding strain present in a specimen (e.g. the ligament substance) during testing.

Structural properties. The tensile properties of the bone-ligament-bone complex as a structural unit, represented by the load-deformation curve. Properties such as linear stiffness, ultimate load, ultimate deformation, and energy absorbed at failure can be obtained from the load-deformation curve.

Viscoelastic properties. The time- and history-dependent mechanical behavior of soft connective tissues such as ligaments. The mechanical properties of such tissues depend upon factors such as the previous strain and loading history, the rate of loading, and the duration of loading. For example, the properties of a ligament tested after one cycle of load will differ from those of a ligament tested after 10 cycles of loading.

Forces and moments

Terms to describe forces and moments applicable while evaluating ligamentous restraints and knee stability in patients are listed as follows:

Force. The influence on a body, such as push or pull, that accelerates (changes either the speed or direction of motion) or deforms (changes either the size or shape) the body (Noyes et al. 1989a). *Active force* is the internally created influence on a body such as active muscle innervation. *Passive force* is the externally applied influence on a body such as external loads. A force has three properties: 1) an orientation or line of action, 2) a sense along its line of action, and 3) a magnitude which is expressed in Newtons. The net effect of a force depends on all three of its properties, on the point of force application (Noyes et al. 1989a), and force duration.

Moment. The influence on a body that causes an angular (rotational) acceleration of the body (Noyes et al. 1989a). *Active moment* is the internally created influence on a body such as active muscle innervation. *Passive moment* is the externally created influence on a body such as external loads. A moment has three properties: 1) an orientation or line of action, 2) a sense clockwise or counterclockwise about its line of action, and 3) a magnitude which is measured in Newton-meter.

Appendix

How to measure tibiofemoral compartmental displacement

Measuring anterior displacement

Anterior displacement of the medial and lateral tibiofemoral compartments is determined on the anterior stressradiograph.

Measuring the medial compartment

- Superimpose the KMT-20 Template© (Figure 21) on the anterior stressradiograph with the lines running strictly parallel to the posterior tibial cortex (PTC). Maintain the lines of the KMT-20 Template© in this parallel relationship with the PTC during the entire measuring process.
- Identify the posterior subchondral contour of the medial femoral condyle.
- Adjust the KMT-20 Template© so that the zero line is tangent to the most posterior aspect of the medial femoral condyle. Now, you have defined the anatomic zero position of the medial compartment.
- Identify the posterior subchondral contour of the medial tibial plateau.
- Determine the anterior final position of the medial tibial plateau.
- Use the vertically oriented millimetric scale above the zero line to determine the distance between the zero line tangent to the medial femoral condyle and the line tangent to the posterior subchondral contour of the medial tibial plateau. The distance in millimeters is the anterior displacement of the medial tibiofemoral compartment.

Measuring the lateral compartment

- Identify the posterior subchondral contour of the lateral femoral condyle.
- Shift the KMT-20 Template© so that the measurement lines remain parallel to the posterior tibial cortex (PTC).
- Adjust the KMT-20 Template© so that the zero line is tangent to the most posterior aspect of the lateral femoral condyle. Now, you have identified the anatomic zero position of the lateral compartment.
- Identify the posterior subchondral contour of the lateral tibial plateau.
- Determine the anterior final position of the lateral tibial plateau.
- Use the vertically oriented millimetric scale above the zero line to determine the distance between the zero line tangent to the lateral femoral condyle and the line tangent to the posterior subchondral contour of the lateral tibial plateau. This distance in millimeters is the anterior displacement of the lateral tibiofemoral compartment.

Measuring posterior displacement

Posterior displacement of the medial and lateral tibiofemoral compartments is determined on the posterior stressradiograph (Figure 22).

Measuring the medial compartment

- Superimpose the KMT-20 Template© on the posterior stressradiograph with the lines running strictly parallel to the posterior tibial cortex (PTC) (Figure 22). Maintain the lines in this parallel relationship with the PTC during the entire measuring process.
- Identify the most posterior contour of the medial femoral condyle.
- Adjust the KMT-20 Template© so that the zero line is tangent to the most posterior aspect of the medial femoral condyle. Now, you have defined the anatomic zero position of the medial compartment.
- Identify the posterior contour of the medial tibial plateau.
- Use the vertically oriented millimetric scale below the zero line to determine the distance from the anatomic zero position of the medial femoral condyle to the posterior final position of the medial tibial plateau. This distance in millimeters is the posterior displacement of the medial tibiofemoral compartment (Figure 22).

Measuring the lateral compartment

- Identify the most posterior contour of the lateral femoral condyle.
- Place the zero line of the KMT-20 Template© tangent to the most posterior aspect of the lateral femoral condyle.
- Measure the distance in millimeters from the zero line to the posterior tangent of the lateral tibial plateau on the scale below the zero line. This distance in millimeters is the posterior displacement of the lateral tibiofemoral compartment.

References

Andrews J G. On the specification of joint configurations and motions. Letter to the Editor. J Biomechanics 1984; 17: 155–158

Bach B R, Warren R F, Wickiewicz T L. The pivot shift phenomenon. Results and description of a modified clinical test for anterior cruciate ligament insufficiency. Am J Sports Med 1988; 16: 571-576

Blankevoort L. Passive motion characteristics of the human knee joint. Experiments and computer simulations. Alblasserdam, The Netherlands, Offsetdrukkerij Haveka B.V., 1991

Blankevoort L, Huiskes R, de Lange A. The envelope of passive knee joint motion. J Biomechanics 1988; 21: 705–720

Butler D L, Noyes F R, Grood E S. Ligamentous restraints to anterior-posterior drawer in the human knee. A biomechanical study. J Bone Joint Surg [Am] 1980; 62A: 259–270

Chao E Y S. Justification of triaxial goniometer for the measurement of joint rotation. J Biomechanics 1980; 13: 989–1006

Clancy W G Jr, Shelbourne K D, Zoellner G B, Keene J S, Reider B, Rosenberg T D. Treatment of knee joint instability secondary to rupture of the posterior cruciate ligament. Report of a new procedure. J Bone Joint Surg 1983; 65A: 310–322

Cross M J, Schmidt D R, Mackie I G. A no-touch test for the anterior cruciate ligament. Brief Report. J Bone Joint Surg [Br] 1987; 69B: 300

Dahlstedt L J, Dalén N. Knee laxity in cruciate ligament injury. Value of examination under anaesthesia. Acta Orthop Scand 1989; 60: 181–184

Daniel D M, Malcom L L, Losse G, Stone M L, Sachs R, Burks R. Instrumented measurement of anterior laxity of the knee . J Bone Joint Surg [Am] 1985; 67A: 720–726

Daniel D M, Stone M L. Instrumented measurement of knee motion. Chapter 23. In: Daniel et al. (eds). Knee ligaments: Structure, function, injury, and repair. New York: Raven Press 1990: 421–426

Danzig L A, Newell J D, Guerra J Jr, Resnick D. Osseous landmarks of the normal knee. Clin Orthop 1981; 156: 201–206

Edixhoven P J. De geinstrumenteerde Schuifladetest van de Knie in vivo. Nijmegen: OnLine Vormvervaardiging 1986: 1–112

Edixhoven P, Huiskes R, de Graaf R. Anteroposterior drawer measurements in the knee using an instrumented test device. Clin Orthop 1989; 247: 232–242

Edixhoven P J, Huiskes R, de Graaf R, van Rens T J G, Slooff T J. Accuracy and reproducibility of instrumented knee-drawer tests. J Orthop Res 1987; 5: 378–387

Forster I W, Warren-Smith C D, Tew M. Is the KT-1000 knee ligament arthrometer reliable? J Bone Joint Surg [Br] 1989; 71B: 843–847

Fukubayashi T, Torzilli P A, Sherman M F, Warren R F. An in vitro biomechanical evaluation of anterior-posterior motion of the knee. Tibial displacement, rotation, and torque. J Bone Joint Surg [Am] 1982; 64A: 258–264

Fung Y C B, as cited by Woo S L-Y, Young E P, Kwan M K. Fundamental studies in knee ligament mechanics. Chapter 7. In: Daniel DM et al. (eds). Knee ligaments: Structure, function, injury, and repair. New York: Raven Press 1990: 132

Galway R D, Beaupré A, MacIntosh D L. Pivot shift. A clinical sign of symptomatic anterior cruciate insufficiency. [Abstract] J Bone Joint Surg [Br] 1972; 54B: 763–764

Galway R D. MacIntosh D L. The lateral pivot shift. A symptom and sign of anterior cruciate ligament insufficiency. Clin Orthop 1980; 147: 45–50

Gollehon D L, Torzilli P A, Warren R F. The role of the posterolateral and cruciate ligaments in the stability of the human knee. A biomechanical study. J Bone Joint Surg [Am] 1987; 69A: 233–242

Granberry W M, Novle C P, Woods G W. Evaluation of an electrogoniometric instrument for measurement of laxity of the knee. J Bone Joint Surg [Am] 1990; 72A: 1316–1322

Grood E S, Noyes F R. Diagnosis of knee ligament injuries. Biomechanical precepts. Chapter 9. In: Feagin JA Jr (ed). The Crucial Ligaments. New York: Churchill-Livingstone 1988: 245–260

Grood E S, Stowers S F, Noyes F R. Limits of movement in the human knee. Effect of sectioning the posterior cruciate ligament and posterolateral structures. J Bone Joint Surg [Am] 1988; 70A: 88–97

Grood E S, Suntay W J. A joint coordinate system for the clinical description of three-dimensional motions. Application to the knee. ASME Transactions. J Biomechan Eng 1983; 105: 136–144.

Gurtler R A, Stine R, Torg J S. Lachman test revisited. Contemporary Orthopaedics 1990; 2: 145–154.

Hughston J C, Andrews JR, Cross MJ, Moschi A. Classification of knee ligament instabilities. Part I. The medial compartment and cruciate ligaments. J Bone Joint Surg [Am] 1976; 58A: 159–172

Hughston J C, Andrews J R, Cross M J, Moschi A. Classification of knee ligament instabilities. Part II. The lateral compartment. J Bone Joint Surg [Am] 1976; 58A: 173–179

Jacobsen K. stressradiographical measurement of the anteroposterior, medial and lateral stability of the knee joint. Acta Orthop Scand 1976; 47: 335–344

Jacobsen K. Gonylaxometry. stressradiographic measurement of passive stability in the knee joints of normal subjects and patients with ligament injuries. Accuracy and range of application. Acta Orthop Scand 1981; 52 (Suppl 194): 1–263

Jakob R P, Hassler H, Stäubli H-U. Observations on rotatory instability of the lateral compartment of the knee. Experimental studies on the functional anatomy and the pathomechanism of the true and the reversed pivot shift sign. Acta Orthop Scand 1981; 52 (Suppl 191): 1–32

Jakob R P, Stäubli H-U (eds). Kniegelenk und Kreuzbänder: Anatomie, Biomechanik, Klinik, Rekonstruktion, Komplikationen, Rehabilitation. Berlin, Heidelberg: Springer-Verlag 1990: 1–21

Jakob R P, Stäubli H U, Deland J T. Grading the pivot shift. Objective tests with implications for treatment. J Bone Joint Surg [Br] 1987; 69B: 294–299

Kärrholm J K, Selvik G, Elmqvist L-G, Hansson L-I, Jonsson H. Three-dimensional instability of the anterior cruciate deficient knee. J Bone Joint Surg [Br] 1988; 70B: 777–783

Kennedy J C, Fowler P J. Medial and anterior instability of the knee. An anatomical and clinical study using stress machines. J Bone Joint Surg [Am] 1971; 53A: 1257–1260

Lemaire M. Ruptures anciennes du ligament croisé antérieur du genou. Fréquence, clinique, traitement (46 cas). J Chir [Paris] 1967; 93: 311–320

Levén H. Determination of sagittal instability of the knee joint. Acta Radiolog [Diagn] 1977; 18: 689–697

Losee R E, Johnson T R, Southwick W O. Anterior subluxation of the lateral tibial plateau. A diagnostic test and operative repair. J Bone Joint Surg [Am] 1978; 60A: 1015–1030

Markolf K L, Graff-Radford A, Amstutz H C. In vivo knee stability. A quantitative assessment using an instrumented clinical testing apparatus. J Bone Joint Surg [Am] 1978; 60A: 664–674

de Montmollin B, Pol Le Coeur. La rupture isolée fraîche du ligament croisé antérieur du genou. Rev Chir Orthop 1980; 66: 367–371

Moyen B, Lerat J L, Jenny J Y, Brunet-Guedi E. A comparison of the pre-operative evaluation of the anterior knee play by passive dynamic x-rays and by arthrometer KT 1000. S. 38. In Abstract Book. Fourth Congress of the European Society of Knee Surgery and Arthroscopy. Stockholm, Sweden, June 25–30, 1990: 36–38

Müller W, Biedert R, Hefti F, Jakob R P, Munzinger U, Stäubli H-U. OAK knee evaluation. A new way to assess knee ligament injuries. Clin Orthop 1988; 232: 37–50

Noyes F R, Grood E S, Torzilli P A. Current Concepts Review. The definitions of terms for motion and position of the knee and injuries of the ligaments. J Bone Joint Surg [Am] 1989a; 71A: 465–472

Noyes F R, Mooar L A, Moorman C T, McGinniss G H. Partial tears of the anterior cruciate ligament. Progression to complete ligament deficiency. J Bone Joint Surg [Br] 1989b; 71B: 825–833

Nyga W. Röntgenologische Darstellung von Kreuzbandverletzungen des Kniegelenkes. Z Orthop 1970; 107: 340–344

Rauschning W. Serial cryosectioning of human knee specimens for a study of functional anatomy. Science Tools 1979; 26: 47–50

Selvik G. Roentgen stereophotogrammetry. A method for the study of the kinematics of the skeletal system. Dissertation. Lund: AV-centralen. 1974. Acta Orthop Scand 1989; 60 (Suppl 232): 1–46

Shino K, Inoue M, Horibe S, Nakamura H, Ono K. Measurement of anterior instability of the knee. A new apparatus for clinical testing. J Bone Joint Surg [Br] 1987; 69B: 608–613

Shoemaker S C, Daniel D M. The limits of knee motion: In vitro studies. Chapter 9. In: Daniel et al. (eds). Knee ligaments: Structure, function, injury, and repair. New York: Raven Press 1990: 153–162

Stäubli H-U. Stressradiography. Measurements of knee motion limits. Chapter 25. In: Daniel et al. (eds). Knee ligaments: Structure, function, injury, and repair. New York: Raven Press 1990: 449–459

Stäubli H-U, Birrer S. The popliteus tendon and its fascicles at the popliteal hiatus: Gross anatomy and functional arthroscopic evaluation with and without anterior cruciate ligament deficiency. Arthroscopy 1990; 6: 209–220

Stäubli H-U, Jakob R P. Begriffe, Definitionen und Glossar. In: Jakob RP, Stäubli H-U (eds). Kniegelenk und Kreuzbänder. Anatomie, Biomechanik, Klinik, Rekonstruktion, Komplikationen, Rehabilitation. Berlin, Heidelberg: Springer-Verlag 1990a: 1–21

Stäubli H-U, Jakob R P. Posterior instability of the knee near extension. A clinical and stressradiographic analysis of acute injuries of the posterior cruciate ligament. J Bone Joint Surg [Br] 1990b; 72B: 225–230

Stäubli H-U, Jakob R P. Anterior knee motion analysis. Measurement and simultaneous radiography. Am J Sports Med 1991;19: 172–177

Stäubli H U, Noesberger B, Jakob R P. The drawer sign of the knee in extension. A prospective study. Transactions of the 29th Annual Meeting of the International Society of the Knee. Orthopaedic Transactions. J Bone Joint Surg [Am] 1983; 65A: 585

Stedtfeld H-W, Strobel M. Ein neues Haltegerät für die Anfertigung gehaltener Röntgenaufnahmen des Kniegelenkes.[A new device for stress-X-rays of the knee joint.] Unfallheilkunde [Traumatology] 1983; 86: 230–235

Torg J S, Conrad W, Kalen V. Clinical diagnosis of anterior cruciate ligament instability in the athlete. Am J Sports Med 1976; 4: 84–93

Torzilli P A, Greenberg R L, Insall J. An in vivo biomechanical evaluation of anterior-posterior motion of the knee. Roentgenographic measurement technique, stress machine, and stable population. J Bone Joint Surg [Am] 1981; 63A: 960–968

Torzilli P A, Greenberg R L, Hood R W, Pavlov H, Insall J N. Measurement of anterior-posterior motion of the knee in injured patients using a biomechanical stress technique. J Bone Joint Surg [Am] 1984; 66A: 1438–1442

Trillat A, Dejour H, Bousquet G (eds). Chirurgie du Genou. [Surgery of the Knee.] Villeurbanne, France: Simep-Editions 1978: 1–16

Woo S L-Y, Young E P, Kwan M K. Fundamental studies in knee ligament mechanics. Chapter 7. In: Daniel et al. (eds). Knee ligaments: Structure, function, injury, repair. New York: Raven Press 1990: 115–134