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From the Department of Orthopaedic Surgery T-3, Gentofte Hospital,
University of Copenhagen, Hellerup, Denmark.

Gonylaxometry

Stress Radiographic Measurement of Passive Stability in the Knee Joints of Normal Subjects and Patients with Ligament Injuries

Accuracy and Range of Application

BY

KLAUS JACOBSEN

MUNKSGAARD . COPENHAGEN

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Chapter 1

INTRODUCTION AND OBJECT

Interest in ligament instability of the knee joint has been on the increase throughout this century. An explanation may be the increasing number of ligament injuries in modern industrial society, due to accidents at work, in the traffic, and during sports performances. Bircher (1933) stated that athletic injuries constituted the largest single group in his material, 20 out of 84 surgically confirmed cruciate ligament injuries, or 24%, Palmer (1938) reported 34% of 58 operated ligament injuries, Jonash (1958) 32%, Solonen and Rokkanen (1967) 24%, Liljedahl and Nordstrand (1969) 62%, Gillquist (1971) 79%, Gillquist et al. (1971) 84%, and Alm (1974) 90%. However, epidemiological or incidence studies are not on record.

So far, the assessment of instability in the knee joint has been based predominantly on clinical findings. For scientific reasons it would be advantageous to be able to measure the stability of the joint in physical units. In that case, the effect of a therapeutic method could be evaluated by stability measurements before and after the treatment.

The object of the present studies was to develop a method for reliable measurement of ligament stability in the knee joint. Measurements on radiographs before and after application of differently directed traction and pressure actions upon the joint have proved suited. On the films it is possible to measure directly a change in the distance between the articular bones, represented by further defined landmarks as a measure of stability or instability. Radiological measurement obviates an incalculable inaccuracy due to the shift of soft tissues when a measuring apparatus is fastened externally on the joint. The method of Kennedy and Fowler (1971) could be elaborated so that to the original measurement of anterior and medial instability it was possible to add posterior and lateral as well as various forms of rotatory instability. Therefore, this was the method selected and designated by the present author, in its extended form, "gonylaxometry", viz. measurement of knee laxity.

The present investigations were carried out to extend these authors' method to the measurement of instability in known units, mm, for research purposes and to assess the reliability of the method. This required examinations of normal persons as well as of a series of patients with knee ligament *injuries confirmed surgically after the measurement.*

In this connection it was endeavoured also to assess the value of the apparatus as a diagnostic aid for clinical use.

For elaborating the method it was necessary to arrive at a more accurate measuring technique on the X-ray films. To this end, anatomical and radio-anatomical investigations were carried out to fix the landmarks. In this connection the area intercondylaris tibiae was subjected to particular study. Suited angles of knee flexion and suited projections had to be selected. Various positions of rotation of the foot were used to elucidate the influence of such positions in examining the knee joint. Lastly, methods were developed for calculating the conversion of the distances read from the films into displacement or rotation during various actions upon the joint.

It was endeavoured also to elucidate a possible relationship between given traumatic mechanisms and instability patterns.

Chapter 2

METHODS FOR ASSESSING LIGAMENT INSTABILITY OF THE KNEE JOINT

Historical Development and Present Status on the Basis of the Literature

2 a: Clinical Evaluation of Instability

Injuries to the cruciate ligaments were first described by Stark (1850), and about the turn of the century they were still considered extremely rare (Fick 1904, 1911). Insufficiency of the collateral ligaments, as of the cruciate ligaments, was studied by cutting experiments on human cadavers by Weber and Weber (1836). These latter authors mentioned lateral (varus) and medial (valgus) instability, but not the drawer sign. Goetjes (1913) mentioned sagittal instability and Felsenreich (1934) the drawer sign, but attached less importance to it than to instability in the frontal plane (varus/valgus), also in injuries to the cruciate ligaments. Bircher (1933) used the terms medial and lateral instability as well as drawer sign, as described below, in his material of 84 cases with rupture of the cruciate ligaments among 831 arthrotomies on the knee joint. The most thorough review of the literature and study of a major patient material so far we owe to Palmer (1938). He described the clinical symptoms and signs of ligament injuries, supplemented by studies on human cadavers, and it is his description of medial and lateral instability and the drawer sign which forms the basis of the following account.

Instability in the frontal plane, meaning instability at ab- or adduction+) is evaluated on the slightly flexed knee. In this position the cruciate ligaments and the posterior articular capsule are so lax that an isolated injury to a collateral ligament is demonstrable, as reproduced experimentally on cadavers by Palmer (1938) and Hallén and Lindahl (1965 a). Major instability in a slightly flexed knee indicates associated injury to the cruciate ligaments and posterior knee capsule, while instability found in a fully extended knee is definite evidence of associated injury to these structures, as demonstrated experimentally by the same authors. Clinically, the instability can be measured only approximately with a goniometer, and only under general anaesthesia, as the instability is normally demonstrated instantaneously because a pain reaction immediately makes the knee return to the neutral position.

+) For more accurate definitions, cf. Chapter 5.

An anterior drawer sign without simultaneous rotation of the knee joint (cf. definitions in Chapter 5) cannot be induced in cases of isolated collateral ligament injury (Palmer 1938). This requires an injury to the anterior cruciate ligament, ACL, but not necessarily to the collateral ligaments. A posterior drawer sign (tibia in relation to the femur) is observed in injuries to the posterior cruciate ligament, PCL, but does not necessarily presuppose injury to the collateral ligaments or the posterior knee capsule (Palmer 1938). This investigation is done with the knee in 90° flexion. When extended the knee joint is stable even in the presence of isolated destruction of both cruciate ligaments, cf. cadaver experiments on human knee joints by Weber and Weber (1836) and Palmer (1938). The drawer sign increases with increasing destruction of the collateral ligaments (Palmer 1938).

Several authors have tried to grade the drawer sign clinically from 0, +, ++, to ++++ (O'Donoghue 1963) or +++ (Kettelkamp and Thompson 1975 , Hughston et al. 1976, Marshall et al. 1977). The examiner uses his finger thickness, possibly a tape measure, and comparison with the patient's good knee in the assessment.

Investigation of rotation on an axis in the longitudinal direction of the tibia in knees with intact ligaments was first performed on human cadavers by a Dane (Winslow 1719) and later by Weber and Weber (1836), Fick (1911), Brantigan and Voshell (1941), Hallén and Lindahl (1965 b), while normal rotation in living subjects has been studied by Meyer (1853), Ross (1932), and Ruetsch and Morscher (1977). Abnormal rotation giving rise to symptoms did not attract clinical attention until a late date.

Slocum and Larson (1968) have suggested a clinical test for demonstrating external rotatory instability of the tibia in relation to the femur, due to injury to the medial collateral ligaments. Provided that the lateral ligamentous structures are intact, the clinical rotatory instability test is deemed positive when the tibia can be pulled forward with the "foot and lower leg" in 15° external rotation. The knee joint is in 90° flexion. The presupposed lateral stability is first investigated, also clinically. It is to manifest itself in a stable knee joint on forward sagittal traction with the foot and lower leg in 30° internal rotation. Nicholas (1973 a) extended the instability definitions, defining initially simple instability as instability in one plane and complex instability as instability in two or more planes at the same time. This must be taken to mean that medial and lateral instability, i.e. abduction and adduction instability respectively, and drawer signs into a purely sagittal direction represent simple instab-

ility, but when combined or associated with simultaneous abnormal rotation they are types of complex instability. Nicholas has taken particular interest in rotation combined with drawer signs (Fig. 1). The examination is carried out clinically, with the knee flexed 20° - 30°. According to this definition, complex anteromedial instability means abnormal forward movement (on traction) of both tibial condyles in relation to the respective femoral condyles plus a difference in the forward movement, the medial condyle moving more than the lateral one. In other words, there occurs a forward displacement plus an external rotation (supination) of the tibia. Complex anterolateral instability represents abnormal displacement forward, the lateral condyle moving more than the medial one, an internal rotation (pronation) thus being added. Posteromedial and posterolateral complex instability is defined as abnormal backward displacement of both tibial condyles plus
(1) greater displacement of the medial condyle and
(2) greater displacement of the lateral tibial condyle
respectively.

Trickey (1977) has defined anteromedial instability as a combined medial instability and external rotation in 30° flexion of the knee. This was demonstrated on formalin-fixed preparations with cut medial ligaments and intact cruciate ligaments.

Trickey's anterolateral instability consists in forward displacement of the lateral tibial condyle causing internal rotation and occurs, according to Trickey, when the ACL and possibly the posterolateral capsule are cut.

Hughston et al. (1976 I and II) chose another classification: a: Drawer sign in neutral position, "straight anterior or posterior instability", b: drawer sign with knee and foot in external rotation, c: drawer sign with knee and foot in internal rotation, and d: simple medial and lateral instability "straight abduction or adduction instability".

Most recently, anterior displacement of the lateral tibial plateau has attracted interest (Kennedy and Swan 1972, Slocum et al. 1976, Losee et al. 1978, Kennedy et al. 1978). This displacement, also called anterolateral rotatory instability by the named authors, has been found in all the materials in patients having injury to the ACL and rupture, scarring, or laxity of the posterolateral capsule. This is in exact accordance with the investigations of Trickey (1977). Several clinical tests have been suggested for demonstrating this instability, all characterized by the tibia, while in position between full extension of the knee and 30° flexion,

COMPLEX ROTATORY INSTABILITY

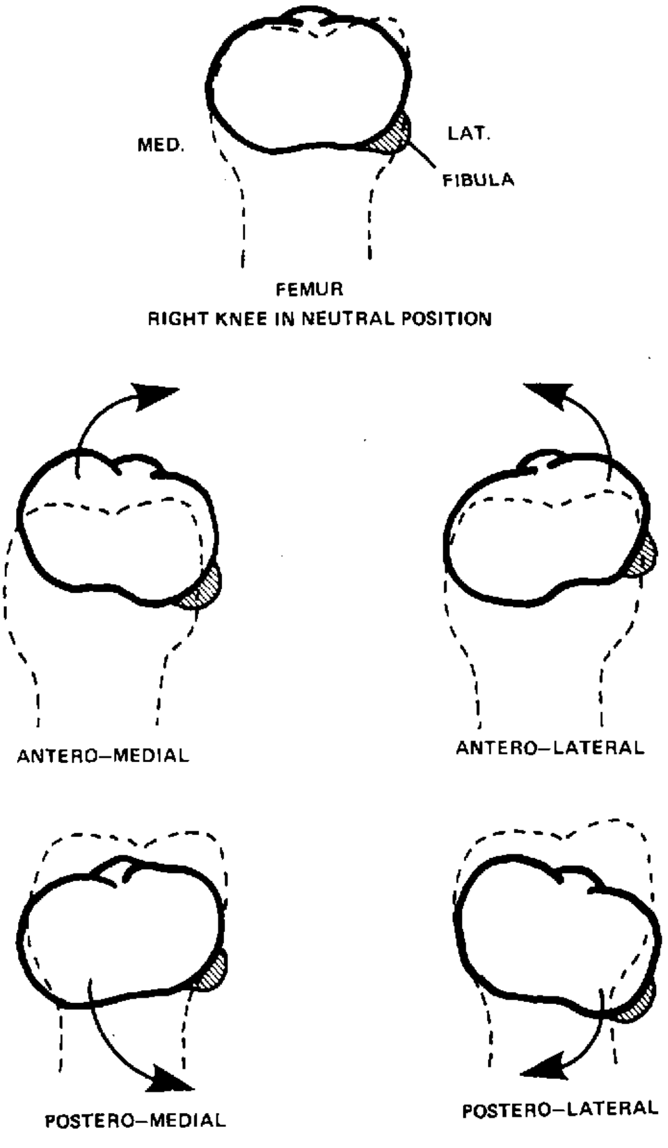

Figure 1: Complex rotatory instability in accordance with the present author' definitions (from (6) Acta orthop. scand. 49 195-204,1978): Right knee viewed from above in 90° flexion. Tibia indicated by solid lines. The changing centres of rotation in injured knees are in fact unknown. External rotation is present in anteromedial and posterolateral complex rotatory instability. Internal rotation in anterolateral and posteromedial complex rotation. Note a simultaneous drawer sign in the four pathological situations.

The figure has been modified from J.A.Nicholas: J.Bone Joint Surg. 55 A, July 1973, 899-922, Figure 3, with the author's kind permission. The figure reflected that Nicholas performs his examination (and makes his definitions) on the basis of a knee in 20° flexion.

being displaced forward and rotated inwards, and thereafter reduced with an audible click. The positioning of the patient and the examiner's manipulations differ somewhat, but the principle is identical in all the tests: The "MacIntosh pivot shift symptom", Galway et al.(1972),Slocum et al.(1976), the "jerk test" (Hughston et al. 1976), Losee's test (Losee et al. 1978). The mechanism is a sliding of the lateral femoral condyle upwards, over the posterior horn of the lateral meniscus, LM, when the lateral tibial plateau is displaced forward and a reduction with an audible click or - if the meniscus has already been destroyed or removed - a jumping movement of the femoral condyle over the lateral tubercle. The phenomenon and the named mechanisms were described as early as 1938 by Palmer who also described the sequel to spontaneous displacement in the form of osteochondral fractures of the lateral tubercle. Hyperextension of the knee joint as a sign of rupture of the cruciate ligaments and posterior capsule were also described by Palmer (1938), and in Stark's opinion (1850) it was the most important sign.

2 b: Instrumental Measurement of Knee Stability

2 b 1: Early historical development

Measurements on preparations of human knee joints were carried out early, by Weber and Weber (1836) who used a compass in order to adjust the initial position (compass north pole) and read the various excursions in degrees. A metal wire introduced into the tibial tuberosity served as a pointer. Brantigan and Voshell (1941) and Hallén and Lindahl (1965 a, b) have used similar methods, fixing devices direct in bony tissue of human knee preparations, so that the measurements could be rendered quite exact.

The Weber brothers also measured knee flexion and extension in two living persons (Weber and Weber 1836). Meyer (1853) was the first to measure rotation in the knees of living normal persons. His experimental design was simple, with an indicator fixed to the sole, external fixation of the femur, and immobilization of the ankle joint by strapping. Ross (1932) used a pointer fixed with plaster to the malleoli, whereas Ruetsch and Morscher (1977) employed a metal rod indicator fixed with an elastic bandage on the skin over the proximal part of the medial tibial surface. All three studies were rotation measurements on knees in 90° flexion in normal living persons by means of grading scales beneath the soles.

More advanced instrumental measurement of ligament instability in the knee joint in vivo has not come into use until the past few decades. A distinction may be made between measurement by externally fastened apparatus, viz. external measurement, and radiological measurement.

2 b 2: External measurement of knee instability in vivo may be by: (1) various forms of goniometry, (2) measurement of anteroposterior displacement in mm, (3) a combination of these two methods, and (4) photographic methods.

2 b 2.1: Goniometry, by apparatus fastened externally on the limb for measuring medial and lateral knee stability in vivo was first mentioned by Klein (1962). His apparatus consisted of metal cases for the lower leg and thigh with a mechanical joint and grading scale at the level of the knee. It was intended exclusively for measuring medial and lateral instability on extended knees. A method for measurement on 10° flexed knees was described by Kalenak and Morehouse (1975). Kittleson et al. (1967) developed an apparatus very similar to Klein's (1962), but which permitted flexion of the knee in measuring the medial and lateral instability. Moreover, it could measure a possible drawer sign.

Electrogoniometry has been used for measuring excursions in the sagittal plane and for measuring rotation during normal persons' walking by Kettelkamp et al (1970) and Lamoreux (1971) and for the measurement of medial and lateral instability by Lowe and Saunders (1977). All have used graphic analysis, the measurement being transmitted to curve shape by a potentiometer device.

2 b 2.2: External measurement of the drawer sign has been described by Sylvin (1975). This method has been developed to measuring exclusively sagittal instability in the 90° flexed knee joint in mm, and the force is not reproducible or measurable, as the traction on the tibia is manual. It has been attempted to eliminate these inaccuracies by repeating each measurement five times and calculating the mean. A similar method has been employed by Tillberg (1977).

2 b 2.3: Markolf et al. (1978) designed an apparatus combining electrogoniometric measurement of medial and lateral instability with electrically recorded anteroposterior stability, with the knee in 90° flexion, in full extension, and in 20° flexion. The action upon the lower limb is manual, but an interposed dynamometer continuously measures its force which is also recorded electrically in a curve.

2 b 2.4: Photographic methods have been used by Levens et al. (1948) and by Sprague and Asprey (1965). The former drilled metal wires into the subject's bones, which presumably will restrict the use of this method. The latter traced lines on the films from skin marks and performed goniometry. Owing to the shift of the soft tissues, this marking cannot be assumed to give particularly accurate measurements, reflected indeed in a low correlation coefficient in a test/retest study of healthy subjects.

2 b 3: Radiological methods

2 b 3.1: Radiological demonstration of medial and lateral instability and of the drawer sign was published first by Kirchmayer (1920), of medial and lateral instability by Palmer (1938), and of the drawer sign by Böhler (1943). Jonash (1958, 1968) refined and standardized the technique by exposures of abduction and adduction instability. All these authors used in vivo exposures. Martin (1960), in his studies on human knee preparations, clearly defined his measuring method of medial instability, measuring on the X-ray film the "clear space" between the condyles 5 mm from the medial tibial margin. In his in vivo studies he used general anaesthesia or spinal anaesthesia to obtain complete relaxation of the muscles in the affected leg. Roser et al. (1971) did their measurements in the same way, but 1 cm from the medial margin in measuring medial instability and 1 cm from the outermost edge of the lateral condyle in measuring lateral instability in athletes. Nyga (1970) used manual traction for measuring anterior displacement and a double exposure - first without and then with traction. Finally, there is reason to mention an analysis by Wirth and Artmann (1974) done to elucidate the rolling-sliding movement of the condyles in knee joints with and without ACL. They utilized Fisher's principle (1907) which involves the construction of parallel tangents at points of contact between matching femoral and tibial condyles on radiographs. This method is extremely time-consuming and not routinely applicable. It was employed for demonstrating the drawer sign in patients with confirmed injury to the anterior cruciate ligament.

2 b 3.2: Stress radiographic methods are taken here to mean methods in which the action upon the knee joint is done by the aid of set-ups or apparatuses permitting standardization of the force used, in contrast to simple manual actions. Thereafter, the measurements of instability are performed on X-ray films made before and during the stress actions. All the methods to be mentioned below are intended for use in vivo. Ouellet et al. (1968) have standardized the force for the measurement of medial and lateral in-

stability and also instability in the sagittal plane, fastening the thighs and exerting the action by strings from cuffs around the tibia and passed over pulleys to vertically suspended weights. Roser et al. (1971) used the same method.

Volkov (1971) has designed an apparatus which, by a handle, pulls at the proximal end of the tibia with a force of 15-20 kg. The force can be read on an interposed dynamometer. Other parts of the apparatus serve to fix the patient's thigh and lower leg, so that the knee maintains a 90° flexion throughout the examination. The patient is positioned on an X-ray table, and exposures are made before and during the traction. Anterior displacement of the tibial condyle is measured on the X-ray films, according to which criteria is not stated.

2 b 3.3: The apparatus described by Kennedy and Fowler (1971) for measuring medial instability with the knee in 20° flexion and anterior drawer sign with the knee in 90° flexion also operates with a standardized, measurable force and X-ray exposures during these actions, followed by measurement of any instabilities demonstrable on the X-ray films. The actions are exerted by gas-operated cylinders connected, when measuring medial instability, to a shoe guided by a slide in the frontal plane of the leg. In measurements of the anterior drawer sign the cylinder is connected to the proximal end of the tibia by a piston. The direction and force of the actions are guided from an instrument panel. The subject is fastened on a seat whose height can be altered from one type of measurement to the other. Exposures are made with an anteroposterior beam, a-p views, during abduction action, and lateral views during traction. During the former exposure the foot is fixed, during the latter only the ankle. The stress exposures are compared with exposures at rest. The set-up secures a constant X-ray projection and a comparable force of action from one exposure to the other. The measurement on the X-ray films is done with the aid of two superposed layers of transparent celluloid film scored with lines at right angles which are placed according to landmarks or the X-ray film. In the lateral view, used in measuring the drawer sigr, the measurement is done by the aid of pieces of lines cut from a baseline of tangents to the anterior points of the femoral condyles and the posterior aspects of the tibial condyles (cf. Fig. 11). The measurements are made with a Vernier gauge, with 0.1 mm accuracy on a horizontal viewing box. There are certain divergences between Kennedy and Fowler's and the present author's landmarks and positioning of the baseline, and they will be mentioned later. The medial instability is

measured on a tangent to the medial aspect of the medial tibial condyle, at right angles to a baseline through the most distal points of the tibial joint surfaces on the X-ray film (cf. Fig. 9). The parameter is cut off on the named tangent of a line through the most distal points of the contours of the femoral condyles. It is the credit of Kennedy and Fowler to have introduced such well-defined criteria of measurement.

Chapter 3

ANATOMY OF THE KNEE JOINT ON THE BASIS OF THE LITERATURE

3 a: Bones

The lateral femoral condyle, whose joint surface anteriorly starts about 10 mm proximally to that of the medial condyle, has a considerably larger "guiding ridge" for the patella than the medial one. Both femoral condyles have a "linea condylopatellaris" (Spalteholz 1953) at the junction of the patellar surface of the femur and that part of the joint surface which articulates with the tibia. Just distal to this line each femoral condyle has a groove which has no name in anatomical nomenclature, but in German literature it is referred to as "die Grenzrinne" and in Anglo-Saxon literature as "the limiting groove". In extension the anterior parts of the respective menisci are situated in these grooves.

The articular surfaces of the tibial condyles differ somewhat in shape. While both are retroverted and retroposed in relation to the tibial shaft, and both concave in the frontal plane, the medial joint socket is definitely concave in the anteroposterior direction, while the lateral one is convex or quite flat (in a few cases slightly concave). As a rule it is less retroverted than the medial one. Accordingly, the medial condyle is tallest anteriorly, whereas the lateral condyle is usually tallest in the middle and posteriorly.

The area intercondylaris, situated between the tibial condyles, may be divided into the area intercondylaris anterior, the intercondylar eminence, and the area intercondylaris posterior. The eminence consists of the medial and lateral intercondylar tubercles and between them a crest, the crista intertubercularis. The area intercondylaris posterior is a deep excavation between the tibial condyles, sloping backwards and downwards from the crista intertubercularis. The sesamoid bone situated in the extensor apparatus of the knee joint, the patella, articulates with the femoral condyles anteriorly, proximally to the limiting grooves. It was not used as a landmark in the present study.

3 b: Ligaments

In general, the ligaments of the knee joint are made up of collagenous connective-tissue fibres possessing very little elasticity (Palmer 1938). An intact ligament, thus, is an inelastic organ, and a certain laxity in a given position of the joint is present merely to permit normal movements

(Humphry 1858). Stretching the ligament beyond this position requires a great force and entails permanent prolongation of the tissue in the form of gliding of the fibres in relation to each other (Palmer 1938), possibly demonstrable only microscopically (Noyes et al. 1974, Kennedy et al. 1976).

The medial collateral ligament consists of a superficial and two profound ligaments.

3 b 1: The superficial medial collateral ligament, SMCL, originates on the medial epicondyle of the femur and inserts, deep to the pes anserinus, superficially to the anterior crus of the semimembranosus tendon, anteriorly on the medial tibial surface. It is about 12 cm in length and 10 mm in width (Palmer 1938). At the level of the joint the ligament gives off a thin layer of fibres which posteriorly intertwine with fibres from the deep ligament, DMCL, the posterior joint capsule, and the semimembranosus tendon. Anteriorly there may be interposed a bursa between the SMCL and DMCL, facilitating the gliding movement between the two ligaments (Brantigan and Voshell 1943). In a width of about 10 mm the anterior long fibres are free of the meniscus and other tissues inhibiting movement (Warren et al. 1974).

The joint-stabilizing function of the ligaments is determined by their state of tension in the various phases of joint movement. This varying tension will therefore be described under the term function: The anterior, free 10 mm wide part of the SMCL is taut in extension as well as in any flexion in the sagittal plane. This is due to the elliptical zone of attachment on the femoral epicondyle (Fig. 2). On flexion, pivotting of this attachment oval occurs, causing eversion (superficial backward movement) of the anterior fibres in relation to the posterior ones. Thereby, all fibres obtain constant tension to which contributes also the elevation of the anterior parts of the femoral condyles in flexion (Palmer 1938).

On the other hand, the posterior fibres of the SMCL, which form a thin, triangular sail, are taut only in extension and gradually slacken in flexion (Lanz and Wachsmuth 1938, Palmer 1938, Voshell 1956).

At external rotation of the tibia both parts of the ligament become taut in any position of flexion from the fully extended position. On internal rotation of the tibia both parts slacken a bit. In 20° flexion, the position in which the present investigations for medial and lateral instability were made, the ligament is somewhat slacker than in full extension. It must be borne in mind that in this position the external rotation of the tibia has decreased, the "final rotation" being abolished (Fick 1911, Brantigan and Voshell 1941).

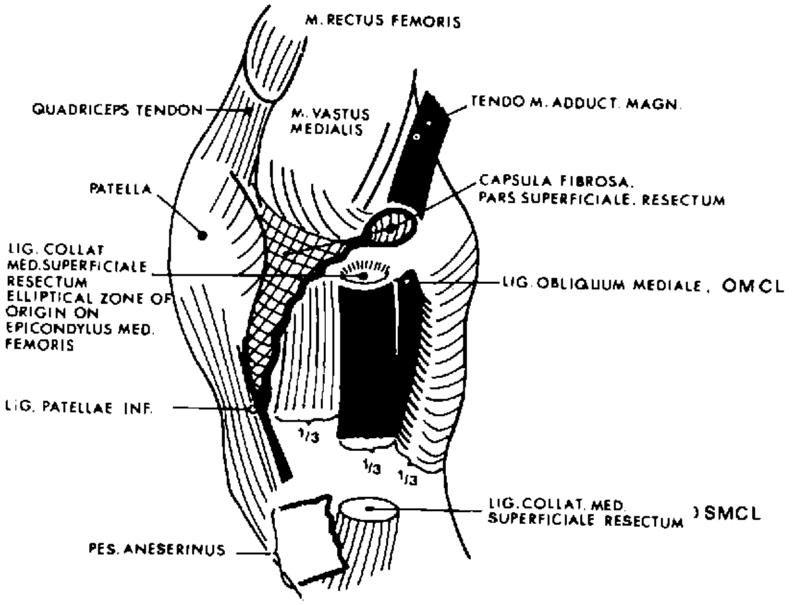

Figure 2: Medial ligaments and extensor apparatus of the knee joint. The pes anserinus is indicated, whereas the tendon insertions from the semimembranosus muscle are omitted. The outer layer of the fibrous joint capsule has been resected, giving a view into the deep fibrous capsule or layer with its ligamentous reinforcements. This layer is divided into three approximately equally large parts, the anterior third being very thin, the middle third made up of the deep medial collateral ligament, DMCL, and the posterior third of the oblique medial ligament, OMCL, and the posteromedial capsule.

3 b 2: The deep medial collateral ligament, DMCL, has its origin on the distal part of the medial epicondyle of the femur, fixes the medial meniscus by collagenous fibril bundles, and inserts on the tibia distally to the cartilaginous junction. In American literature this part of the ligament is termed "the short internal collateral ligament" or "the medial capsular ligament" (Slocum and Larson 1968).

3 b 3: The oblique medial ligament, OMCL, originates posteriorly on the medial epicondyle of the femur and backwards, towards the adductor tubercle, interchanges fibres with the medial meniscus, and inserts below the car-

tilaginous junction posteromedially on the tibia where it intertwines into the posterior capsule of the joint. This ligament has been described by Hughston and Eilers (1973). Palmer has described the latter two ligaments combined (1938), but there are no essential differences between the two descriptions. The OMCL is termed "the posterior oblique ligament" by Hughston and Eilers (1973).

Function: The DMCL as well as the OMCL are taut in extension and in any external rotation of the tibia. They anchor the medial meniscus and restrict its forward movement in extension, as they tighten (Hughston and Eilers 1973). In flexion the medial oblique ligament and the medial meniscus are guided backward by fibres from the semimembranosus muscle via the oblique popliteal ligament according to Kaplan (1962) and Hughston and Eilers (1973), but this has been called in question by Oretorp and Risberg (1978).

In rupture experiments on human knee preparations (Kennedy and Fowler 1971) it has been demonstrated that the DMCL and the OMCL may rupture without a simultaneous rupture of the SMCL, if the knee is forced into violent external rotation while in 90° flexion. In other words, these two deep ligaments contribute to preventing too marked an external rotation of the knee joint in 90° flexion. However, Warren et al. (1974) have attributed most importance to an intact SMCL, both in medial and lateral stability and in external rotatory stability at 0°, 30°, 45°, and 90° knee flexion. This view has been supported by Schweiberer and Hertel (1977). The two latter studies were cutting experiments on human cadaveric knees.

3 b 4: The lateral collateral ligament, LCL, is situated deep to the lateral capsule of the knee joint and the iliotibial tract. Its origin is from the lateral epicondyle of the femur and its insertion on the head of the fibula. Its central part is surrounded by loose connective tissue, gliding tissue, and is not in fibrous connection with the lateral meniscus (Last 1950). At the insertion on the head of the fibula the ligament is enveloped by the insertion fibres of the biceps tendon (Marshall et al. 1972).

Last (1948, 1950) mentioned a deep lateral collateral ligament, described as strong strands in the fibrous capsule of the joint, of a deep situation adjacent to the synovial capsule, "the short external lateral ligament". Its origin is deep to the superficial lateral collateral ligament on the lateral epicondyle of the femur, its insertion anteriorly on the head of the fibula and anterior aspect of the capsule of the proximal tibio-fibular joint (Fig. 3). On this figure there are also illustrated arcuate strands of the iliotibial tract from the lateral epicondyle of the femur (marked e)

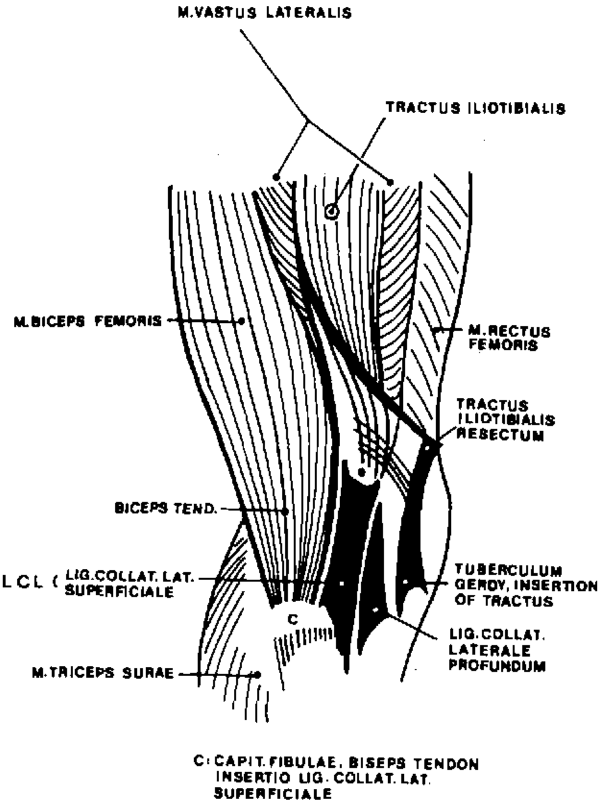

Figure 3: Lateral ligaments of the knee joint and the muscles on its lateral aspect. c: head of fibula, e: lateral epicondyle of the femur.

to Gerdy's tubercle, forming an accessory lateral collateral ligament (Kaplan 1958). Further, minor ligamentous strands have been mentioned by Kaplan (1961).

Function: The superficial LCL is taut in extension, slackens increasingly in flexion, both at 20° and 90°, and tightens in internal rotation as well as extreme external rotation (Palmer 1938, Lanz and Wachsmuth 1938, Edwards et al. 1970).

3 b 5: Cruciate ligaments: The origin of the cruciate ligaments from the femur is at the edge of the inside of the condyles to the roof of the fossa intercondylaris femoris: The anterior cruciate ligament, ACL, on the inside of the lateral condyle of the femur far posteriorly, the posterior cruciate ligament, PCL, on the medial condyle of the femur, far anteriorly. Both insert on the tibia, the ACL in the area intercondylaris anterior and upwards on the steep side towards the medial tubercle (area 10, see (1)), the PCL deep in the area intercondylaris posterior (area 13 (1)). Thus, these ligaments cross each other in both planes, in the normal anatomical position of the body. The ACL is lined with a thin layer of synovial membrane distally in the joint, a somewhat thicker layer anterosuperiorly. The PCL is lined anteriorly with a thicker synovial layer. Both ligaments consist of innumerable fibres of varying course, determining the very complicated function of these ligaments. Owing to the arrangement of these fibres, parts of the ligaments are always taut, both in flexion and extension. Only the ACL is totally relaxed in a given position of flexion and external rotation of the tibia in relation to the femur (Lanz and Wachsmuth 1938). Both ligaments can be divided into two parts (Weber and Weber 1836, Fick 1911, Brantigan and Voshell 1941, Spalteholz 1953, Girgis et al. 1975). The ACL can be divided into: (a) posterolateral fibres which are taut in extension (Fig. 4) and slack in 90° flexion (Fig. 5). These fibres again tighten on further flexion (Fick 1911). However, the latter is of no significance in gonylaxometric measurements. (b) anteromedial fibres which are taut in 90° flexion and also taut, but not quite as taut as the posterolateral ones, in full extension of the knee (Fick 1904, 1911, Lang and Wachsmuth 1972, Furman et al. 1976) (Fig. 4). In external rotation of the 90° flexed knee the cruciate ligaments get untwined (Palmer 1957), and as the tibia rotates outward the origin and insertion facets of the ACL gradually approach the same sagittal plane. This phenomenon has also been illustrated by Spalteholz (1953, Fig. 213 a). In internal rotation of the tibia the opposite occurs, the ligaments tightening and twining. This phenomenon influences examination in the gonylaxometer in different positions of rotation and also in the Slocum and Larson (1968) clinical test for external rotatory instability in the presence of injury to the medial collateral ligaments. When the cruciate ligaments are lax in external rotation of the tibia they do not inhibit the forward displacement which occurs in the presence of this ligamentous injury on traction on the proximal end of the tibia.

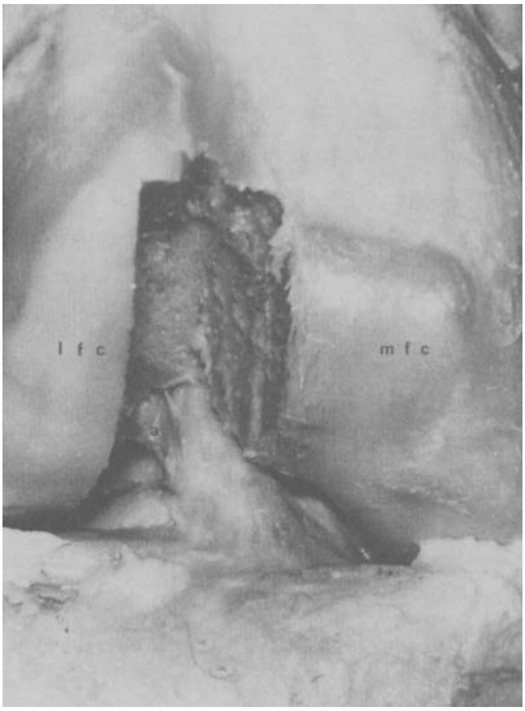

Figure 4: Photo of one of the present author's preparations of a right knee joint in extension, anterior view. A block of bone has been chiselled off the lateral femoral condyle(lfc), so that the anterior cruciate ligament is visible in its entire extent from the origin on the posteromedial edge of the lateral condyle of the femur to the insertion on the area intercondylaris anterior tibiae. Medial femoral condyle (mfc). Note the fairly well-defined bundles of fibres: (a) the posterolateral and (b) the anteromedial. Both bundles are taut. The posterior cruciate ligament is not visible in this position of the knee joint.

The PCL can be divided into an anterior and a posterior fibre bundle. The anterior fibres are lax in full extension, but taut in increasing flexion to become completely taut at 90°. The posterior fibres are taut in extension and laxer in flexion (Fick 1904, 1911).

3 c: Menisci

The menisci are of semilunar shape when viewed from above, the lateral one in fact almost quite circular (Fick 1904). They consist of fibrous cartilage

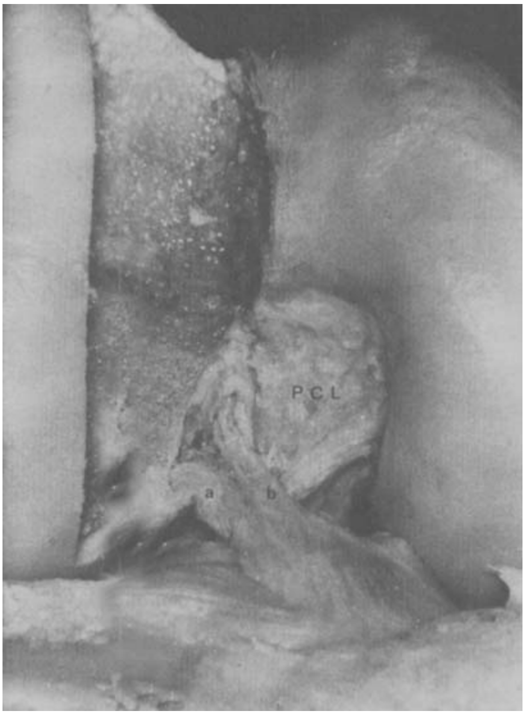

Figure 5: The same knee joint as in Fig. 4, but in 90° flexion. From the left: The posterolateral fibres of the anterior cruciate ligament are very lax (a), and the anterior fibres are more taut (b). The posterior cruciate ligament (PCL) is very taut. It is the anterior part of the posterior cruciate ligament which is visible here. For details of the posterior part of this ligament, cf. e.g. Girgis et al., p. 224.

and are vascularized only in the periphery (Pfab 1927). The medial meniscus, MM, attaches anteriorly on the area intercondylaris anterior, in front of the insertion of the ACL. The anterior horn of the lateral meniscus, LM, has a considerably smaller area of attachment more centrally and laterally on the area intercondylaris anterior. Anteriorly the two anterior meniscal horns are often connected by a transverse band. The most medial of the insertion fibres of the LM nearly always intertwine anteriorly with the most lateral insertion fibres of the ACL (Fick 1904). The posterior horn of the MM attaches on the posterior edge of the medial tubercle, that of the LM posteriorly on the lateral tubercle and at the top of the entire crista intertubercularis. Also, the posterior horn of the LM attaches on the medial femoral condyle by two, at times only one, fibrous band proceeding upwards on the posterior and anterior aspects of the PCL and finally intertwining with the PCL fibres. They are known as the ligamenta menisci lateralis (Robert 1855, Humphry 1858, Spalteholz 1953). The menisci are of great importance to the stability of the knee joint and enter into intimate connection with its ligamentous apparatus. Fibrous strands from the popliteal muscle attach on the posterior edge of the LM (Last 1950, Kaplan 1962). The fibrous connections pull the menisci backwards in flexion, the posterior edge of the menisci adapting themselves to the femoral condyles, so that they are not squeezed beneath them. The edge of the LM is free where it passes the popliteal tendon, but farther anteriorly it is attached to the capsule (Hughston et al. 1976 I) just as the MM is attached medially by the DMCL and OMCL. Micro-anatomical studies of human knees by Oretorp and Risberg (1978) have demonstrated that the attachment is by fibres coursing direct from the ligaments into the substance of the meniscus in a V-shaped figure in the peripheral part of the meniscus. Therefore, meniscectomy may interrupt the connection between the proximal and distal part of the DMCL and the OMCL, compromising the function of these ligaments. Thus, part of the meniscal substance enters into the named ligaments.

Function: The menisci play a role in the transmission of weight in the knee joint. In human knee joints about 45% of the weight is borne by the menisci as shown by Shrive et al. (1978) in experiments on human specimens. Furthermore, removal of the MM weakens the tensile strength of the SMCL by about 10% (Oretorp et al. (1978) in experiments on dogs), and this ligament as well as the LCL show instability. Rotatory instability too occurs as demonstrated by Nicholas (1973 b) and by Wang and Walker (1974) in human knees.

The menisci move forward in extension and backward in flexion. The gliding movement between the menisci and tibia combined with the rolling movement of the femoral condyles on the menisci and tibial condyles in the "menisco-femoral joint chamber" takes place simultaneously with rotation on one or more vertical axes. The lateral meniscus is more mobile than the medial one, taking part in the wider movement of rotation in the lateral joint chamber in positions of flexion (Winslow 1719, Fick 1911).

3 d: Joint Capsule

The capsule consists of an outer fibrous capsule and an inner synovial membrane. The latter forms the synovial fluid and thereby nourishes part of the intraarticular cartilaginous structures. The synovial cavity and its recesses have been described by Lindblom (1938) and by Brantigan and Voshell (1941).

3 d 1: The medial fibrous capsule is described as two layers, an inner and an outer one. Between the two the anterior part of the SMCL slides freely. The outer layer consists of connective-tissue fibres from the vastus medialis muscle and of the medial patellar retinaculum (Lanz and Wachsmuth 1938, Fig. 187). The inner layer may be divided into 3 approximately equal parts (Fig. 2). The anterior third is made up of a thin layer of collagen fibres, the middle third of the DMCL, the posterior third of the OMCL and its intertwining with capsular fibres (Slocum and Larson 1968, Hughston and Eilers 1973). Thus, the latter two ligaments can be considered fortified strands in the inner layer of the medial fibrous capsule.

3 d 2: The lateral fibrous capsule has only one layer, viz. collagen fibres from the vastus lateralis muscle intertwined with the iliotibial tract which is a palm-wide fortification in the fascia lata inserting on the tubercle of Gerdy (Fig. 3). As on the medial side there is intertwining with the lateral patellar retinaculum (Lanz and Wachsmuth 1938, Fig. 189).

The iliotibial tract also sends fibres to the lateral condyle of the femur just proximally to the lateral epicondyle. By virtue of strong, arcuate fibres from the latter to the tubercle of Gerdy, this part of the iliotibial tract acts as an accessory ligament on the lateral aspect of the knee (Kaplan 1958) (Fig. 3). The medial and lateral capsules of the knee joint act as part of its extensor apparatus.

3 d 3: The posterior capsule of the knee joint is very strong. It is strengthened posteromedially by the tendon of the semimembranosus muscle which, after dividing, sends across the posterior surface of the joint a part forming the oblique popliteal ligament. At the posterolateral site, this ligament mixes with fibres from the deeper arcuate ligament.

Function: In extension the posterior capsule tightens, while it slackens in flexion, increasingly with its degree. It affords no resistance to displacements in the anteroposterior direction in normal 90° flexed knees (Palmer 1938, Hallén and Lindahl 1965 a).

3 e: Muscles

The muscles and tendons which pass the knee joint exert a stabilizing effect upon it. The extensor apparatus of the knee joint consists of the quadriceps femoris muscle, its tendon, the patella, the medial and lateral patellar retinacula, and the inferior patellar ligament.

Function: The extensor apparatus carries out knee extension right to the final phase in which the knee is locked by an external rotation of the tibia in relation to the femur, the so-called "final rotation" or the "final supination" (Barnett 1944, Last 1948). The final supination amounts to 5° during the last 10° of extension (Fick 1911).

The sartorius, gracilis, and semitendinosus muscles, which insert in the pes anserinus (Fig. 2) belong to the flexors of the knee (mainly the semitendinosus). They are also internal rotators - and as such stabilize against external rotation (mainly the sartorius and gracilis). The effect increases with flexion of the knee and with external rotation of the tibia in relation to the femur, the so-called "wind-up effect" (Noyes and Sonstegard 1973).

The semimembranosus muscle inserts posteromedially on the knee joint by a very strong tendon divided into several branches: a direct, vertical one on the medial tibial condyle (Kaplan 1957), a branch curving from it forward beneath the pes anserinus and SMCL, a third one curving backward in the fascia overlying the popliteal muscle, and lastly a branch curving upward-backward in the form of the oblique popliteal ligament. Thus, the insertion of this muscle greatly strengthens the fibrous capsule of the knee joint posteriorly. The popliteal muscle strengthens the postero-lateral capsule by its insertion into this capsule, the LM, and the arcuate popliteal ligament (Last 1950). The plump part of the popliteal tendon, which inserts on the lateral epicondyle of the femur, also has a rotatory function, rotating the tibia inward (Last 1950). On the posterior aspect of the knee there are the origins of the medial and lateral gastrocnemii and the plantar muscle. On the lateral side the biceps femoris inserts on the head of the fibula. The vastus lateralis and the overlying iliotibial tract have been mentioned already. The biceps is a knee flexor and external rotator, especially in flexion. The iliotibial tract is primarily a stabilizer of the knee joint (Kaplan 1958).

3 f: Innervation of the Knee Joint and Comments on Its Active and Passive Stabilizers

In the cruciate ligaments and in the medial collateral ligament Skoglund (1956) has demonstrated nerve endings presumably concerned with proprioceptive, afferent impulses and which record the position of the joint. Vater-Pacini-like corpuscles in the capsule presumably record deceleration and acceleration in the joint. Skoglund's findings have been confirmed by Freeman and Wyke (1967). Adrian (1943) has demonstrated cerebellar areas having a function in regulating synergists and antagonists as well as muscle tone around the knee joint. The three studies just mentioned were performed on decerebrate cats.

Kennedy et al. (1974), studying the course of the nerve fibres in the anterior cruciate ligament in man, found the ligament to be a multifascicular structure with looser connective tissue in between the fascicles. In the loose connective tissue they found vessels and nerves in close relation to each other, indicating that the nerve branches might have a vasomotor function. However, there were also nerve branches situated separately, presumably conveying impulses such as pain from the cruciate ligaments. It has not yet been possible to demonstrate the passage of impulses through the entire reflex arc. Palmer (1958) is presumably the worker who has got closest to demonstrating such a passage of impulses by electromyographic studies using ligamentous stimulation during operations on man.

The nerve supply of the ligaments influences the way in which a partially ruptured ligament, a so-called passive stabilizer, is protected by the patient's own, active muscular stabilizers, both during an examination and during a further stress. It is of decisive importance to the function of the "kinetic chain" described by Payr (1927) that intraligamentous nerve fibres are demonstrable. And there is then an explanation, viz. the reflex arc, of the almost spastic condition of the muscles surrounding the knee in case of partial ligamentous rupture - and the striking absence of this condition in total ligamentous rupture, as demonstrated by Palmer (1938).

Chapter 4

PRESENT ANATOMICAL STUDIES

These investigations were performed on 13 fresh and 75 macerated human knee joint preparations (1). They were started shortly after the first pilot studies+) of the gonylaxometer, as Kennedy and Fowler's (1971) identification of the tibial condyles on the lateral view seemed insufficient. The area intercondylaris tibiae with the medial and lateral tubercles of the intercondylar eminence appeared to constitute applicable landmarks. The transition of these structures into the posterior surfaces of the tibial condyles rendered possible an identification of the contours of the lateral and medial tibial condyles on lateral films (1).

The medial tubercle starts ascending farther anteriorly than does the lateral tubercle, and as a rule it is taller. It has only one peak from which the posterior wall slopes steeply downwards, towards the deep area intercondylaris posterior and towards the medial tibial condyle, reaching its horizontal surface far anteriorly to the posterior condylar edge. The lateral tubercle usually has two peaks and proceeds, in an even curve, into the posterior surface of the lateral tibial condyle. This arcuate, biphasic contour is well-suited for identifying the lateral tibial condyle on the film (1), also during rotation (2). The posterior part of the medial tibial condyle presents itself as a slightly concave contour.

The description of these structures is most important to the measuring method of gonylaxometry.

Perusal of the anatomical textbooks, however, disclosed divergent descriptions of the area intercondylaris by Hamilton (1956), Gray (1962), Hollinshead (1964), Frazer (1965), Cunningham (1972), and Lang and Wachsmuth (1972). Therefore, further studies were conducted. The most detailed of the earlier studies, those of Robert (1855) and Parsons (1906), had not found their way into the textbooks.

The first of the present studies (1) showed that the area could be sub-divided into 15 parts, and it showed also that for each insertion of the cruciate ligaments and menisci, and for other soft-tissue attachments, there is a corresponding bony surface structure which is also identifiable on macerated bone preparations. Certain small areas lined with thin cartilage, which articulate only with the meniscal horns, were described for the first time. An accurate knowledge of the various areas of insertion may be of

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+) These pilot studies will not be further mentioned here. They were conducted before the investigations of 100 normal subjects to be described below.

diagnostic importance when the radiographs of the knee joint show intraarticular avulsions of bone. In the present investigations certain findings of this nature were considered to contra-indicate stress radiography (vide infra).

It has often been stated that the PCL is stronger than the ACL, e.g. by Humphry (1858). This is because the PCL, at the level of the LM, receives one or two strong reinforcement bands from the meniscus, the ligamenti menisci lateralis. It has been demonstrated by the present author, using computerized planimetry, that the circumference of the PCL distally is in the same order as the distal part of the ACL, the insertion areas on the tibia being, on the average, equally large (1). This is another finding which has not been reported previously.

Chapter 5

PRESENT STRESS RADIOGRAPHIC STUDIES: METHOD

5 a: Introduction

The laxity or stability to be measured by gonylaxometry bears relation to the structure of the intact ligaments (cf. Chapter 3 b). Under normal conditions the ligaments possess a certain laxity in all positions except full extension. Great force is required for stretching the ligaments beyond their normal length, and it leaves permanent deformation. Measurement of a deformation rate or the reverse concept "stiffness" at the breaking point is not clinically relevant and not intended in the gonylaxometric method.

In measurements on injured knees, it is important to avoid tearing fibres which are still intact, and therefore fairly little force is applied.

5 b: Definitions

The knee is extended in the position in which there is resistance to further extension. This applies to uninjured knees. An injured knee has to be compared with the contralateral knee. *All other positions* will be *designated by the angle between the femur and the tibia.*

External rotation in the knee joint signifies external rotation of the *tibia* in relation to the femur on a longitudinal axis through the tibia through the medial tubercle (accurate position not stated). This movement may also be called supination in the knee joint.

Internal rotation in the knee joint, in analogy, signifies an inward turning of the *tibia* in relation to the femur and may also be called pronation.

This nomenclature is in accordance with Meyer (1853), Ross (1932), and Hallén and Lindahl (1965 a, b).

Total ligament rupture is taken to mean that all fibres of the ligament are torn and displaced from each other. The term applies to each ligament separately. Thus, each of the three medial collateral ligaments is considered a unit. If some of the collagen fibres of the ligament are intact, the rupture is designated *partial*.

Medial instability signifies laxity and a possibility of rocking movements, the tibia being movable farther laterally than normal in relation to the femur, viz. instability on the medial side of the knee (valgus instability, abduction instability). In the present study this phenomenon was always measured starting at an angle of 160° between the femur and tibia. The space, parameter c, on the a-p radiograph is defined here as medial instability (Fig. 9).

Lateral instability, correspondingly, signifies an increased possibility of rocking movements because of laxity on the lateral side of the joint. This means an increased possibility of moving the tibia inward in relation to the femur (varus or adduction instability). The starting position and measurements are as described above. Here, parameter d is defined as lateral instability (Fig. 9).

Anterior drawer sign signifies a possibility of moving the tibia farther forward than normal in relation to the femoral condyles, the starting point being a neutral position of the foot and 90° flexion in the knee (vide infra). The measurements are done on the lateral radiograph.

Posterior drawer sign, correspondingly, signifies a possibility of moving the tibial condyles backward more than normal in relation to the femoral condyles. Same starting position.

Forward or backward movement of the tibial condyles within the range of normal is called merely displacement. This term will also be preferred for abnormally marked shifts when the starting position is different from neutral position of the foot and 90° flexion of the knee.

DEFINITIONS IN RELATION TO ROTATION IN THE KNEE JOINT:

Movements of rotation are possible in any position of knee flexion, and the range of the total rotation depends upon the degree of flexion.

Rotatory instability is defined as a possibility of rotation which exceeds the normal limit to rotation (internal or external) in the knee joint at the given degree of flexion in the joint.

Simple rotatory instability is taken to be an abnormally marked rotation without the co-existence of a drawer sign.

Complex rotatory instability is taken to be rotation co-existing with a drawer sign, i.e. a very pronounced and also unequal displacement of both tibial condyles.

The term complex instability will be used in this paper only to signify rotatory instabilities examined in 90° flexion of the knee, and thereby the definition differs from that of Nicholas (1973 a) (Fig. 1).

Anteromedial complex rotatory instability is present, on traction on the tibia, when both tibial condyles move so far that there is an anterior drawer sign as well as extra anterior displacement of the medial tibial condyle in relation to the lateral one. This gives rise to external rotation.

Anterolateral complex rotatory instability: Anterior drawer sign plus an extra anterior displacement of the lateral tibial condyle (internal rotation).

Posteromedial and posterolateral complex rotatory instability: Posterior drawer sign plus a further backward movement of the medial or lateral tibial condyle.

5 c: The Gonylaxometer and Selection of the Force Applied

5 c 1: Apparatus:

This is an apparatus for application of forces to the lower limb, not a measuring apparatus per se. As such it would have the same drawbacks as other externally fastened apparatuses: A shift of the soft tissues, especially the femoral muscles, subcutaneous tissue, and skin beneath the fastening appliances, and this would make it impossible to read with accuracy displacements in the knee joint. Therefore, it is equipped with cassette holders for X-ray films and operates in combination with an X-ray tube suspended from the ceiling, and the actual reading of knee stability is made on the X-ray films after exposure (3).

The apparatus (Fig. 6) is mounted on a steel frame with an aluminium floor and four wheels. The central part of the floor can be raised and lowered to adapt to the lower-leg length in a person placed with 90° flexed knees for anterior or posterior stress upon the lower limb. This trolley is fitted with a dental chair for the patient to sit in. The arrangement makes it possible to raise and lower the chair, rotate it, and move it anteriorly or posteriorly - also to adapt to the person's dimensions. Anteriorly on the seat there are semicylindrical, cup-shaped steel thigh supports with a rigid canvas cuff and an inflatable cuff (Fig. 6). Beneath and between the thighs there are cassette holders for X-ray films. Anteriorly the trolley has a control panel with handles for guiding the various actions, a regulator valve for controlling the pressure, and a manometer. The panel has an electrically operated hydraulic pump which operates three oil pressure cylinders. Two of the latter operate slides on ball bearings, controlled by rails in the panel, mounted with fastening gear and boots intended for valgus and varus stress upon the patient's legs (Fig. 6). The latter too can be adjusted to different lower-leg lengths. The third cylinder is mounted on rails, so that it may be moved to be in front of the patient's right or left knee. At this site it is to act upon the proximal end of the tibia, by traction, for measuring anterior stability or by pressure in measuring posterior stability. Fixation is by a canvas cuff connected to the cylinder by a piston rod and by boots on the floor. A grading scale on the floor

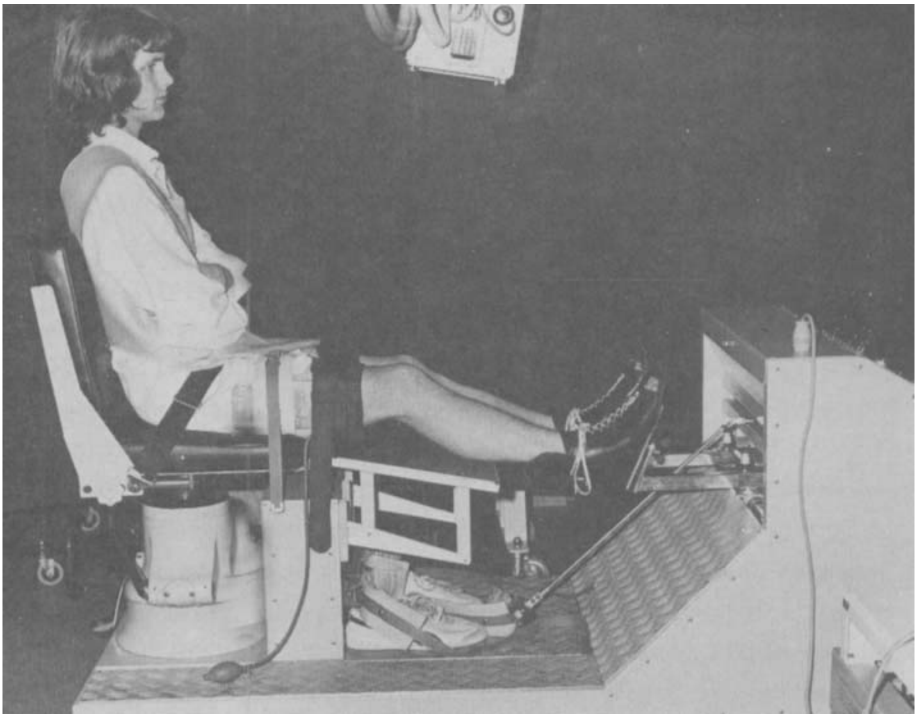


Figure 6: The gonylaxometer with the patient and X-ray tube in position for an exposure to visualize medial and lateral instability. Note the cassette holder beneath the patient's knees.

indicates the position of the foot. Boot and foot can be fixed in the way that the second metatarsal bone points forward in the direction of the traction or pressure, zero or neutral position, or into various positions of internal or external rotation.

Let it be stressed that the pressure generator is double-secured. A fixed position of a valve guided by a steel spring prevents the pressure in the cylinder from exceeding 30 kilopond (kp). Moreover, the pressure cannot be released until two electric switches have been turned on, both of them interposed only for safety. Thereafter, the pressure is slowly raised by a manually operated regulator valve, and action is slowly exerted upon the joint while the operator is simultaneously reading the pressure on the manometer. About half a minute passes until the joint has reached its extreme position. This is unlike the sudden stress in other methods, e.g. that of Markolf et al. (1978).

The transition from taking lateral views of one knee during traction and pressure and to the same exposures of the other knee is facilitated by the fact that the entire steel frame can be raised and turned 180° on a central swivel foot. The axis of this swivel foot coincides with that of the vertical film cassette midway between the patient's knees. Thus, it is unnecessary to move the X-ray tube.

5 c 2: Discussion on selecting the force of the action:
When the method was developed, the following statements on the stress that should be applied to the knee were available: Ouellet et al. (1968) had advocated a static traction using weights over pulleys. For valgus and varus actions they used about 1/8 of the subject's body weight, i.e. 9 - 10 kg for adults and presumably weights in the same order of magnitude for traction and pressure upon the 90° flexed knee. An unknown part of the weight is borne by the pulley system. Kennedy and Fowler (1971) used 244.74 kiloNewton per m^2 (kN/m^2), which is 35152 kp/m^2 or ~3.5 kp per cm^2. Since, however, they do not state the diameter of the gas cylinders, the final pressure is unknown.

In the gonylaxometer the cross section area of the piston is 1 cm^2, equal to the lumen of the cylinder. For adduction and abduction the pressure in the cylinder is 9 kg per cm^2, equivalent to the total pressure of the piston at its target point. This is the pressure which is read from the manometer. If greater force is used, the pressure is uncomfortable for the patient, cf. (3), (4), and Addendum I. In this examination there is a rotatory moment of force (lower-leg length x the force applied), but also a loss of force in the foot fastening gear. In the same person, however, these values are constant from one examination to another. On anterior or posterior stress upon the 90° flexed knee there is no rotatory moment of force, the point of action being the middle of the head of the tibia straight in the direction of the force. The force is that read from the manometer: 20 kp in fairly small persons, later increased to 30 kp, as this proved necessary to overcome the resistance of the quadriceps, biceps, and pes anserinus muscles in muscular persons (3), (4). Thus, the abduction and adduction pressure corresponds approximately to the static pressure used by Ouellet et al. (1968), the point of action being the same.

In the gonylaxometer the anterior and posterior stress appears to be somewhat higher than in Ouellet's (1968) as well as in Kennedy and Fowler's (1971) methods. In a person weighing 60 kg 20 kp is 3.27 N per kg body weight. At a 30 kp action: 4.01 N per kg body weight, cf. Addendum I, p.

These loads may be compared to those maximally tolerated in animal experiments. Noyes et al. (1974) used rhesus monkeys. In experiments on their ACLs in situ the maximum load at the yield point was about 100 kp, equal to 981 N or 124.18 N per kg body weight. Noyes and Grood (1976) demonstrated that in the rhesus monkeys the CL are stronger than in man. They had a sectional area 2.3 times that in man per kg body weight, and the strength of the ligament per area unit was about twice that in young people. Neverthless, the force applied in the gonylaxometer is far below the permissible peak loads. In Scandinavia Alm et al. (1974) demonstrated a mean tensile strength of the ACL of dogs of 59.4 N per kg body weight. The strength decreased upon simultaneous rotation of the tibia in relation to the femur. Kennedy et al. (1976) tested ligaments of human cadavers (age unknown) dissected from their bony attachments, which must be presumed to have reduced their tensile strength. They found the following total strengths: Load at time of rupture about 50 kp for the ACL and about 50 kp for the SMCL, 100 kp for the PCL.

5 d: Radiographic Technique

5 d 1: Set-up: The radiation source is a telescope-suspended X-ray tube on rails in the ceiling. Further, the tube can be rotated and tilted, and its inclination can be read on a scale. The distance from the film cassette to the outer filter of the tube is kept constant, 1 m, the distance to the centre of the radiation source about 1.25 m. The central beam is always at right angles to the cassette. Cassettes with a raster are used.

5 d 1.2: Exposure: The exposures are done using about 50-60 kV and 60 mAs, exposure times 0.16 to 0.20 sec. The number of exposures in the most intense experimental series reached 27 exposures per subject. The gonads, trunk, and upper part of the thigh are always shielded.

5 d 1.3: Magnification on the film was measured by 21 measurements on subjects in the anteroposterior and lateral views by the aid of short metal wires placed on the skin over various juxta-cutaneous bony prominences in the knee joint. Bony parts close to the film show less magnification than those far from the film: Range (21 measurements) 1.03 - 1.15, mean 1.08 $\approx 1.1 = \frac{11}{10}$ (or a 10% magnification on the film). In this paper no correction is made for the magnification. Thus the parameters given are distances measured direct on the film.

5 d 1.4: Positioning of the subject during measurement: Measurements were made in two positions:

(1) In measuring abduction and adduction instability (medial and lateral instability respectively) the knees are 20° flexed. The exposure is made with anteroposterior direction of the beam of both knees at the same time. The starting position, in which the knees are unloaded and feel

relaxed, the feet 5 $^{\circ}$ outward rotated in relation to the anatomical normal position, is called: neutral position 160°.

(2) For measuring anteroposterior instability the knees are 90° flexed. The exposure is in the lateromedial projection of each knee separately. The starting position, with the foot resting on the floor of the trolley and with the patellar apex, tibial tuberosity, and the second metatarsal bone in a vertical plane through the tibial axis, is called: neutral position 90°. The second metatarsal bone points forward in the longitudinal direction of the apparatus, i.e. in the direction of traction.

In measurements with 90° flexion in the knee and rotation in the ankle joint, the rotation of the foot is given in degrees outward (15° and 30°) or inward (30°) from the position just defined. This provides accurately adjusted and reproducible X-ray films.

In examining for abduction and adduction instability, the cassette hold with the film cassette (30 x 40 cm) is placed beneath the patient's knees (Fig. 6) and the X-ray tube at the above-mentioned distance above the cassett The tube is tilted 10° in relation to the horizontal plane, like the cassette The central beam, tilted 10° in relation to the vertical plane, is at right angles to the cassette and directed midway between the patient's knees. Then by, the thigh and lower leg form a flat, isosceles triangle with a vertical angle of 160°, base angles of 10°, and the baseline at the plane of the cassette. The perpendicular bisector to the baseline is at the same time the bisector of the vertical angle and its direction is that of the central beam.

In lateral projections to detect anteroposterior instability or rototory instability the X-ray tube is lowered to about 60 cm above the floor, these exposures being made with horizontal beam. A cassette of 24 x 30 cm is placed midway between the patient's knees. The beam is latero-medial in relation to the knee concerned, at right angles to the cassette. In this set-up exposures have to be made of each knee separately (Fig. 7). The position of the X-ray tube may be maintained, the gonylaxometer being turned 180° on the centre of the cassette, by means of the swivel foot.

5 d 2: Measurement of parameters on the X-ray films. Radiographic anatomy. Landmarks:

5 d 2.1: Measuring technique on the films: The measurement is made with the film on a horizontal viewing box illuminated from below. Two transparent celluloid films, with thin lines scored at right angles to each other, are placed on top of the X-ray film in relation to further defined

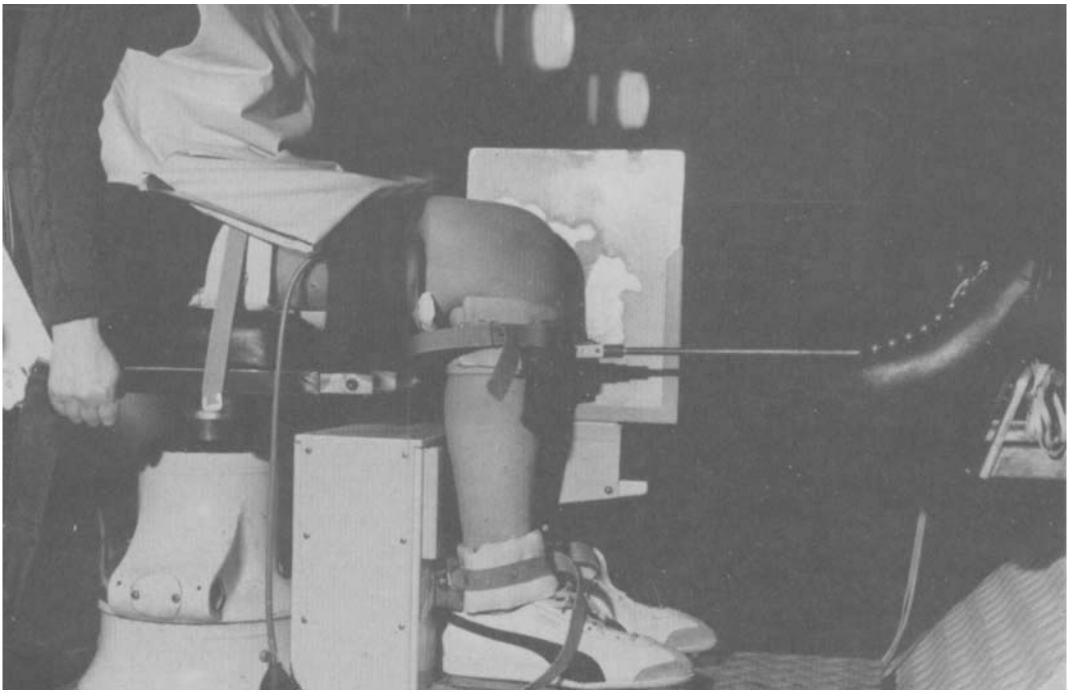


Figure 7: Piston shaft for anterior and posterior stress actions upon the head of the tibia. The fastening cuff of the piston shaft is passed around the proximal part of the lower leg. The subject is in the "neutral position 90°" before the procedure is started. Rotation of foot 0°. The cuff around the thigh has been inflated.

landmarks. These landmarks were fixed by radiographic-anatomical studies (1) and (2).

5 d 2.2: The radiographic anatomy is described separately for the lateral and for the a-p views, dealing with the contours traced on the two-dimensional picture of the three-dimensional object.

The contours on the lateral view are traced on Fig. 8. The large guiding ridge for the patella on the lateral femoral condyle lends it a larger contour , with the limiting groove located approximately in the middle. The groove on the medial femoral condyle is seen more anteriorly and proximally located, only 1/3 to 1/4 down the curve. The limiting grooves are the best landmarks for identifying the femoral condyles. The appearances do not alter upon changing from lateromedial to mediolateral beam or upon rotation (2).

Figure 8: Contours on the lateral view of the right knee in the neutral position, unloaded. Note that in this case the medial articular socket of the tibia is of a considerably higher situation than the lateral one. On the right, graphic presentation of the contours: Broken lines: Lateral condyle of femur, lateral condyle of tibia, lateral tubercle. Solid lines: Medial condyles of femur and tibia, medial tubercle of intercondylar eminence, tibial tuberosity, and tibial shaft. Dash-and-dot lines: Distally: Posterior margin of intertubercular crest of the eminence continuing in the area intercondylaris posterior of the tibia. Proximally:

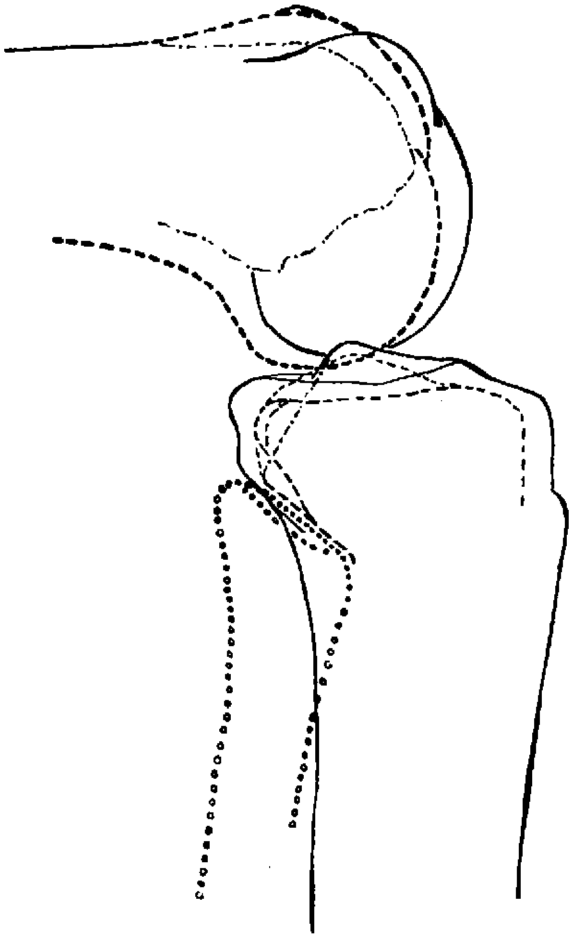


Figure 8

Femoral articular surface for the patella and the "roof" of the fossa intercondylaris femoris. On the lateral view this latter line is named "Blumensaat's line". Small circles: Fibula. Note how clearly the joint is seen between the lateral tibial condyle and the head of the fibula on this radiograph (and on the graphic presentation).

Note the landmarks: for the lateral femoral condyle (limiting groove - Grenzrinne - sulcus condylopatellaris) around the middle of its curve, for the medial femoral condyle just after the upper third of the curve, for the lateral tibial condyle the direct junction with the contour of the lateral tubercle.

The femoral articular surface for the patella may be traced as a strong contour behind the proximal curves of the femoral condyles. After an angulation of about 90°, it continues in a strong, slightly irregular contour representing the "roof" of the fossa intercondylaris femoris. On the lateral view the latte contour is called Blumensaat's line (1938). Its anterior point, the peak of t angulation, is the landmark for the most anterior part of the origin of the PC The posterior angulation is the landmark for the most posterior part of the origin of the ACL (2). Behind these contours the ossified epiphyseal line is visible. These three lines form Ludloff's triangle (1903).

The lateral tibial condyle may be identified by following the lateral intercondylar tubercle which continues, from its peak, backwards in an evenly convex arch, unlike the medial tubercle which slopes steeply down backward from its peak. The convex arch of the lateral tubercle proceeds direct into the posterior contour of the lateral condyle of the tibia (1). The contours of the socket of the lateral condyle are one or more, slightly convex or horizontal lines continuing posteriorly in a curve down into the posterior contour of the condyle which is more pointed and narrower than that of the medial one.

The proximal posterior corner of the medial tibial condyle does not continue in the contour of the medial tubercle, but is formed by the junction of the two arcuate contours of the central and medial margins of the socket. This point is always identifiable (point B on Fig. 11). The medial socket is concave and more retroverted than the lateral one, so that its anterior part is at a higher level. The long concave line can be traced from point B in the anterior direction right to the beginning of the medial tubercle (point A on Fig. 11). The anterior, A, and posterior, B, points of this line serve as landmarks for setting up a baseline, gl, on Fig. 11. On this line the parameters on the lateral film are measured. In the "neutral position 90°" as well as in rotation the posterior arcuate contour that can be traced from the lateral tubercle should be used as a landmark when measuring the parameters and so should the proximal 1 cm of the posterior arch of the medial condylar contour. The fact is that these two are the easiest contours to follow during rotation.

On the anteroposterior films in the "160° position" the femoral condyles always present each as a sharp convex contour, well-suited for placing a connecting line, "tangent" l_1, Fig. 9, through the two distal points. In between, the fossa intercondylaris presents as a concavity. Approximately parallel with the concave arch of the fossa there is the arch of the inter-

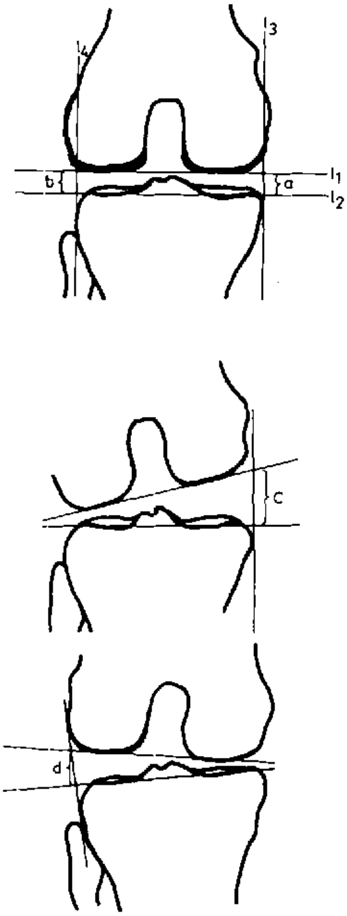


Figure 9: Placing measuring lines on the a-p film and reading of parameters. Top: without load. Centre: abduction. Bottom: adduction. The lateral aspect of the joint is indicated by the head of the fibula. From (4): Acta Radiologica, Diagnosis 18 (1977) 113-125.

condylar eminence, biphasic in the great majority of cases, the medial and lateral tubercles being clearly distinguishable. In a few cases, however, the two tubercles form an even convexity. As a rule, the medial tubercle is taller (1).

The tibial condyles usually form two contours each, their margins - and the landmarks selected are the distal points on the distal contours. These landmarks are employed for placing the tangent, l_2, on Fig. 9. As a rule, these points are on the anterior edges because the knee is flexed 10° in relation to the central beam. Extra contours may occur, the tubercles continuing into the joint surfaces. Dense contours may also be seen beneath the joi surface, being formed by dense trabecular formations subchondrally. Empirically, the distal point of the medial tibial condyle can always be located. If the distal point on the lateral condyle cannot be located, l_2 is placed through the corner of the socket laterally.

The radiographic anatomy of the corners of the lateral and medial condyles is extremely varied. Therefore, special rules were needed for placing these measuring lines, l_3 and l_4, on Fig. 9. They are placed at a right angl to l_2, tangentially to the most medial point of the medial tibial condyle an most lateral point of the lateral tibial condyle respectively. The contours medially and laterally on the tibial condyles may be regular as in Fig. 9, but they may also be irregular as shown in Fig. 10: Instead of arching direc into the outermost point of the condyle, the cartilage-lined joint surface may be separated from it at its edge by a small incisure. If so, l_3 or l_4 is placed at the incisure or at the most prominent point just proximal to it. In placing the lines, no regard is paid to osteophytes, if present (4).

5 d 2.3: The following <u>parameters</u> were measured on the a-p view (Fig. 9): distance a, cut off on l_3 and distance b on l_4 applying to the unloaded knee joint in "neutral position 160°". Distance c, cut off on l_3 during valgus stress and distance d on l_4 during varus stress (3, 4). Then, abduction instability or "medial instability" may be expressed, as suggested by Kennedy and Fowler (1971): c-a and adduction instability or "lateral instability": d-b for each lower limb separately. Another possibility (3, 4, 5, 6, 7) is to tabulate the maximally possible distance between the condyles during stress, viz. c and d, in a material of normal, uninjured control persons (for use particularly in patients with bilateral injuries). Or else the differences in these distances between the right and left knee: $c_R - c_L$ and $d_R - d_L$ (for use in unilateral injuries which are by far the most common). The distances are measured by a Vernier gauge in mm with one decimal.

The parameters in the lateral view (4) are measured on the named baseline, gl, through points A and B on Fig. 11. All other measuring lines are at right angles to it. l_1 is placed as a "tangent" to the anterior con-

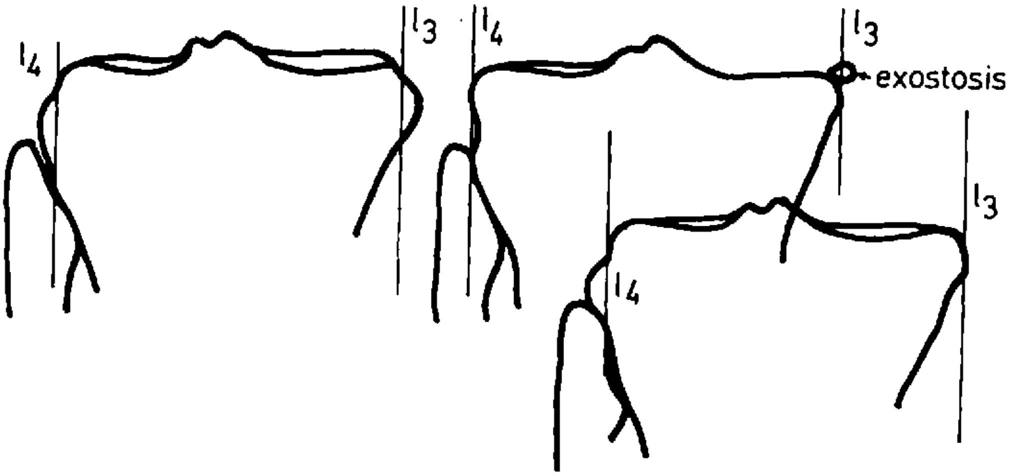


Figure 10: Different configurations of the tibial condyles in the a-p view to illustrate the rules for placing tangents l_3 and l_4 to the medial and lateral tibial condyle respectively at right angles to l_2 (cf. Fig. 9). Note l_3 drawn through osteophyte (exostosis) without paying regard to it. From: Acta Radiologica, Diagnosis 18 (1977), 113-125.

tour of the medial femoral condyle, and l_5 as a "tangent" to the anterior contour of the femoral articular surface for the patella. l_2 is a "tangent" to the posterior contour of the lateral tibial condyle, l_4 to the posterior contour of the medial tibial condyle. The proximal 1 cm of the posterior margin of this condyle forms a rounded arch; l_4 should be placed through the posterior edge of this arch. Point S is the point of intersection between the posterior contour of the medial tubercle and the baseline (gl).

Distance e is cut off on the baseline between l_1 and l_2, distance f betweel l_3 and l_4, and distance E between l_5 and point S on the lateral film of the unloaded knee. During forward stress on the tibia the corresponding distances are called g, h, and G respectively, and during posterior stress i, j, and I respectively. Distances e and g express the position of the

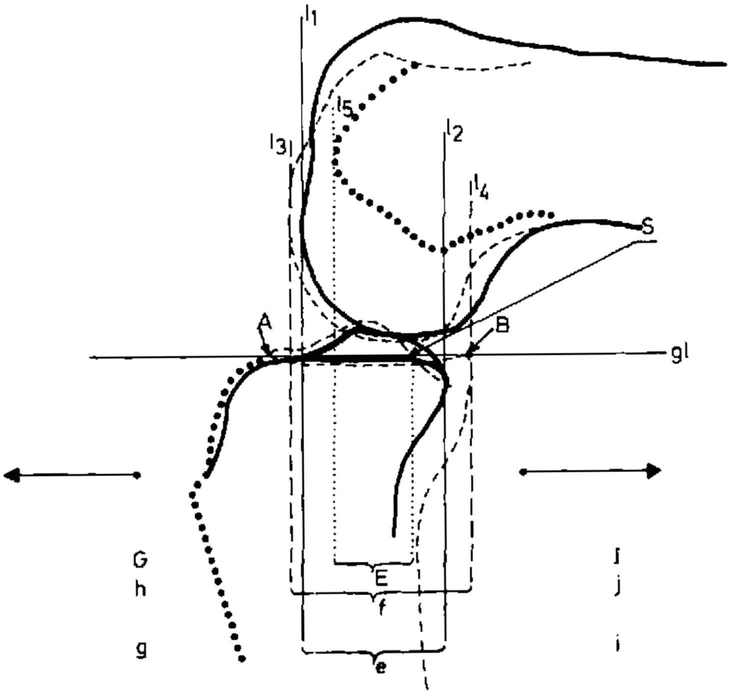


Figure 11: Contours of the knee joint and measuring technique on the lateral radiograph. Unbroken lines: Lateral femoral condyle, tibial condyle, and lateral tubercle. Broken lines: Medial femoral condyle, tibial condyle, and medial tubercle. Dotted lines: On the femur: Femoral articular surface for the patella and Blumensaat's line. On the tibia: Anterior margin, tuberosity, crest of area intercondylaris anterior. gl: Baseline through the anterior point, A, and the postero-superior point, B, of the medial tibial joint socket. S point of intersection between the posterior contour of the medial tubercle and the baseline. Lines l_1 to l_5 are at right angles to gl.

Distances E, f, and e are shown on the drawing as they appear on the unloaded joint. The corresponding distances during traction are indicated on the left: G, h, and g, during pressure on the right: I, j, and i.

From Acta Radiologica,Diagnosis 18 (1977), p. 118.

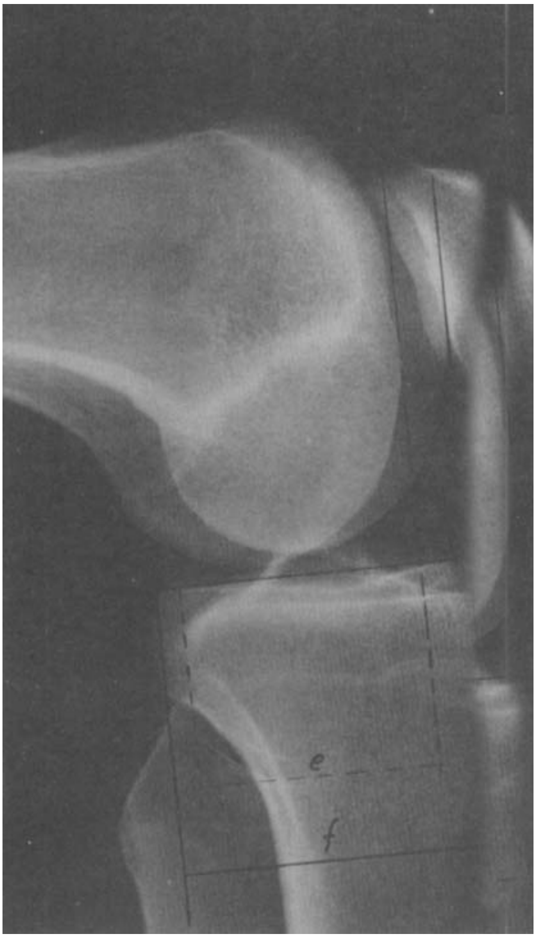
lateral tibial condyle in relation to the lateral femoral condyle, in the unloaded knee and during forward stress on the proximal end of the tibia (traction). Then, e-g signifies the forward displacement of the lateral tibial condyle during traction and, in analogy, f-h the corresponding forward displacement of the medial tibial condyle. E-G denotes anterior displacement measured between centrally situated points. Therefore, this distance is theoretically less affected by possible rotation in the joint. Table 1 gives a survey of the distances measured and the anteroposterior displacements. All calculations were carried out for the right as well as the left knee, and it is therefore possible to assess differences between the two sides.

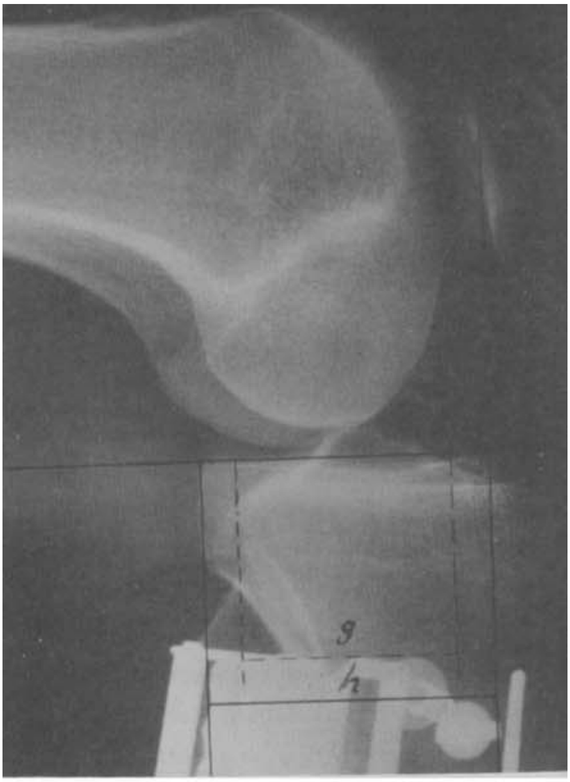
To express the total anterior displacement of the tibial condyle the method uses the mean of the anterior displacement of the lateral and medial condyles: ((e-g) + (f-h))/2. E-G is an approximate measure of the total anterior displacement. Correspondingly, the posterior displacement during pressure on the lateral tibial condyle is i-e, on the medial condyle j-f, the central tibial part (I-E), and the total posterior displacement ((i - e) + (j - f))/2. The formulae for the total anteroposterior displacement are given in Table 1.

5 d 2.4: Rotation as calculated from the parameters:

Parameters and measuring lines are shown on radiographs, Fig. 12. The above-mentioned rotation during traction and pressure actions in the normal knee joint may be seen from this figure merely by following the movement of the fibula.

During forward stress (traction) on the proximal end of the tibia the lateral tibial condyle in sound knee joints is seen to become considerably more displaced than the medial one. This indicates internal rotation of the tibia in the 90° flexed knee on a vertical axis (in the longitudinal direction of the tibial shaft). This rotation during traction is not equal to the maximum possible internal rotation of the tibia in relation to the femur (pronation) in the unloaded 90° flexed knee joint. The rotation during traction takes place with taut ligaments unlike the lax ligaments at rest which permit greater rotation. Expressed by parameters, this manifests itself in (e - g) > (f - h) in normal knees. On pressure there occurs: External rotation, supination, expressed by (i - e) > (j - f). Thus, the total anteroposterior movement is shown to be greater in the lateral than in the medial joint chamber, in accordance with centuries of anatomical knowledge (<u>vide supra</u>). The figure also demonstrates the change in parameter size


e
f


g
h

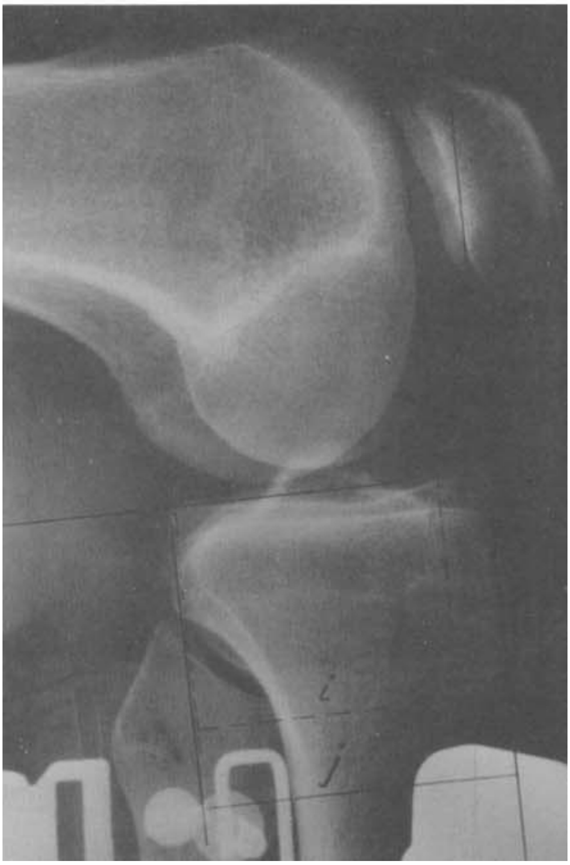

i
j

Figure 12: Radiographs of the unloaded joint (middle) and the joint during traction on the tibial condyles (drawer manoeuvre forward) (top) and pressure (bottom); position of foot neutral, i.e. rotation = 0. Measuring films furnished with lines at right angles to each other indicated in position for measurement. The measurements are normally made on the baseline, but in order to preserve the contours in the area measured e, f, g, h, i, and j are projected distally.

Note how the fibula moves forward on traction and backward on pressure in relation to the femur as well as tibia. The lateral tibial condyle moves in the same way in relation to the medial tibial condyle. In other words, the lateral tibial condyle moves most, i.e. a rotation is detectable with the naked eye: external on pressure and internal on traction (in accordance with the definitions of rotation in (6).

Moreover, it can be seen that $i > e > g$ and that $j > f > h$.

Table 1 Parameters measured on the lateral radiograph and formulae for calculating anterior and posterior displacement of the tibial condyles.

Distance between anterior points (on the femur) and posterior points (on the tibia)	Names of parameters and formulae for displacement
Measurements in "neutral position 90^{o}" (no stress on the knees):	
for lateral pair of condyles	e
for medial pair of condyles	f
for central points (1_5 and S)	E
Measurements during traction on the tibia:	
for lateral pair of condyles	g
for medial pair of condyles	h
for central points	G
anterior displacement of lateral tibial condyle	e-g
anterior displacement of medial tibial condyle	f-h
anterior displacement of central part of tibia	E-G
anterior displacement of proximal end of tibia (mean of lateral and medial condyles)	$\frac{(e-g)+(f-h)}{2}$
Measurements during pressure on the tibia:	
for lateral pair of condyles	i
for medial pair of condyles	j
for central points	I
posterior displacement of lateral tibial condyle	i-e
posterior displacement of medial tibial condyle	j-f
posterior displacement of central part of tibia	I-E
posterior displacement of proximal end of tibia (mean of lateral and medial condyles)	$\frac{(i-e)+(j-f)}{2}$
Total anteroposterior displacement:	
of lateral tibial condyle	i-g
of medial tibial condyle	j-h
of central part of tibia	I-G
of proximal end of tibia (mean of lateral and medial condyles)	$\frac{(i-g)+(j-h)}{2}$

from neutral position to decrease during traction and increase during pressure: for the lateral tibial condyle $i > e > g$, for the medial condyle $j > f > h$.

For rotation, the following formulae can be set up by the aid of the parameters already described (cf. also Addendum I):

As regards rotation without traction or pressure stress, Fig. 13, it applies in external rotation that distance e increases: $e_{\text{ext. rotated}}$ ($e_{\text{r ext.}}$ or $e_{15^{\circ}\text{ ext.}}$ etc.) $>$ e_{neutral} (e_n), the lateral tibial condyle moving backward. $e_{15^{\circ}\text{ ext.}}$ or $e_{30^{\circ}\text{ ext.}}$ indicates the rotation of the foot in circle degrees; rotation in the knee is considerably less. The formula $(e_n - e_{\text{r ext.}})$ is negative. The medial tibial condyle, on the other hand, moves forward in relation to the femoral condyle, so that parameter f decreases. Therefore, the formula $(f_n - f_{\text{r ext.}})$ is positive.

The reverse applies in internal rotation: $(e_n - e_{\text{r int.}})$ being positive and $(f_n - f_{\text{r ext.}})$ negative.

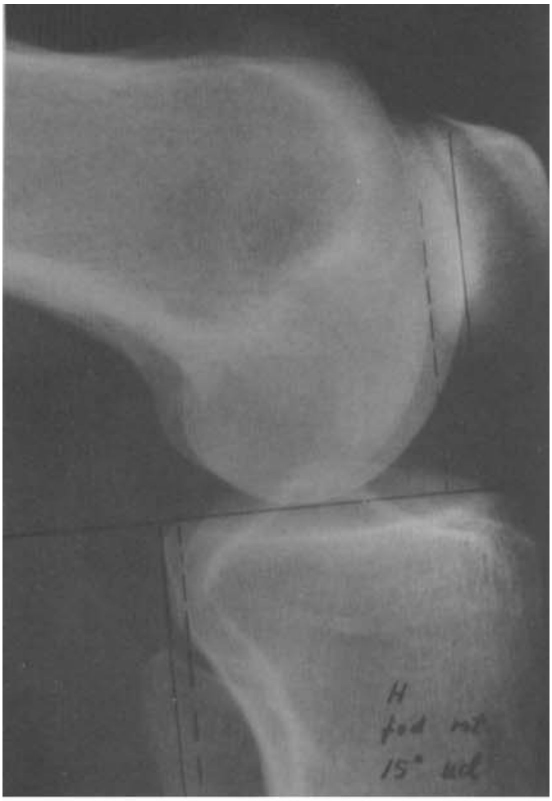
As an expression of total rotation of the tibia the difference between the two oppositely directed movements is used, calculated with + and - signs. The formula $((e_n - e_r) - (f_n - f_r))$ may be used generally for rotation without a pressure or traction stress, induced e.g. by a rotation action upon the foot. The formula is negative in external rotation of the tibia, positive in internal rotation. Numerically it increases with increasing rotation, as it corresponds to the sum of the numerical values; the negative or positive sign indicates the direction of rotation, cf. Addendum I.

During traction on the proximal end of the tibia the formula $((e - g) - (f - h))$ is applicable as an expression of rotation. It is negative in external rotation, positive in internal rotation, Addendum I.

During pressure $((i - e) - (j - f))$ is used. This formula is positive in external rotation, negative in internal rotation. The latter two sets of formulae can be used also on traction and pressure stress from an initial position of rotation, Addendum I.

Further mathematical formulae can be set up for measurement during traction and pressure with rotated foot, compared with the unloaded initial position "neutral position 90°", Addendum I. It was necessary to find normal values, in the form of upper 97½% fractiles in normal knees, for all these quantities before an assessment of injured knees was possible. In addition, the calculations are best based on the difference between a person's two knees for all these formulae (3, 4, 5, 6, 7, and Addendum I).


H
fod neutr.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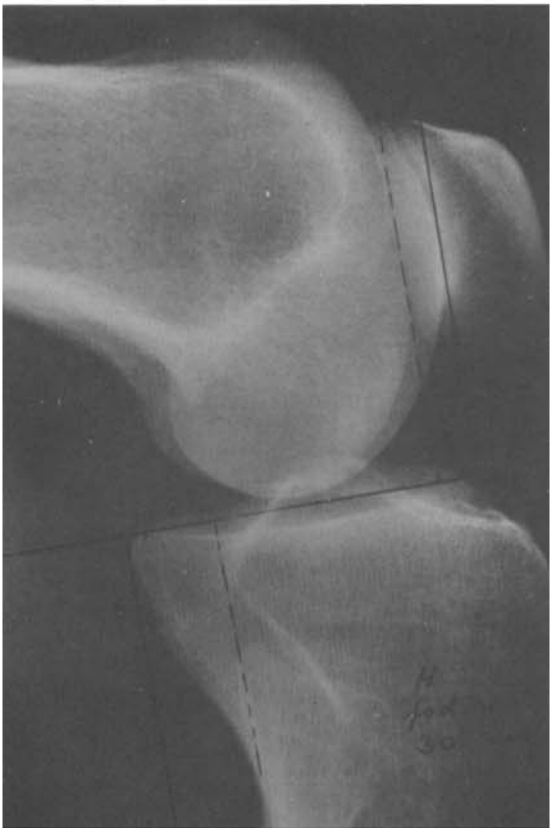

H
fod
30

Figure 13: Radiograph of the right knee of a 26-year-old woman. The baseline is shown. Parameter e is cut off between the two broken tangents, parameter f between the two unbroken tangents. In the middle: neutral position of the foot; at the top: exposure with 15° externally rotated foot; at the bottom: exposure with 30° internally rotated foot. The rotation in the knee joint is observed by looking at the head of the fibula which moves backward on external rotation and forward on internal rotation, in relation to the tibial condylar massive. It will be seen also that $e_{15^\circ\ \mathrm{ext.}} > e_{\mathrm{neutral}} > e_{30^\circ\ \mathrm{int.}}$ and that $f_{15^\circ\ \mathrm{ext.}} < f_{30^\circ\ \mathrm{int.}}$. By the measurement it can be ascertained that $f_{15^\circ\ \mathrm{ext.}} < f_{\mathrm{neutral}} < f_{30^\circ\ \mathrm{int.}}$.

5 d 3: Accuracy of Method: Error of Method and Inaccuracy of Measurement

Theoretically, a distinction can be made between errors of method due to the apparatus and radiological method and inaccuracy of measurement on repeated radiography and measurements on the X-ray films of the same distances (parameters) in the same subjects.

5 d 3.1: Error of method

5 d 3.1.1: Magnification: This can be regarded as a constant error of method for which correction can be made. However, this applies only with approximation.

The named magnification factor of 1.1 or 10% magnification on the X-ray film is a mean. A range from 3% to 15% for the articular parts closest and farthest from the film must be taken into consideration.

A 15% magnification has been found, on the lateral view in 2 cases, of a metal wire placed on the skin over the head of the fibula. This is a landmark not used in the measurements. It represents the absolutely outermost point of the knee joint. Simultaneous measurement of a metal wire over the tibial tuberosity showed a range of 6% to 9%. In this view the landmark for the lateral tibial condyle is at the same plane parallel to the film as the tuberosity. Therefore, the magnification is up to 9% in "neutral position 90°". The landmark for the medial tibial condyle is closer to the film and therefore the magnification is less. In this position the magnification at the level of the landmarks therefore hardly exceeds 10%.

A tibial rotation of 90° is required to bring the posterior surfaces of the tibial condyles merely in the vicinity of the named extreme position with 15% magnification. Such rotation was not observed, not even in the injured material. In the normal material rotation of the knee may amount to about 15° at 45° rotation of the foot (Addendum I).

The difference in magnification between the medial landmarks close to the film and lateral landmarks far from the film, which are in fact fairly close to each other, is estimated to be about 5%, viz. from about 5% medially to about 10% laterally. The distance between the two landmarks on the tibia measured on a specimen is about half the diameter of the entire tibial console, Addendum I.

On the a-p view the head of the fibula and the posterior medial corner of the medial tibial condyle are the areas close to the film and at the same time to the skin. Here, the measured magnification is 3% to 7%, while at the level of the tibial tuberosity it is 6% to 11%. As the anterior margins of the tibia are used as landmarks in this projection, the latter figures are more relevant.

The difference in magnification between landmarks close to and far from the film may be imagined to exert an influence in the following situations (distortion):

Assessment of the displacement of the two tibial condyles in the anteroposterior direction on the lateral view. This includes a contemplation as to whether the greater mobility of the lateral tibial condyle may be imagined to be due to the projection. This can be rejected (reflection 1), as the named movement in normal knees during traction and pressure in the "neutral position 90°" averages 7.5 mm for the lateral and 3.9 mm for the medial tibial condyle. The ratio 7.5/3.9 = 192.3%. In other words, the lateral condyle moves, on the average 92.3% ~ 100% more than does the medial one (6). Thereof, the difference in magnification can amount to only about 5%.

Role of the rotation of the object, viz. the tibia, in calculating rotation on the lateral view: On internal rotation of the tibia in relation to the femur, the landmarks on the posterior aspect of the tibia move outward. The magnification of their contours increases by about the same percentage. Therefore, the parameters (distances) measured to the reference tangents to the femoral condyles are magnified to the same extent. All the rotation formulae are expressed as a difference between these distances. The resulting line segment, used to express rotation, is therefore increased by the same percentage.

During external rotation the difference decreases numerically, the magnification getting reduced when the landmarks on the posterior aspect of the tibia approach the cassette. This is reflected in the figures which are lower than during internal rotation (6).

These two factors tend to eliminate each other in calculations (by the formulae) of the total, greater mobility of the lateral tibial condyle. It consists of the numerical value for internal rotation plus the numerical value for external rotation. Therefore, the conclusion of reflection 1 remains valid.

5 d 3.1.2: Parallax arises when the radiation source moves in relation to the object or the object moves in relation to the radiation source, while the plane of the film is unchanged (Schinz 1928). The angle between the central beam through a point in the object in the two extreme positions is defined as the parallax. It gives rise to distortion on the X-ray film, a parallax error. It was endeavoured to counteract this error by the radio-

graphic technique used. In the lateral projection the X-ray tube was moved, during the stress action into the same direction as the object (the knee joint). Thus, the central beam has been constantly at right angles to the cassette and also constantly directed towards the lateral epicondyle of the femur. Thus the radiation source and the object have moved equally in the same direction, in planes parallel to that of the film. Thus, parallax errors do not occur.

Neither object nor radiation source moves in the a-p projection (for abduction or adduction stability) in which the thighs are fixed. An angulation through the centre of the knee only moves the central landmarks slightly, and in practice the possibility of a parallax error can be disregarded.

In the a-p projection there occurs a special form of rotation in which the entire knee rotates, the femur and tibial condyles at the same time and in the same direction. This rotation occurs mainly in the hip and ankle joints. Rotation between the femur and tibia is minimal. In abduction, in which the whole knee rotates slightly inwards, measurement will, theoretically, show parameter c to be the smaller the greater the internal rotation, the landmarks being closer to the film. In adduction, in which external rotation occurs, parameter d, now closer to the film, will theoretically appear the smaller the greater the rotation. But this was not reflected in the measurements, neither among the 100 normal subjects nor in 2 specially examined ones.

5 d 3.2: Inaccuracy of Measurement

5 d 3.2.1: Inaccuracy of measurement in repeated exposures of the same parameter in the same person. Measurements on X-ray films carry a certain inaccuracy, the three-dimensional bony object being projected to a two-dimensional picture with many contours superimposed on each other. The contours alter during possible rotation, and therefore any changes in the contours and changes of the landmarks had to be studied during rotation of the knee joint in a beam of constant direction (2). These investigations showed that given landmarks can very easily be followed during rotation, but that some, slight change of the contours occurs. This is reflected in some inaccuracy in assessing and measuring linear distances on the film. In this sense, the physical factors mentioned under Error of Method contribute to the measuring error. It was tested during abduction and adduction stress of 9 kp as well as during traction and pressure of 30 kp. From Addendum I it will be seen that greater abduction and adduction forces (18 kp) and lesser traction (13 kp) or pressure forces (18 kp) proved unsuited. The inaccuracy of the measurement was tested by duplicate studies (the test-retest method) in 34 cases and

triple studies in 33 cases. In this investigation the author used coding of film envelopes and blind, randomized measurement of the parameters as well as two different statistical methods, one in the test-retest study and another one in the triple study. The results agreed.

At these stress forces the inaccuracy of the measurement was determined, with 95% confidence limits, as ± 1.2 mm for medial and lateral stability and as ± 2.4 mm for anteroposterior stability, without correction for magnification on the film. With correction, the corresponding values were ± 1.1 and ± 2.2 mm. Such investigations were not reported by Kennedy and Fowler (1971).

5 d 3.2.2: The reading inaccuracy of the measurement on repeatedly reading the same parameter on the same film is of less interest. It was tested for parameters c, d, e, and f, in 45 knees of the material C_b, i.e. twice 45 parameter readings (right knees) for each of the named parameters. These readings were blind and randomized like those mentioned above. For the duplicate readings the same statistical formula was used as in studying the inaccuracy of the measurement in the test-retest investigations. For the named parameters the inaccuracy of reading was about two-thirds of the inaccuracy of measurement (Addendum I).

5 e: Examination Procedure

5 e 1: The first step is investigation of abduction and adduction stability in the "neutral position 160°". After the apparatus has been connected to the power supply, the subject is dressed in a lead cape and fastened to the seat. The feet are fastened in the boots on slides anteriorly. The cuffs around the thighs are inflated before each action upon the joint and deflated after each exposure. The height and anteroposterior position of the seat as well as the anteroposterior position of the boots are adapted to limb length and to 20° flexion in the knee joints. The angle measurements are made with a long-armed goniometer from the greater trochanter to the lateral epicondyle of the femur (vertex) and lateral malleolus. The large cassette holder, which forms an angle of 10° with the horizontal plane, is mounted. The X-ray tube is adjusted so that its centre is above the joint line of the knee, midway between the two knees, tilted 10°. An exposure is made in the resting position, with the limbs unloaded and at such short distance that the patient feels that the leg is relaxed and unaffected. Thereafter, an exposure is made during simultaneous abduction of both lower legs and another exposure during simultaneous adduction of both lower legs (force normally 9 kp). The adjustment of the foot support and the height of the cassette holder are recorded

(for use in possible subsequent repeat measurement). In all examinations the patient is told to relax his/her muscles as completely as possible.

Then, the patient's feet are fastened in the boots on the floor of the machine, and cuffs are applied around the malleolar region. The piston shaft for anteroposterior stress upon the knee joint is fastened to the right knee by a cuff around the proximal end of the tibia. After adjustment to neutral position 90° a lateral film is taken first of the unloaded knee joint. The X-ray tube is adjusted at right angles to the cassette, now placed sagittally between the patient's knees. The lateral epicondyle of the femur is marked with India ink, and the central beam is directed against it. In exposures during traction and pressure (force normally 30 kp) this point will be displaced (often by 30 mm) in spite of the cuff, owing to shifts in the soft tissues of the thigh. Therefore, the tube is moved, so that the central beam again hits this point. This counteracts distortion on the film (parallax error). For each exposure the cuffs around the thighs are inflated to a pressure of about 300 - 350 mm Hg, but are deflated between each exposure to allow free circulation in the lower limbs.

Before exposures of the left knee are started, the gonylaxometer is turned 180° on its central swivel foot, so that the X-ray tube need not be moved. All actions upon the joint are kept within the pain limit in healthy subjects (i.e. the stresses mentioned above) to avoid harm to the ligaments. Control measurements of the hydraulic stress action (checking the manometer scale) were done for each 10 subjects. In patients, effusion in the joint is drained before the examination, and in the case of fresh injuries local anaesthesia is applied to tender sites around the joint. General anaesthesia coul not be used in such a busy department.

5 e 2: Determining the number of standard exposures and the standard method for calculating instability:

The number of exposures should be restricted as far as possible while at the same time as much information as possible is collected. The restriction is out of regard to the radiation dose and to the time factor. For these reasons two suggestions will be made below.

The former must be an absolute minimum demand. It consists of two a-p exposures of both knee joints at the same time, one during abduction to measure parameter c and one during adduction to measure parameter d, and three lateral views of each knee joint in a neutral position of the foot, one at rest, one during traction, and one during pressure stress. This affords a possibility of measuring lateral and medial instability (set of A and B formulae, Table 1, Addendum II). Further, it permits measurement of anterior and posterior displacement of the tibia in relation to the femur (C_n, D_n, and E_n) and supplies two expressions of rotation (F_n and G_n). These two formulae procured 66% of the information concerning rotation found in the clinical series (Addendum II).

The second suggestion is a slight extension of the number of exposures, viz. 2 laterals of each knee in 15° external rotation, one without loading and the other one with 30 kp traction. This gives, in addition to the abovementioned information, another four expressions for rotation (formulae F_{15}, C_{15}, $H_{n15^o\ ext.}$, and $F_{n15^o\ ext.}$, where 15^oext. signifies 15^o external rotation). As is apparent from Addendum II, this extension, which increases the number of exposures to 12, gave 92% of the rotation findings.

Further examinations were made with pressure in 15^o external rotation as well as in 30^o internal rotation and 30^o external rotation of the foot (unloaded position, traction and pressure), but the extra gain from these examinations was slight.

5 e 3: Establishing Critical Levels

As the inaccuracy of the measurement had proved to be $\pm$ 1.2 mm for lateral and medial stability and $\pm$ 2.4 mm for anteroposterior stability, it seems most reasonable to state the results in whole mm in the future. Measurements and calculations are still performed with 1 decimal. The critical levels of 2.0 and 3.0 mm used in (5) are thus also rounded off to whole ciphers:

2 mm for medial and lateral stability and

3 mm for anteroposterior displacement and rotatory instability.

This means that:

values $\leq$ 2 mm are normal and values $\geq$ 3 mm abnormally elevated for medial and lateral stability.

As regards anteroposterior displacement and measurement of rotation: values $\leq$ 3 mm are normal and values $\geq$ 4 mm abnormally elevated (calculating the parameter value of the injured minus that of the uninjured knee).

Such rounding off is in fact a very slight "moving of the critical level" from 2.0 to 2.4 and 3.0 to 3.4 mm respectively, cf. Addendum II. The diagnostic probabilities: the predictive value of a positive test, $PV_{pos.}$ (in Danish: diagnostisk specificitet) and the predictive value of a negative test, $PV_{neg.}$ (in Danish: diagnostisk sensitivitet) (Vecchio 1966, Wulff 1973 a), are only slightly altered by this re-adjustment. In fact, the $PV_{pos.}$ is not altered at all, neither for medial and lateral stability nor for anteroposterior stability. This probability has a very high score, i.e. the prediction of a pathological condition is very certain (Addendum II). This means that if the test is positive, also with these new critical levels, it is almost 100% certain that there is an injury to the tested structure, either a collateral or a cruciate ligament. The $PV_{neg.}$ alters in the case of anteroposterior instability only from 96% to 94%. This means that here too it may be deduced with an almost equally great certainty that a negative result of the test means that there cannot be a (total) rupture of a cruciate ligament. For medial instability, however, the $PV_{neg.}$ changes from 92% to 86%. But as mentioned in Addendum II, this lowering is due to the fact that small injuries with small instabilities are no longer caught by the test. Now, it has to be said, with a probability of about 14%, that in spite of a negative result of the test there may be a ligament injury. Since, however, such slight injuries usually do not indicate surgery, a lowering of just this $PV_{neg.}$ is not of much importance.

The clinical value of the test, thus, remains unaffected by these adjustments of the critical levels (cf. Wulff 1973 b).

In general, the risk and discomfort to the patient at gonylaxometry are slight. 8 - 12 exposures of the knee do not amount to a large irradiation dose, and the method as used here does not result in further rupture of partially ruptured ligaments. In a few cases, however, it has entailed pain, and if so it has been interrupted (fresh injuries).

Thus, even after rounding off the calculated values and critical levels to whole ciphers in the way stated, the test has proved fully valid according to prospective clinical testing (Addendum II).

Whether it is reasonable to use the 97½% upper limit from a "knee sound" population as the critical level in a test depends upon the consequences of fixing this level, and such examples of fixing different critical levels have been discussed by Wulff (1973 a) and by Baden et al. (1971). In their cases, however, enzymatic tests were made, with marked overlapping between the test values for normal and diseased populations. In gonylaxometry, which is performed in cases of well-defined injuries, there has been, with the rounded critical levels based upon 97½% fractiles, little overlapping of results for normal persons and persons with clinically significant injuries.

5 f: Contra-indications to the Examination

Contra-indications will be discussed in Addendum II, but will be briefly outlined here:

(1) Life-threatening conditions to be given preference to orthopaedic surgery.

(2) Conditions in which the popliteal artery is injured or threatened (e.g. dislocation of the knee) and conditions in which the peroneal nerve is paralysed.

(3) Complicating, major fractures of adjacent bones.

(4) Intra-articular fractures of the knee.

(5) Conditions in which rupture of a ligament has been ascertained by plain radiography (bone avulsions at the sites of insertion or origin) in which it may be feared that the method will increase the injury.

CHAPTER 6

PRESENT INVESTIGATIONS: RESULTS

6 a: Examination of the Knees of 100 Normal Persons and Discussion

5 a 1: Composition and relevance of the material

The presuppositions for being able to describe and measure disorders by a given method are knowing the normal limits, the "normal range", and the accuracy of the method. The latter aspect was described in the preceding chapter, but the deductions drawn there are also based on the examination of the normal knees to be discussed here.

100 normal persons with sound knees were examined (Addendum I). The criteria of normality are described in the Addendum. It was substantiated that the composition of the group with respect to age and sex was completely homogeneous and corresponded in age to the group of patients who empirically are most apt to sustain injuries to the knee ligaments, vis. mainly during the age range 20 to 50 years. Thus, the age distribution of the normal material is relevant.

Among the last 50 controls (group C_b), it was demonstrated that no systematic difference exists between the parameters of the right and left knee Therefore, it is possible to calculate the normal difference between the two legs as regards the various parameters for ligament instability by using the numerical difference (/c_R - c_L/(medial instability) as an example). It was found that despite a marked difference from one person to another in all parameters - the "normal range" being very wide - the difference, including the error of measurement, between the two normal knees of the same person was always very small. Accordingly, it is permissible to use as critical levels, i.e. the borderline against disorders, 2 mm for medial and lateral instability and 3 mm for anterior or posterior displacement for the difference between a person's two knees. This method of calculation proved to apply unchanged from 20 kp to 30 kp traction and pressure, and it renders the values independent o sex, height, leg length, and body weight which affect the upper 97½% limits fo the variations in the paramters for each leg separately. The fact is that a greater dimension causes significantly higher values for the parameters. This applies to height, leg length, as well as body weight. It has been demonstrated also that the difference in parameter size between the two sexes is due to a difference in dimension between the two sexes (Addendum I).

6 a 2: Different possibilities of measuring the various types of instability were investigated. Thus, medial instability was measured as a line segment, a, on the radiograph of the unloaded knee joint in "neutral position 160°" in relation to the analogously cut off line segment, c, during abduction, the difference, c-a, indicating medial stability or instability. In the same way a difference between line segments, measured laterally at rest and during adduction, denoted lateral stability or instability. These measurements were soon simplified to calculating the difference between the subject's two knee joints during stress, viz. $/c_R - c_L/$ for medial instability and $/d_R - d_L/$ for lateral instability. This alteration was done because the position at which the subjects felt the knees were at rest did not seem well-defined. However, subsequent control calculations have shown that these quantities measured at rest, a and b respectively, did not carry a greater inaccuracy than the measurements during stress, medially c and laterally d. It must be admitted, then, that the method of Kennedy and Fowler (1971) (c-a) is just as accurate as $/c_R - c_L/$. However, the method of Kennedy and Fowler was abandoned for another reason: one exposure and two measurements with appurtenant calculations were obviated (Addendum I).

It was attempted also to use "landmarks" in central parts of the joint to measure anterior or posterior displacement of the proximal end of the tibia - i.e. a single difference in parameter to denote a possible anterior or posterior drawer sign (4). This is practicable too, and the inaccuracy of this method is practically the same as that of the present one. The latter consists in measuring the displacement of each tibial condyle separately in relation to the respective femoral condyle and using the mean as a measure of the displacement of the proximal end of the tibia. This is done on the same X-ray film, so that it does not increase the number of exposures. It gives the same result as measurement by the aid of central "landmarks", and - most important of all - it simultaneously affords a possibility of calculating the rotation. Therefore, measurement from central "landmarks" was abandoned - again to restrict the number of parameters (Addendum I).

6 a 3: Rotation can be found at traction and pressure in the neutral position, and it can be demonstrated by rotation of the foot only, without traction or pressure, and by traction and pressure in positions of rotation of the foot. The formulae for rotation in these cases have been given above under "Method, and their critical levels have also been deduced and investigated on the basis of the normal material (Addendum I). These formulae express the rotation as

the difference in displacement between the tibial condyles in mm instead of as degrees of an arc.

Other methods were also tested with this set-up, i.e. the gonylaxometer, because other workers have measured by externally fastened apparatuses, using the degrees of an arc - so that conversion to such degrees facilitates a comparison. This revealed a mean external rotation in the knee joint of 15° at 45° external rotation of the foot and an internal rotation in the knee joint of 13° at internal rotation in the foot of 45° from the "neutral position 90°". In these extreme positions the subjects reported a sensation of pain in the knee joints - and forced rotation against such pain was not attempted. The mean of the total excursion of 28° would probably have been higher in that event, as indicated by previous studies in vivo. In the cadaver, on the other hand, the rotation has proved less at 90° flexion in the knee (vide infra). Attempts at a trigonometric calculation of the rotation on the basis of the parameters measured on the X-ray films showed a fair agreement with the external measurements in a small series of 12 subjects (Addendum I). However, both of these latter forms of measurement carry marked inaccuracy - an inaccuracy which increases in the presence of deviations from normal, i.e. in ligament injuries and abnormal rotations, the very objects of study for which the apparatus was developed. The inaccuracy will be explained in more detail in Addendum I. It is less than it would be on rotation measurement in a case of ligament rupture in the way suggested by Ouellet et al. (1968). These workers used the rotation centre, and thereby the length of the radius, in their calculation. This is not possible in an injured knee, in which the rotation centre is unknown. By the trigonometric method used in connection with the gonylaxometry, the calculation is still possible, but the inaccuracy increases with increasing rotation. Therefore, it was abandoned.

More than half the rotation takes place in the ankle joint in this set-up, as it is not stiffly immobilized. The same applies to the clinical test of Slocum and Larson (1968). Therefore, investigations were carried out with the foot fixed, both in 15° external rotation and in 30° external rotation in order to imitate as far as possible the test of Slocum and Larson (1968). In clinical practice, they performed this test according to discretion, describing it as being performed with a 90° flexed knee "and the foot and leg externally rotated 15 degrees", a somewhat inaccurate statement, as according to the present findings the foot rotates more than twice as much as the knee joint.

The magnitude of rotation in normal knees can be stated in different ways, cf. Chapter 5, d 2. The numerical values for the formula $((e_n - e_r) - (f_n - f_r))$

Table 2. Standard values of knee stability in healthy subjects: $\overline{X}_n \pm t_{2\alpha} \times SD$, 17♂ + 17♀. Abduction - and adduction - force: 9 kg, pushing - and pulling - force: 20 kg. For 34 subjects: $t_{2\alpha} = 2.03$.

stability measured	parameter	standard values (mm) $\overline{X} \pm t_{2\alpha} \times SD$	SD	upper limit (right-left) $\overline{X} + t_{2\alpha} \times SD$	SD
medial=valgus=abd.	c	men : 5.8-12.1	1.3	men & women:	
		women : 5.2-9.8	1.2	1.4	0.4
lateral=varus=add.	d	both sexes: 9.2-16.9	1.9	2.0	0.6
ant. displacement:					
lateral cond.	e - g	both sexes: 0.2-8.8	2.1	3.1	1.0
medial cond.	f - h	both sexes: 0.0-5.5	1.5	2.5	0.7
average	$\frac{(e-g)+(f-h)}{2}$	both sexes: 0.0-7.0	1.7	2.6	1.5
posterior displacement:					
lateral cond.	i - e	both sexes: 0.2-6.0	1.4	2.9	0.8
medial cond.	j - f	both sexes: 0.0-3.4	0.8	1.9	0.5
average	$\frac{(i-e)+(j-f)}{2}$	both sexes: 0.8-4.1	0.8	1.9	0.8
total a-p displacement:					
lateral cond.	i - g	both sexes: 3.1-12.0	2.2	3.1	0.9
medial cond.	j - h	both sexes: 0.2-7.5	1.8	3.1	0.9
Average	$\frac{(i-g)+(j-h)}{2}$	both sexes: 2.0-9.5	1.8	2.7	1.8

From : Acta orthop. scand. 47, 335 - 344, 1976 which denotes rotation in the knee joint on rotation of the foot alone, without anterior or posterior stress, are given in Addendum I, Tables 22, 23, and 33. For each knee it averages 4 mm at a 15° external rotation of the foot, 8 mm at 30° external rotation of the foot, and 6 mm at 30° internal rotation. The 97½% upper limit is 12 mm at 30° external rotation. Rotation of the knee at traction and pressure in a neutral position of the foot is somewhat less: range at traction up to 5 mm and at pressure up to 7 mm. Difference between right and left knee < 3 mm. These and other rotation measurements are given in Addendum I, Tables 29, 30, 31, and 32.

6 a 4: Magnitude of lateral and medial stability and a-p displacement

Contemplation of Table 2 affords an impression of the magnitude of medial stability, parameter c, on valgus stress upon normal knees: 5 - 12 mm. Lateral stability, parameter d, ranges from 9 - 17 mm. The difference between a person's two knees is within much narrower limits: upper limit of $/c_R - c_L/$ 1.4 mm, of $/d_R - d_L/$ 2.0 mm.

Table 2 also shows the a-p displacements of the tibial condyles at a neutral position of the foot. Here too, the difference between a person's two knees is considerably less marked. Incidentally, the anterior and posterior displacement of the tibial condyles in relation to the femoral condyles in the same knee during traction or pressure vary according to the initial position in which the foot has been fixed (Tables 19, 25, 26, and 27 in Addendum I). There may be anterior displacements up to 10-12 mm for one condyle in a normal knee and up to 17 mm of total anteroposterior displacement for one condyle. However, the total anteroposterior movement is always greater in the lateral joint chamber, cf. Tables 19, 25, 26, and 27, 5th column, in Addendum I.

Within the normal material about 6400 parameter readings were made on X-ray films.

6 a 5: Discussion of method and findings in 100 normal subjects

The advantage of the present method over non-radiological methods, in which the apparatus has to be fastened externally on the soft tissues of the lower limb, is that it avoids the incalculable uncertainty due to shifts of the soft tissues (3). In Tillberg's (1977) method, for instance, the measuring equipment was fastened externally with tape on the thigh and lower leg in their long axes. In that way, it can hardly be avoided that soft-tissue shifting influences the results of the measurements, especially if the subject is obese.

External measuring equipment which is based upon bony parts close to the skin may also be influenced by soft-tissue shifts over these bony parts (3, 4).

Gonylaxometric studies on normal subjects can be compared with the methods of others which have often been tested, to a major or minor extent, on normal subjects. Such comparable specifications have been given by Sylvin (1975). His measurements are not based on X-ray films, but on repeated external measurements using the mean of the results obtained. Further, he recommends using the difference of measurements between a person's two knees as a measure of instability, this value being lower and more constant than the total excursions which vary a great deal from one person to another. The present author shares this view. Sylvin found the difference between anterior displacement in the two knees of normal persons to average 1 mm. This is in agreement with the present findings, the difference among 34 persons, at a 20 kp load, averaging 0.9 mm ~1 mm (corrected for 10% magnification on the X-ray film: mean = 0.8 mm). Upper limit (97½%) 2.6 mm, corrected 2.4 mm.

Sylvin reported that this limit was 2.5 mm. A closer agreement can hardly be found between 2 apparatuses for measuring anterior stability. As the principles of the methods differ, the extremely identical results confirm each other to quite a particular extent. Sylvin's apparatus cannot measure other forms of instability.

For anterior displacement in one knee Sylvin found mean values from 3.02 mm in young women to 5.00 mm in men between 21 and 30 years of age, and 4.80 in men from 41 to 5o. The mean for all subjects is stated to be somewhat below 5 mm, in good keeping with the 4.1 mm found in the present study (Addendum I, Table 19).

Markolf et al.'s method (1978), electrogoniometry, (cf. Chapter 2 b), using manual stress upon the tibia in sudden jerks, has no mechanical safeguard against too forceful stress actions. Their finding of a 4.8 mm a-p instability as the mean in sound knees agrees with the gonylaxometric findings in which the mean was 5.7 mm measured on the X-ray film, corrected 5.1 mm. Thus, in both methods the rounded figure is 5 mm. On the other hand, their finding of a very marked difference between the two knees of the same person must be due to an inaccuracy of their method. They state mean values of 26 - 35%. In the gonylaxometer the corresponding mean values were 17.5% for medial instability, 15.5% for lateral, and 20% for a-p instability, including the inaccuracy of the measurement which constituted the greater part of this difference in normal knees.

In a short paper Nyga (1970) has reported an anterior displacement of 2 - 5 mm in normal subjects. He used a simple measuring technique, making no distinction between the displacement of the lateral and medial condyles, and no mention is made of the number of normal subjects or any patient material.

According to Volkov (1971), anterior displacement of the proximal end of the tibia of 10 mm or over is abnormal, signifying total rupture of the ACL (confirmed by surgery in 22 cases). The difference from the uninvolved knee was not calculated. It is not stated whether studies on normal subjects had been performed.

In the normal material (Addendum I) the use of 20 kp traction showed an upper critical level (97½% level) of 7.0 mm, and at 30 kp of 7.4 mm (range up to 8.5 mm). This is in quite good agreement with the critical level selected by Volkov.

Kennedy and Fowler (1971) have given a thorough description of several series which can easily be compared with the present study. Their normal material comprised measurements on 110 knees, which may be interpreted as measurements of the knees of about 55 young people, active athletes without a history of knee injuries. As these measurements were made on X-ray films in fundamentally the same way as in the present study - with a few exceptions, cf. (4) - the numerical values for the various parameters can be compared. Kennedy and Fowler reported *the range of medial instability at 20° flexion in the knee of* normal persons to be 0.8 mm to 3.5 mm. This parameter they measured as the c-a (expressed like the formulae of the present study). This method of calculation was soon rejected in the present study, but yet the range for 34 normal subjects (17 males and 17 females) at 9 kp loading can be given (Addendum I, 68 measurements): 1.1 mm to 6.1 mm. After correction for magnification on the X-ray films this amounts to 1.0 mm - 5.5 mm. Kennedy and Fowler do not mention whether such correction was performed. Even after correction for magnification, the highest value measured was 57% higher in the present material than in Kennedy and Fowler's. Thus, the present author found a considerably wider "normal range" by his own method, using instead $/c_R - c_L/$ or $(c_{injured} - c_{uninjured})$, statistical analysis showing no systematic difference in the size of the parameters between the right and left knee (Addendum I). However, the results of the measurements agree roughly with Kennedy and Fowler's. For anterior stability in the normal knee Kennedy and Fowler found a displacement from 0.0 - 5.0 mm, and this applied to both condyles. The present author found considerably greater mobility of the lateral tibial condyle in relation to the femoral condyle, up to 9.1 mm at 20 kp traction and up to 10.2 mm at 30 kp traction in the neutral position than of the medial one: 5.5 mm at traction of 20 kp and 7.4 mm at 30 kp. This difference in mobility between the lateral and medial tibial condyle applies also to pressure exerting the same forces

(Addendum I and (4)), the total displacement of the lateral tibial condyle at neutral position of the foot (force: 30 kp) being twice that of the medial one calculated from the mean values (Addendum I). This is confirmed by the findings of Hertel and Schweiberer (1975). X-raying cadaveric knees with metal marks on the tibial condyles and using a simpler measuring technique than the present one, they found the mobility of the lateral condyle to be greater than that of the medial one in the intact knee flexed 90°. Incidentally, this phenomenon has long been known by anatomists (Winslow 1719, Weber and Weber 1836, Fick 1911, Palmer 1957, Kaplan 1962). One explanation why Kennedy and Fowler did not recognize this fact may have been a deficient use of landmarks on the X-ray film, cf. (2) and (4). It has nothing to do with the projection or with distortion on the radiograph, and it applies unchanged at exposures with 15° and 30° externally rotated foot as well as with 30° internally rotated foot - with slight deviations in the means, $\bar{x}$, (Addendum I, Tables 19, 25, 26, 27).

Kennedy and Fowler (1971) had no well-defined baseline on which to perform the measurements on the lateral radiograph. They measured on a line parallel with the lower edge of the film. This may give rise to varying results under unfortunate circumstances (4).

Rotatory stability is measured in the gonylaxometer with the foot supported, but the joint does not even bear the weight of the thigh which is supported by inflated cuffs (3). Because the foot is supported, however, the situation differs essentially from the set-up with hanging lower leg. The best comparison is, therefore, with the results of authors who have used the same experimental conditions: 90° flexed knee and supported foot and thigh. In "external" examination of rotation by means of the scale on the floor of the gonylaxometer a total rotation of 28° in the knee is found, external (45°) plus internal rotation of the foot (45°) totalling 90°. Determination of maximal rotation was not attempted as by the workers to be quoted below.

In the 90° flexed knee Meyer (1853) found a total rotation of 42°. Ross (1932), in 100 normal subjects, found a total rotation averaging 37°, 18° internal and 19° external rotation. Brantigan and Voshell (1941), using fresh, intact cadaveric knees, found a rotation of up to 24° in 90° flexion, Hallén and Lindahl (1965) an average of 26°.
Ruetsch and Morscher (1977), measuring the total rotation in 21 normal subjects, found a mean of 36°. This is in quite good conformity with the present findings, although no attempt was made at identical experimental conditions. The greater possibility of rotation in living knees than in cadaveric

knees is striking in the named series. Lastly, it is worth pointing out the good agreement between the experiments of Ross (1932) and Ruetsch and Morscher (1977) (total rotation of 37° and 36° respectively) under experimental conditions which were entirely identical. Considering the greater rigidity of cadaveric knees, the experimental results and also cutting experiments on cadaveric knees must be regarded with same reserve.

6 b: Investigations of Injured Knees and Discussion

6 b 1: Agreement between results of measurement and operative findings

The scientific value of gonylaxometry is clearly based on the fact that it measures in known physical units which can be stored and used for comparison in possible later follow-up.

It is a presupposition of the method as a measuring instrument of scientific value that it is applicable also clinically. In other words, that it can distinguish with great accuracy between normal and injured knees.

It is a different matter altogether whether it is going to gain general ground in clinical practice as a diagnostic aid. This must depend on whether other diagnostic methods afford approximately the same diagnostic reliability and are at the same time cheaper and less time-consuming.

Both aspects will be elucidated by the present investigations of patients with knee injuries (5, 6, 7, and Addendum II).

The clinical signs which have previously been most thoroughly investigated are medial and lateral instability as well as the anterior and posterior drawer sign. It was natural, therefore, to select these four signs in a clinical study of the practical value of gonylaxometry and to omit rotation measurements, as there is still great clinical disagreement concerning the genesis of rotatory instability and the various rotation patterns. For instance, Trickey (1977) and Warren et al. (1974), unlike Slocum and Larson (1968) and Hughston and Eilers (1973), feel that the SMCL plays a greater role in rotatory stability (controlling external rotation) than do the DMCL and OMCL.

This view formed the basis of the analysis in Paper 5 which reported on a prospective, consecutive comparative study of

(1) stress radiography,
(2) clinical examination of lateral and medial instability and the drawer sign, and
(3) investigation of the same signs under general anaesthesia.

The operative diagnosis was in all cases the final check on the preoperative, tentative diagnoses. On this basis it could be evaluated which of the preoperative findings were true positive, TP, true negative, TN, false positive, FP, and false negative, FN. This makes it possible to calculate the $PV_{pos.}$ and $PV_{neg.}$ of the various methods (Vecchio 1966, Wulff 1973 a, (5), and Addendum II). But a presupposition is complete investigation, as done here: all the patients examined underwent operation, also those in whom the measurements had given negative results. The last-mentioned were patients having haemarthrosis of the knee and who were subjected to operation on the clinical indication of suspected ligament rupture, and in whom there were other intraarticular injuries as well. It was apparent from the study that gonylaxometry was the best of the tests tried. judging by the diagnostic probabilities, the $PV_{pos.}$ and $PV_{neg.}$, but so closely followed by examination under general anaesthesia that with 95% confidence limits it was not possible to distinguish definitely between the two tests. Considerably poorer results were obtained by ordinary clinical assessment. Furthermore, the comparison of the three types of examination was reduced to a purely qualitative diagnosis: lateral/medial instability or not, total anteroposterior instability to an abnormal extent or not. The clinical examiners (senior registrars or consultants) were not able to carry out further grading with any certainty. The ability of gonylaxometry for quantitative evaluation, thus, did not even come to a test in this assessment.

The results concern 153 injured knee joints. Medial instability, defined as the difference between the injured and uninjured knee, was > 2 - 4 mm in cases with rupture of the DMCL and OMCL. The SMCL might be partially, but never totally ruptured at this magnitude of instability. If total rupture was present, the instability was > 4 mm and ranging up to 17 mm ($c_{injured} - c_{uninjured}$) in entire agreement with Warren et al. (1974)and with Schweiberer and Hertel (1977). In cases of marked instability there was co-existing rupture of the cruciate ligaments (5, Fig. 2) and posterior fibrous capsule, as also reported by Hallén and Lindahl (1965 a). In one case the lateral instability ($d_{injured} - d_{uninjured}$) was 20.8 mm. In this case too rupture of both cruciate ligaments and of the posterior capsule co-existed. The named patients had fresh ligament ruptures. In older ruptures the difference was less marked (Figs. 3 and 4 in (5)).

Anterior and posterior drawer signs of 14 - 18 mm were observed in fresh as well as in older ruptures of the cruciate ligaments. Below the critical limit of 3 mm there were only TN and partial ruptures, and two cases of total ruptures in which the knee was locked by a meniscal bucket handle injury, plus one case of an older injury (5).

The test for the ability of the method to distinguish normal from injured knees and to measure the size of the ligament injury, thus, was in conformity with the operative findings. There can be no doubt concerning its suitability as a clinical scientific measuring instrument.

6 b 2: To <u>assess the clinical, diagnostic value of the method</u> its diagnostic probabilities had to be compared with those of other methods. This comparison was made with clinical testing and with testing under general anaesthesia.

The "predictive value of a positive test", PV_{pos}, (Wulff 1973 a) is defined as the probability of the presence of a given ligament injury, if the test for this injury has been positive (Vecchio 1966). The "predictive value of a negative test", PV_{neg}, is defined as the probability that the given structure is not injured, if the result of the test has been negative.

PV_{pos} and PV_{neg} are best evaluated in the 90 cases of fresh knee injuries (5), as the injury presents itself most clearly at operation in the acute stage, before it has become blurred by cicatricial tissue. Table 3 lists the predictive values for medial instability. It must be mentioned that the confidence limits to PV_{pos} are extremely narrow for gonylaxometry and the testing under general anaesthesia, while for PV_{neg} they are wide. This is because the sum of positive findings is high and that of negative findings low, cf. Table 3. The explanation is that already at the institution of the clinical diagnostic procedure the patients not requiring surgery were sorted off. This was done for ethical reasons, as people were not to be exposed to a subsequent operation except on an indication of haemarthrosis with a suspicion of major internal derangement or of meniscal injury. It was not possible to collect a major series of such persons. Therefore, as is apparent also from the table, the wide confidence limits for PV_{neg} are due to the small numbers, i.e. few persons and, besides, in particular very few false negatives. These confidence limits are accordinly not immediately comparable with those of the PV_{pos} - which indicate a very great accuracy of the measurements. The few FN in the clinical test also represent the ethically founded disinclination to involve patients with negative clinical findings in further examinations and surgery. Nevertheless, the findings of clinical testing were the poorest ones. The same applies to the drawer signs. Table 4, setting out the findings for the drawer signs, is a simplification of Table 14 in Addendum II. Moreover, it must be emphasized that as FN the author included injuries which at subsequent operation proved to be partial ruptures - which hardly afford an indication for surgery.

Table 3

Predictive values in knee injuries $\leq$ 14 days. Medial instability.

Genylaxometry: TN = 21, FN = 5, TP = 63, FP = 0, N = 89

predictive value of pos.test = $PV_{pos} = \frac{TP}{TP + FP} = \frac{63}{63 + 0} = \underline{100\ \%}$

(95 % confidence limits: 94 - 100 %)

predictive value of neg. test = $PV_{neg} = \frac{TN}{TN + FN} = \frac{21}{21 + 5} = \underline{81\ \%}$

(95 % confidence limits: 61 - 93 %)

Clinical test: TN = 10, FN = 2, TP = 66, FP = 12, N = 90.

$PV_{pos} = \frac{TP}{TP + FP} = \frac{66}{66 + 12} = \underline{85\ \%}$ (75 - 92 %)

$PV_{neg} = \frac{TN}{TN + FN} = \frac{10}{10 + 2} = \underline{83\ \%}$ (52 - 98 %)

Testunder General Anaesthesia TN = 20, FN = 3, TP = 65, FP = 2, N = 90

$PV_{pos} = \frac{TP}{TP + FP} = \frac{65}{65 + 2} = \underline{97\ \%}$ (90 - 100 %)

$PV_{neg} = \frac{TN}{TN + FN} = \frac{20}{20 + 3} = \underline{87\ \%}$ (66 - 97 %)

TN = true negative, TP = true positive, FN = false negative,

FP = false positive, N = number of patients tested.

From : Acta orthop. scand. 48, 301 - 310, 1977

Table 4: Predictive value of positive test, PV_{pos}, and predictive value of negative test, PV_{neg}, for drawer signs in knee injuries $\leq$ 14 days.

Anterior drawer sign	Gonylaxometry	Test under general anaesthesia	Clinical test
PV_{pos}	94%	83%	59%
PV_{neg}	86%	83%	79%
Posterior drawer sign			
PV_{pos}	100%	100%	86%
PV_{neg}	99%	99%	96%

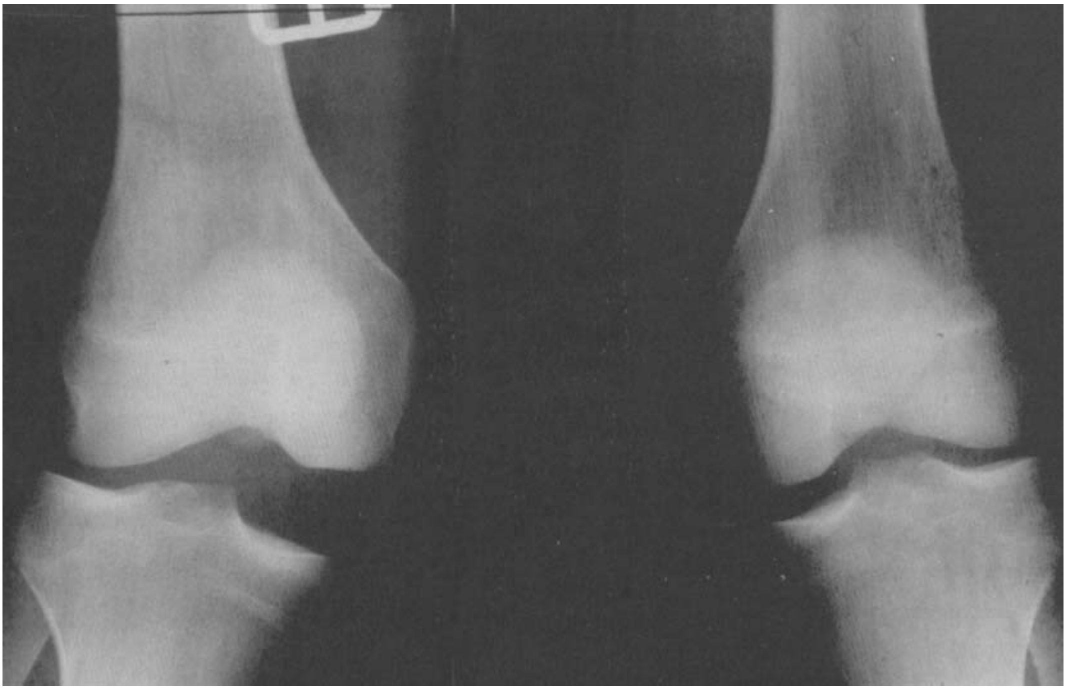
Gonylaxometry, as carried out in this investigation, using local anaesthesia, gave the best results. Under general anaesthesia it would presumably be able to afford even greater precision. It will, therefore, be the best tool in clinical scientific work. However, clinical testing under general anaesthesia gave results very close to those of gonylaxometry, and it is cheaper and easier, so that it must be expected to be fully justified for general clinical diagnostic use.

6 b 3: Anterior drawer sign was found in the presence of injury to the ACL, connected in most cases with total or partial rupture of the MCLs (5, Fig. 2). But isolated anterior drawer signs, in cases of isolated rupture of the ACL, were found also in the group of patients with acute injuries, Cases 64, 67, and 75, the last-mentioned one having a very small tear of the SMCL. However, these drawer signs are small ones and only just exceed the critical levels. Indeed, this agrees with Trickey's (1977) findings in the more rigid, formalin-prepared cadaveric knees: that isolated cutting of the ACL in such knees does not give rise to a drawer sign. Dexel et al. (1977), however, fou in radiological studies with manual traction on specimens, a few mm anterior drawer sign after isolated cutting of the ACL. So did the present author fin this phenomenon on stress radiography in a few patients with isolated ruptur of the ACL. The slight degree of the drawer sign is presumably the reason why its existence was denied by Hughston et al. (1976, I) whose examination was purely clinical. In their paper they claim that an anterior drawer sign arises only if the PCL is injured. It should be borne in mind, however, that in their investigations they defined the anterior drawer sign both with the foot in the neutral position and in internal and external rotation. On the

basis of my clinical findings, I can agree partly with these authors - but without subscribing to their sharp formulation. Judging from Cases 87 and 88 in Addendum II, I can consent to the following formulation: In rupture of the PCL with an intact ACL (plus rupture of the DMCL and OMCL and of the fibrous capsule posteromedially - i.e. including the oblique popliteal ligament) there may be an anterior drawer sign along with a posterior one. However, I must adhere to the formulation: that rupture of the PCL normally gives rise to a posterior drawer sign, sometimes also rotatory instability due to rupture of other structures, e.g. the medial ones as in Case 87 in Addendum II. In that case I demonstrated external rotatory instability due to rupture of the medial structures by a traction test with 15° rotation of the foot. In Hughston et al.'s nomenclature, this is called an anterior drawer sign with externally rotated foot. Operation disclosed rupture of the PCL, but an intact ACL. With the foot in neutral position there was no anterior drawer sign. It must be noted, then, that in this respect the disagreement is on a purely abstract level, viz. in the definitions. There is agreement in this case as well as in the previous one, when correct translation is made from one nomenclature to the other.

There may be yet another cause of the disagreement concerning the role of injury to the PCL in the various forms of anteroposterior instability: Even on close inspection it may be difficult to detect minimal intraligamentous partial ruptures which have been demonstrated microscopically by Noyes et al. (1974) and by Kennedy et al. (1976) after experimental, violent stress actions. Such fine ruptures of individual fibres may presumably lead to a slight lengthening of the ligament. They occur before an actual rupture is visible.

Incidentally, it must be emphasized that anterior drawer sign, with the foot in neutral position, was observed in association with injury to the ACL, and posterior drawer sign in connection with rupture of the PCL, in agreement with Palmer (1938) and more recently Furman et al. (1976) and Dexel et al. (1977). Further, the present material confirms the great importance of a minimal injury to the collateral ligaments in demonstrating an anterior drawer sign which would otherwise hardly be visible clinically (Palmer 1957). The drawer sign is the greater, the greater the co-existing injuries to the collaterals. Figures 14 and 15 (Cases 76 and 90) show the stress radiographic appearances of drawer signs, Figure 16 of lateral instability (Case 70).



a

Figure 14: Stress radiography in Case 76:

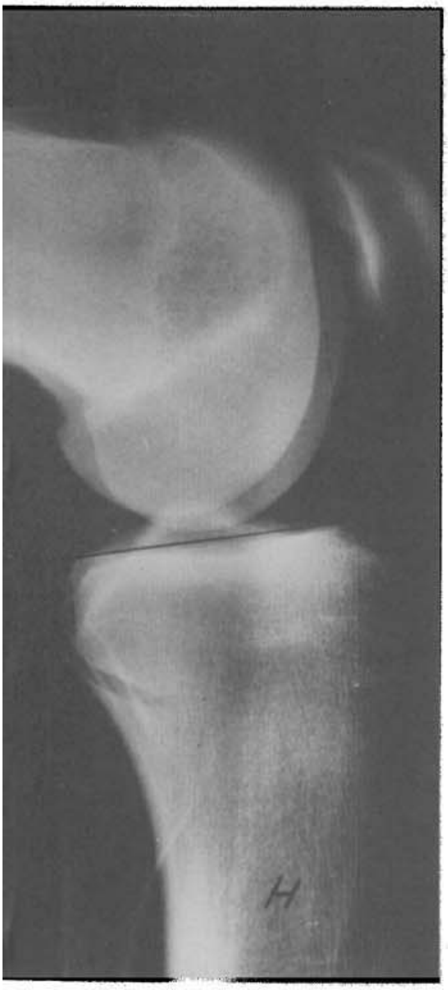
a Very marked medial instability, so marked as to occur only with co-existent rupture of all medial ligaments, the posterior capsule, and both cruciate ligaments. At the same time, the lateral views show anterior and posterior drawer sign,

b and d respectively.

c Neutral position without loading.

The posterior drawer sign is quite marked.

b



c

d

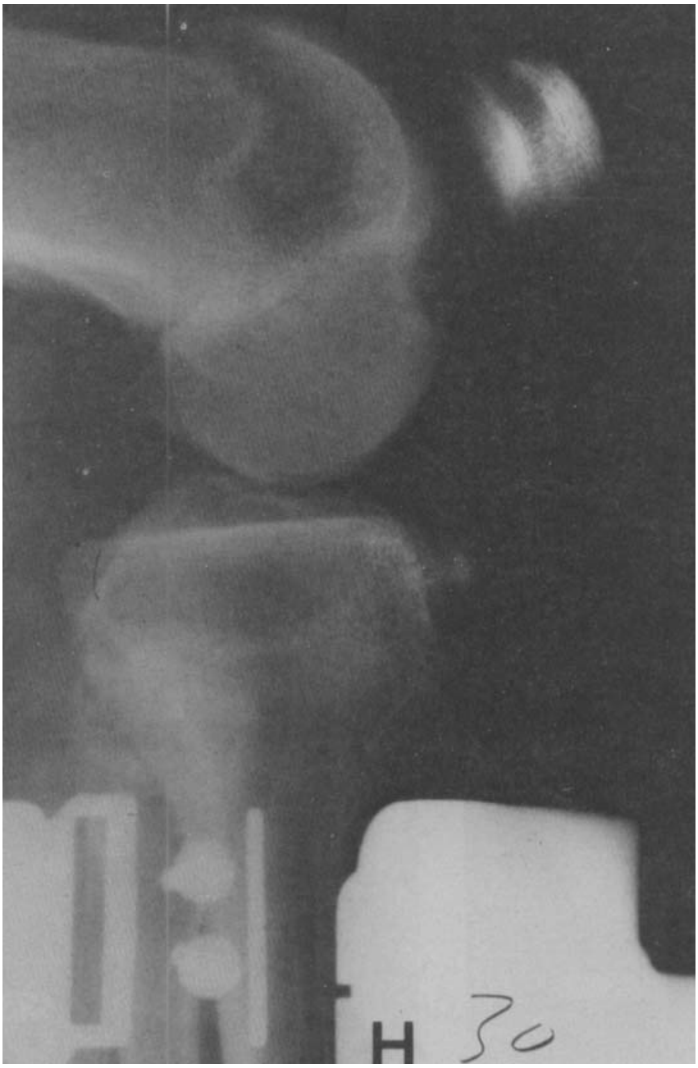


Figure 15: Case 90. Posterior drawer sign, shearing fracture of the digital impression of the area intercondylaris anterior, and impression fracture of the medial femoral condyle. Hyperextension injury.

Figure 16: Lateral instability in rupture of the LCL, iliotibial tract, both cruciate ligaments, posterior capsule, popliteal and biceps tendons. Case 70. Such marked instability does not occur until both cruciate ligaments, the posterior capsule, and the lateral structures have ruptured.

In partial ruptures of the cruciate ligaments a drawer sign was generally not demonstrable. There is an anatomical explanation: The ACL is composed of a posterolateral part, taut in extension and looser in 90° flexion of the knee, and an anteromedial part which is taut in 90° flexion. This phenomenon was described in Chapter 3 b. In 8 of the FN measurements in partial ruptures, the rupture was of the posterolateral fibres (hyperextension injuries), whereas the anteromedial fibres, which are taut in 90° flexion of the knee, the position in which the stress radiography is done, were preserved. In this situation there is no possibility of producing a drawer sign. Therefore, these FN values can in fact hardly be blamed on the measuring abilities of the method.

It is important to point out that there is no free interval between the upper limit of a normal a-p mobility and positive drawer signs due to cruciate injury or between lateral/medial stability and lateral/medial instability. There are quite even transitions from normal values through slightly abnormal values, to large drawer signs or lateral/medial instabilities. This is to be expected in a biological material in which complex injuries are common, and in which the severity of the signs also depends upon the state of other ligaments and of the capsular apparatus (Addendum II). Previous, conflicting findings must have been caused by too strict a clinical selection of the materials (Kennedy and Fowler 1971, Sylvin 1975).

6 b 4: Rotatory instability

Clinical examination was not merely inferior in diagnostic ability (measured by the PV_{pos} and PV_{neg}) for lateral/medial instability and drawer sign. The clinical examiner also had difficulty in assessing whether a rotatory factor entered into the evaluation of the signs. By the gonylaxometer, on the other hand, such an analysis is practicable, even quantitatively, for example Case 105 (Addendum II): Slocum and Larson's (1968) theory could be confirmed: If external rotation is to be demonstrated in the form of an anterior displacement of the proximal end of the tibia with externally rotated foot and tibia, and thus be a sign of injury to the MCLs alone, a test for anterior displacement should be negative in a neutral position, but positive in a position of external rotation of the foot. At the same time, it must be demanded that subsequent operation discloses intact cruciate ligaments and injury exclusively to the MCLs. (Slocum and Larson's test presupposes that it has been ensured a priori that the lateral ligaments are intact). Case 105: Test for anterior drawer sign in "neutral position 90°" (C_n) gave 0.9 mm, i.e. it was negative; with a 15° externally rotated foot it was 3.7 mm, viz. positive; with 30° externally rotated foot it was 6.6 mm, viz. highly positive. A medial instability of 4.5 mm was measured. The operative findings were in agreement with all these findings. There were three similar cases: 101, 106, and 107.

A violent increase of a drawer sign, demonstrated with the foot in a neutral position, was found on repeating the examination in 15° or 30° external rotation in the presence of rupture of the ACL and total rupture of the MCLs (Addendum II, Case 78). This increase in the drawer sign in Slocum and Larson's test also indicates injury to the MCLs.

In all, 59 cases of rotation of different types were demonstrated in

53 knee joints among the 153 cases of knee injury, i.e. some form of rotation in about one-third. Incidentally, all the forms of rotation mentioned under "Definitions" occurred. The most common forms were simple medial rotatory instability (23 cases) and complex anteromedial rotatory instability (20 cases). In most instances the instability and the rotation could be explained by the injuries found at operation (Addendum II). It is likely that the meniscus too influences the rotatory stability, also according to findings in the present material (Case 127 and others).

External rotation (simple medial rotatory instability or complex anteromedial rotatory instability) was found in 32 cases in which the mechanism of the trauma had been identical: abduction-external rotation in a varying degree of knee flexion or on a fully extended knee. This is the most common mechanism of the injury (Addendum II). Internal rotation on pressure was demonstrated in 9 cases. When further looking into these cases it was found that presumably the abduction component had exerted most influence during the trauma. The study does not allow the extraction of any rule as to when the medial ligaments alone rupture in the abduction-external rotation traumas and when the ACL ruptures as well.

It is a very important feature(5 and Addendum II) that in 62% of the injuries sustained more than 3 months previously there was no medial instability when measured from the "neutral position 160°". However, it has been pointed out (5) that this does not indicate anything concerning rotatory instability. In Addendum II it will be demonstrated that 11 of these 23 cases exhibited rotatory instability of some type or other.

6 b 5: Role of the sensory innervation of the ligaments

An interesting phenomenon, mentioned in the description of ligament anatomy (Chapter 3, f), was manifest in the present series of patients.

Payer (1927) and Palmer (1938) suggested that apart from being purely passive stabilizers in the joint, the ligaments presumably had an equally important function as sensory organs, setting the active stabilizers of the joint into action as soon as the joint is approaching an unfortunate extreme position. It was striking, in the present series of injured knee joints, that in many cases of partial ligament rupture, in which some of the nerve fibres must be assumed to have become activated without yet being interrupted, there was resistance against anterior or posterior displacement. In total rupture there was no resistance to displacement, as also pointed out by Palmer (1938, 1958). This has proved to be the case in a number of fresh, isolated partial ruptures of medial collateral ligaments (Cases 12 - 24, 33, 41, Addendum II), in which comparison with the uninjured leg gave a negative value on testing anteroposterior stability. On the other hand, it was possible to demonstrate slight lateral/ medial instability, generally of 2 - 4 mm as compared with the uninjured side. Obviously, it is easier to overcome the reflex-conditioned muscular resistance in the frontal plane in the "160° position" than in the sagittal plane with 90° flexion in the knee. The strong femoral and lower-leg muscles resist anteroposterior displacements of condyles which bear partially ruptured ligaments. The same applies in cases of partial rupture of the cruciate ligaments. The named muscular inhibition of displacement was found also in cases where the ligament fibres had ruptured, but were still assembled beneath the connective-tissue membrane of the ligament.

6 b 6: Practical Scientific Application of the Method

To demonstrate the way in which the method is applicable in practice, let me refer to paper 7. Thirty patients were re-examined about 2 years after surgical treatment of anterior instability due to posttraumatic atrophy of the ACL. The operative method had been that described by Jones (1963, 1970). There were two groups of patients. The former, comprising 25 patients with 25 operated knees, had undergone the operation before the stress radiographic method had been fully developed. The latter, comprising 5 patients with 5 operated knees, had had the operation after the method had become available. In these 5 cases, therefore, there was a possibility of comparing preoperative stress radiographic studies with those at follow-up.

In the former 25 patients the follow-up gonylaxometry was done for medial and lateral instability as well as for anterior and posterior drawer signs, and the result was assessed by comparison with the parameters in the patient's uninjured knee. According to the investigations reported in Addendum I, this ought to be fully satisfactory. The small group of 5 patients acted as controls in this respect (Table 5 in paper 7). These latter patients had had fairly marked drawer signs prior to the operation, and at follow-up they had slight displacements, showing a great, measurable improvement. Moreover, at follow-up the differences between the injured and uninjured knee in these patients were small (exceeding 3 mm in only one case). This agrees with the clinical and subjective evaluation of the results as being good. Those patients of the large group who had similar small drawer signs at follow-up were generally satisfied too. Persisting complaints in two cases were explicable by a posterior drawer sign. A few had slight medial instability. Rotatory instability was not demonstrable in any case. Thus, comparison with the patient's good knee at follow-up is fully up to a comparison of measurements before and after operation. The reason why a few mm of anterior drawer sign was nearly always present at follow-up may be that the new ligament is tightened in the course of the operation with the knee close to extension (175°), whereas at follow-up the measurement is done with the knee in 90° flexion. Therefore, the new ligament represents the posterolateral part of the anatomical ligament which is taut at extension in the knee and lax at 90° flexion (cf. Figs. 4 and 5 in Chapter 3 b), whereas the anterior part of the ACL, taut in 90° flexion, is lacking in the artificial ligament.

In the investigations of injured knees about 3500 parameter measurements were made on the X-ray films.

6 7: Comparison of Present Results with Those of Others Measuring Injured Knees

Clinical testing of an apparatus to determine its diagnostic probability (PV_{pos} and PV_{neg}), *as done here, has not been reported in the literature on this subject* (stability of knee ligaments). Accordingly, it is difficult to compare the diagnostic value of the method with the results of others. But the parameter values can be compared.

Kennedy and Fowler (1971) studied a group of patients with 75 abnormal knees. These were old injuries that can be compared with knees from abnormal group 3 of the present material, viz. injuries older than 3 months. Such patients can be examined without anaesthesia. These authors found medial instability (c-a) of 3.0 mm to 8.5 mm among these patients, or from 0 to 5.0 mm in excess of their "critical level" (3.5 mm). In the present material the critical level ($c_{inj.} - c_{uninj.}$) = 2 mm (inj.=injured knee, uninj. = uninjured knee) in group 3 was exceeded by from 0 to 2.6 mm. Distance $c_{inj.}$ in the most severe case of the group (Addendum II) was 13.6 mm and ($c_{inj.} - c_{uninj.}$) = 4.6 mm. As abnormal materials vary more than do normal ones, there seems to be satisfactory agreement between my findings and Kennedy and Fowler's in this respect.

Kennedy and Fowler's (1971) anterior displacements were measured for each condyle separately, but in cases where the condyles moved equally the values given are mean values, i.e. the anterior drawer sign as defined by the present author. They had two separate groups, one with and one without co-existing medial instability. By Kennedy and Fowler this is reported to have ranged from 6.0 to 12.9 mm in one group and from 7.o to 20.0 mm in the other, i.e. from 1.0 to 15.0 mm in excess of their critical level. No values are given for total displacements in the tables of Addendum II, but they were from 6.3 to 23.8 mm anterior displacement in group 3 (injuries more than 3 months old) in patients with rupture of the ACL, $\overline{x}$ = 11.1 mm. Among fresh anterior drawer signs the range went up to 17.2 mm in the present material. In other words, there is complete agreement between my findings and Kennedy and Fowler's in this respect too.

Kennedy et al. (1974) reported anterior displacements of the same order as above, viz. from 5.1 to 18.2 mm.

Tillberg (1977), measuring the anterior drawer sign by externally fastened apparatus, also reported anterior drawer signs of 10 - 20 mm in older injuries in subjectively very unstable joints. In other words, this is a magnitude about which there is wide agreement.

The last group of patients that Kennedy and Fowler (1971) reported on (their "group I") was characterized by medial instability and anterior displacement of the medial tibial condyle in excess of the critical level (5.0 mm) on traction, while the displacement of the lateral tibial condyle did not exceed this level. To quote these authors "the coincidence of these two displacements suggests external rotational instability or the rotatory instability of Slocum and Larson ....". Thus, already in their first study, Kennedy and Fowler touched upon the possibility of measuring rotatory instability by stress radiography and illustrated it by a case report in which the difference between anterior displacement of the medial and lateral tibial condyle was 9.4 mm. This is a high figure, especially when considering that normally it is the lateral condyle which moves more on traction. Similar values and the same type of rotation were observed in Case 2 of the present material in which the medial tibial condyle was displaced 8.4 mm anteriorly and the lateral one only 2.2 mm, a difference of 6.2 mm. The underlying injury affected only medial structures.

However, most cases of rotatory instability will remain hidden, if this is the only way of investigating the results. A constant comparison of the parameters between the patient's injured and uninjured knee, as introduced in study 6, reveals a far larger number of cases. The explanation is simply that a very great movement of the medial condyle is needed to exceed the normally occurring, greater anterior displacement of the lateral tibial condyle on traction. If this normal condylar movement is "eliminated" by comparison with the patient's good knee, the rotation is not masked by the normally occurring, oppositely directed rotation. Even more cases were detected by means of the formulae developed for the study of rotation.

Roser et al. (1971), in 4 athletes with unstable knees, used a simple stress radiographic method with ropes and pulleys. They measured lateral and medial instability in the 160° position and used "Martin's clear space" (Martin 1960, Chapter 2 b). They found "clear space" medially to be 11 - 21 mm, laterally 10 - 16 mm, and the a-p instability 5 - 11 mm. The latter results are presumably rather inaccurate, as the measurements were made between "the common posterior edges of the femoral condyles" (?) and "the tip of the anterior spine" which may indeed be rounded.

Equipment and methods for measuring rotation in an intact knee were described in Chapter 2 b. This has been measured in normal, living persons by external apparatuses by Meyer (1853), Ross (1932), and Ruetsch and Morscher (1977), but never previously on injured knees.

Let it be mentioned that by the gonylaxometer radiographs of medial and lateral instability can also be taken with extended knees. Demonstration of instability in this position presupposes rupture of both cruciate ligaments and of the posterior capsule (Hallén and Lindahl 1965 a, Dexel et al. 1977). However, such severe injuries are apparent also from the magnitude of the lateral/medial instability in the 160° position (Chapter 6 b and Addendum II).

6 b 8: Comparison with Arthrography

As the diagnostic use of gonylaxometry has been discussed here, arthrography must be mentioned in this connection. The latter method is used for investigating injury to the cruciate ligaments, most favourably in connection with an anterior or posterior drawer manoeuvre. It has been used by Bircher (1933), with single and double contrast, and it has revealed rupture of the cruciate ligaments as well as leakage of contrast medium in capsular injuries in association with ruptures of the collateral ligaments. Lindblom (1938) found arthrography with single contrast to be applicable in old ruptures of the cruciate ligaments, but not in fresh ones, finding that the contours on the radiographs were blurred by clotted blood which rendered the diagnosis uncertain. Palmer (1938) mentioned leakage of contrast medium in capsular injury associated with rupture of the collateral ligaments as a diagnostic sign in some cases, and so did Seyss (1956) and Freiberger et al. (1966). The latter authors used double contrast investigation. Mittler et al. (1972) and Pavlov and Freiberger (1978) recommend double contrast arthrography for visualizing injuries to the cruciate ligaments, but do not give any information about a patient material. According to Butt and McIntyre (1969) and Nicholas et al. (1970), about half the cruciate ligament ruptures are overlooked in

Table 5

Comparison of predictive values from Liljedahl et al.'s arthrographic material (1966) and the present stress radiographic material. Both materials comprise ruptures of the cruciate ligaments (cf. also Table 4).

Liljedahl et al.: Fresh injuries:

TP = 12, TN = 18, FP = 2, FN = 4, total = 36.

$$PV_{pos} = \frac{TP}{TP+FP} = \frac{12}{12+2} = 86\% \ (57\% - 98\%)$$

95% confidence limits

$$PV_{neg} = \frac{TN}{TN+FN} = \frac{18}{18+4} = 75\% \ (53\% - 90\%)$$

Gonylaxometry: From paper 5, Table 4, fresh injuries:

TP = 21, TN = 56, FP = 0, FN = 10, total = 87.

PV_{pos} = 100% (84% - 100%)

PV_{neg} = 85% (74% - 92%).

Partial ruptures are included as ruptures in both materials. All patients underwent surgery.

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this method, FN = 50%. Staple (1972) found single contrast arthrography to be better, but not reliable, and he reported no numerical values from patient Wang and Marshall (1975) stated that the single contrast method was more reliable, but their analysis affords no possibility of a systematic assessment of the method, as only half the arthrographed patients underwent operation. Therefore, it is not possible to assess the FN findings and the predictive values.

The only systematic study that the author has been able to trace is that of Liljedahl et al. (1966). Reviewing an older series from 1940 - 1959, they found a very high percentage of erroneous diagnoses and cases in which the ligament could not be evaluated (36 out of 51 cases) as well as a conside ably better series from 1959 - 1962 (their group I B), and lastly did a syste matic study, immediately followed by operation, on a group (series II) of 36 patients with whom direct comparison is possible. From these authors' Table 3, it is possible to calculate predictive calues (cf. Table 5). The wider confidence limits in Liljedahl et al.'s material are due to its smaller size. Nevertheless, gonylaxometry appears to be more accurate, even when compared with this very carefully performed arthrography material. Examination under general anaesthesia also gives better predictive values.

"Computer-assisted tomography" can visualize an intact cruciate ligament (Pavlov et al. 1978). As yet, there have been no such studies of injured knees.

6 b 9: Comparison with Other Methods

Mention may be made of a few simple measuring apparatuses with which no comparison is possible and which measure only one quality. Klein's (1962), cf. Chapter 2 b, was designed only to measure lateral/medial instability in full extension. In this position the knee is stable in normal persons (Hallén and Lindahl 1965 a). The 2°.3 to 2°.6 abduction and adduction instability measured by Klein may well have been caused exclusively by shifting of the soft tissues. Moreover, the apparatus can reveal only violent injuries, as lateral/medial instability in extension is possible only if rupture has occurred of the collateral ligaments on the side concerned coincident with rupture of both cruciate ligaments and the posterior joint capsule. These injuries are better demonstrated and measured in other apparatuses, e.g. by gonylaxometry, p. 75, Chapter 4 b and Addendum II.

Kalenak and Morehouse (1975) used an apparatus which measured medial and lateral instability "externally" in degrees of an arc. The instabilities they found in normal, uninjured knees on measurement in 10° flexion appear reasonable.

Kittleson et al. (1967), cf. Chapter 2 b "goniometry", did not state any numerical values in their report - and they admit themselves that the apparatus is inaccurate.

Lowe and Saunders (1977) designed an apparatus for acting upon knee joints, one at a time, in a horizontal plane during adduction or abduction in a position ranging from 150° angulation between the femur and tibia through 180° to 190°, and consequently the examinations can be made in these positions. This is possible also in the gonylaxometer, of both legs at the same time. Greater degrees of flexion or a greater measuring potential with regard to the various types of instability are not within the possibilities of their apparatus. The analysis is not radilogical, but graphic goniometry, and the measurements are transferred to a graph by a string-gauge-potentiometer device. An unknown number of subjects had been tested, and at 0° (180° position) a total lateral + medial displacement of 9°.7 is reported. This is in agreement with the fact that full extension and locking of the knee joint in most normal people does not occur until a position of 185° to 187°.

Wirth and Artmann (1974), Chapter 2 b, have performed an analysis of the gliding movement between the tibial and femoral condyles in knee joints with and without the ACL. The method is time-consuming and hardly generally applicable, but the results are very instructive. They show that the proximal end of the tibia without the ACL moves, during the last part (45°) of a loaded extension, in an abnormally great gliding movement at least 10 mm more forward than in a normal knee joint. It returns correspondingly during loaded flexion and this leads to wear on the condylar cartilage. This movement is of an order corresponding to the drawer signs found by me and others (Kennedy and Fowler 1971, Volkov 1971, Tillberg 1977).

CHAPTER 7
CONCLUSION

The object of the present study, viz. to develop further and to investigate the reliability of Kennedy and Fowler's (1971) method for measuring instability in the knee joint for scientific use, was fulfilled as follows:

1. It was demonstrated that the method gives reproducible measurements in physical units, mm. In other words, the inaccuracy when measuring the same parameter in the same person on repeated occasions is suitably small in relation to the parameters measured.

2. Parameter values for injured knees, therefore, can be stored and compared with the findings after treatment has been completed in scientific testing of the value of a therapeutic method.

3. The presupposition is that the ability of the method to distinguish normal from injured knees is sufficiently sharp. This was confirmed by a clinical investigation in which gonylaxometry proved superior to other methods. But first it was necessary to fix the "normal range", i.e. the critical levels in the form of upper limits to the parameter values in non-injured normal knees.

4. The method has a sufficiently wide spectrum of possibilities for measuring various types of instability to cover all known types of instability: lateral and medial instability, anteroposterior instability, simple and complex rotatory instability. The rotation measurements in vivo on injured knees is an innovation, as such measurements have not previously been performed. The author has worked out a standard method including eight exposures which cover the entire spectrum.

5. The method is applicable to different authors' systematic classification of knee instability: Slocum and Larson's (1968), Nicholas' (1973 a), Hughston et al.'s (1976), Trickey's (1977).

Thus the method is the most widely applicable of the scientific measuring methods used so far for measuring instability in the knee, and its accuracy is up to or above that of others known so far.

It seemed reasonable to try assessing the value of the apparatus as a diagnostic aid for clinical use. As used here, with local anaesthesia in acute cases, it exhibited a greater diagnostic certainty (PV_{pos} and PV_{neg}) than investigation under general anaesthesia. However, the difference is so slight that it can hardly outweigh the greater investments in economy and time that gonylaxometry requires. For this reason, the stress radiographic method will hardly come into general use in the clinical departments which will presumabl utilize examination under general anaesthesia also in the future. Ordinary clinical evaluation is very much less reliable than both gonylaxometry and examination under general anaesthesia.

In attempts at elucidating the relationship between the mechanism of a trauma and the pattern of instability, it was possible to demonstrate in the clinical series only that (p 207) abduction-external rotation with the knee i flexion of some extent or other during the trauma may cause simple medial rot tory instability or complex anteromedial rotatory instability combined with medial instability and possibly an anterior drawer sign.

CHAPTER 8
SUMMARY

Chapter 1: The object of the study was to develop a method for reliable measurement of ligament-conditioned stability in the knee joint. The author decided to develop further the method of Kennedy and Fowler (1971) for stress radiographic measurement. Gonylaxometry, viz. measurement of laxity in the knee joint, is a method based on the stress radiographic principle. It is able to measure medial and lateral stability, anteroposterior stability, and rotatory stability. It was the purpose to develop the method for scientific use for measuring these stabilities in mm and to test the reliability of the method.

Chapter 2: On the basis of the literature methods for assessing ligament-conditioned stability in the knee joint are described. In section 2 a the methods reported by others during the past decades for clinical evaluation of stability/instability are reviewed and described. In discussing the various forms of instability, most emphasis is laid on Palmer's (1938) definitions of lateral/medial instability and drawer signs. The systems used by several recent authors for classifying rotatory instability are mentioned. Section 2 b gives a historical survey of instrumental measurement of knee stability, both in specimens of human knees and in vivo. Measuring apparatuses have been designed more for investigating specimens, as in that case they could be fixed direct in bony tissue to obtain accurate results. In vivo measurements have required apparatuses fastened externally and, therefore, giving rise to inaccuracies of the measurement because of shifting of the overlying soft tissues. In the in vivo studies a distinction is made between the above-mentioned form of "external" measurement and radiological measurement. The former comprises:

(1) goniometry,
(2) measurement of anteroposterior displacements in mm,
(3) a combination of (1) and (2), and
(4) photographic methods.

A historical survey is also given of the radiological techniques. The first methods were restricted to demonstrating lateral/medial instability and the drawer signs. In the most recent, most advanced methods it is endeavoured to measure these forms of instability in physical units. Kennedy and Fowler's (1971) apparatus utilizes a measurable mechanical stress action and radiographic exposure in standardized projections, so-called stress radiography. Exposure is made first without stress and then with stress. On the X-ray film it is possible to measure direct a change in the distance between the bones of the joint, represented by further defined landmarks as a measure of stability or instability. This obviates the above-mentioned, incalculable inaccuracy due to shifting of the soft tissues.

Chapter 3: Anatomy of the knee joint elucidated on the basis of the literature. The osseous anatomy is described to the extent that it influences the X-ray anatomy of the knee, including the landmarks to be employed in measuring the parameters on the X-ray film.

The ligaments of the knee joint are built up of collagen connective tissue possessing very little elasticity. Therefore, an intact ligament is an inelastic organ. A certain, slight laxity is present in normal knees to permit normal movements. This function of the ligaments is described for each ligament separately, viz. the superficial and deep medial collateral ligaments, the oblique medial collateral ligament, the lateral collateral ligament, and the cruciate ligaments. Each of the latter can be divided into two functionally different fibre bundles.

The menisci are described in fairly great detail, as recent investigations have shown that the fibres of the medial collateral ligament cross inside the substance of the meniscus, so that injury to the meniscus or its removal close to the periphery damages the collagen fibres of that ligament. The menisci are intimately associated with the ligaments and play a great role in joint stability

The fibrous capsule of the knee joint is composed anterolaterally of one layer, anteromedially of two layers. In between these two layers glides freely the anterior, approx. 10 mm wide, part of the superficial medial collateral ligament. On the medial side the deep layer of the capsule is divisible into three almost equally large parts. The anterior one-third is a thin fibrous layer adhering to the synovial membrane, the middle third is stronger and makes up the deep medial collateral ligament. The posterior third of the fibrous capsule of the knee joint consists of the oblique medial collateral ligament plus collagen fibres which continue into the posterior capsule of the joint.

The extreme strength of the posterior capsule is pointed out.

A summary description is given of the knee joint muscles, because they exert an active, stabilizing action upon the joint. Innervation is described in connection with the role of the reflex arc in activating the muscular stabilizers.

Chapter 4: Anatomical studies had to be carried out by the present author to find suitable landmarks in the joint. Disagreement with the landmarks of Kennedy and Fowler (1971) was found. These findings led to a correction of the method, in particular as regards the identification of the contours of the posterior margins of the tibial condyles on the X-ray film.

Chapter 5: This chapter gives a description of the author's stress radiographic method, gonylaxometry. First, the various types of instability and other concepts are defined. In section 5 b it is emphasized that the gonylaxometer is an apparatus to act upon the lower limb by well-defined stress forces, not a measuring apparatus in itself. A shift of soft tissues beneath the fastening gear also takes place in this machine, and therefore it functions in connection with X-ray exposures during the application of stress. Reading of the parameters is done on the films after exposure. The technique also secures a reproducible direction of the X-ray beam. Pressure is exerted by hydraulic force, the pressure generator being an electrically operated oil pump, doubly secured against too forceful stress actions. The stress action is exerted slowly. Local anaesthesia is applied in cases which are acute or so fresh that a pain reaction is still elicited from the knee joint. The patient is placed in a dental chair, with thighs and feet fastened, the apparatus being adjustable to different leg lengths and different positions of the knee joint. In abduction and adduction exposures a stress force of 9 kp is used, acting at the level of the sole. A rotation moment of force arises (lower-leg length x the force applied). In exposures to reveal drawer signs, a stress force of 20 kp or 30 kp was applied at the proximal end of the tibia and an action straight in the direction of the displacement (no rotation moment). The stress forces applied are appreciably below the tolerance of the ligaments. The exposures are made at 50 - 60 kV and 60 mAs.

Abduction and adduction measurements are made with the knees in 20° flexion (the 160° position). This is an a-p exposure of both knees, before as well as during the application of stress. The film is placed beneath the knees.

In measurements of anterior and posterior instability the knees are flexed 90°. The second metatarsal bone points straight forward, "neutral position 90°". First, an exposure is made of the knee concerned without stress action, thereafter one with pressure and one with traction. The procedure may be repeated with the foot fastened in a position of rotation. Thereafter, the procedure is repeated on the opposite knee, so that the parameters for both knees can be compared.

Measurement of the parameters on the X-ray films is done on a horizontal viewing box illuminated from below. Lateral/medial instability is measured on the a-p view. Two baselines are placed through the most distal points of the femoral condyles and the most distal contours of the articular surfaces of the tibial condyles respectively. Medial instability, parameter c, is cut off on a tangent to the most medial point of the tibial condyle, at right angles to the baseline on the tibial condyle. Similarly, parameter d, lateral instability, is measured on a tangent as the distance cut off between the tibial and femoral baselines. The parameters for anterior and posterior displacement are measured on the lateral radiograph on a baseline on the joint socket of the medial tibial condyle. On this line are dropped perpendicular lines which are tangents to the most anterior and most posterior points of the femoral and tibial condyles respectively. The parameters are cut off on the baseline between these tangents. One parameter is measured for the lateral pair of condyles and one for the medial. On traction, the parameters diminish, the posterior edges of the tibia approaching the anterior edges of the femoral condyles. During pressure the reverse applies. The mean of the differences from the unloaded knee joint indicates the mean displacement in the anterior or posterior direction: If the exposure has been made in "neutral position 90°", this is defined as anterior and posterior displacement respectively, and at abnormally high values as anterior and posterior drawer sign. If the condyles are unequally displaced, there is rotation. Formulae for calculating such displacements are set up. By examinations of normal persons the normal ranges and 97½% upper normal limits, "critical levels", of these displacement patterns were found. Comparison is made preferably with the subject's other knee, and critical levels for the difference between the two knees were also determined.

Magnification on the X-ray film averages 10%. A pssoibility of distortion of the actual appearances on the X-ray film due to different magnification of points close to and far from the film are discussed. It is concluded that the far greater mobility of the lateral than of the medial tibial condyle in normal knees on traction and pressure cannot be explained by such differences in magnification.

Parallax errors do not occur in exposures with a lateromedial direction of the beam. In a-p exposures the possibility of a parallax error is so slight that in practice it is negligible.

Inaccuracy of measurement on repeated exposures and measurements on the X-ray films of the same parameters in the same subjects were studied by triple examinations of 33 persons. The 95% confidence limits proved to be $< \pm 1.2$ mm for medial and lateral stability and $< \pm 2.4$ mm for anteroposterior stability. Less interest attaches to actual inaccuracy of reading the same parameter from the same film from one occasion to another. For 4 parameters investigated it was about two-thirds of the inaccuracy reported above.

For a standard procedure the author recommends a series of stress exposures consisting of two a-p exposures of both knees simultaneously and three lateral exposures of each knee separately in "neutral position 90°". The a-p exposures of the two knees on the same film afford measurement of medial and lateral instability. An a-p exposure of the unloaded knee has proved unnecessary. The six lateral exposures afford measurement of anteroposterior instability and the predominant part of cases with rotatory instability. Thereby, the number of exposures was reduced to eight.

It seems most reasonable to state the results in whole mm. Measurements and calculations were performed with one decimal. The critical level is 2 mm for lateral/medial stability/instability, 3 mm for anterior and posterior displacement in the form of the difference between the patient's injured and uninjured knee. This is saying that levels $\leqq 2$ mm are normal, levels $\geqq 3$ mm abnormally elevated for medial and lateral stability. For anteroposterior displacement and rotation values $\leqq 3$ mm are normal and values $\geqq 4$ mm abnormal.

Contra-indications to the examination are: Life-threatening states, injuries to the popliteal artery or peroneal nerve, major fractures of adjacent bones, intraarticular fractures, and radiologically demonstrated bony insertion avulsions of the ligaments.

Chapter 6: Present investigations and results. The first section deals with the examinations of 100 normal persons. The named inaccuracies of measurement and critical levels were based upon the findings in this material. The normal ranges were found for parameter size, but also for differences between a person's two knees for all parameters. It proved advisable to use this difference, as it varies within a very narrow range, while the parameter values themselves have very wide ranges. Consequently, it is more difficult to state, on the basis of the last-mentioned normal ranges, whether or not a parameter is normal. However, they have to be used if both knees are injured.

On the basis of the landmarks determined by anatomical and radiographic anatomical studies, it was possible to demonstrate that during traction or pressure the lateral tibial condyle moves about twice as much as the medial one in normal knees. In other words, internal rotation occurs on traction, external rotation on pressure. The normal ranges of this movement and of the difference between a person's two knees were also determined. Similar series of investigations were performed with the subject's feet fixed in 15° and 30° external rotation and in 30° internal rotation. Good agreement was found with the studie of several authors, each dealing with their part of the instability "spectrum". The present author disagrees with Markolf et al. (1978) and is of the opinion that their finding of marked differences between the same parameters in the two knees of a normal person are due to an inaccurate method.

Section 6 b reports the testing of the ability of the method to distinguish between normal and injured knees in a material of 153 injured knees. All the examined patients subsequently underwent operation, and thus the gonylaxometric findings could be compared with the operative findings. The gonylaxometer showed anterior drawer sign, with the foot pointing straight forward, in injuries to the anterior cruciate ligament, posterior drawer sign in injuries to the posterior cruciate ligament. Small positive values for medial instability $(c_{\text{injured}} - c_{\text{uninjured}}) > 2$ mm to $\leqq 4$ mm were found in cases with rupture of the deep medial collateral ligament and the oblique medial collateral ligament, without total rupture of the superficial medial collateral ligament. Higher positive values $(c_{\text{injured}} - c_{\text{uninjured}}) > 4$ mm, were found in total rupture of the superficial medial collateral ligament, and even higher values when rupture of the cruciate ligaments and rupture of the posterior joint capsule co-existed. There were only a few injuries of the lateral collateral ligament in the material.

In all, 59 cases of different abnormal rotational phenomena were observed. They consisted in simple medial rotatory instability in 23 cases and complex anteromedial rotatory instability in 20. It was demonstrated that rotatory instability may well exist in a knee with very little persisting lateral/medial instability. In external rotatory instability, simple or complex, the mechanism of the trauma was in most cases the same, viz. abduction-external rotation in combination with a varying degree of knee flexion.

Gonylaxometry was compared with clinical examination and with examination under general anaesthesia in this material. Gonylaxometry showed the greatest diagnostic reliability, estimated by the predictive values, but closely followed by examination under general anaesthesia. It was far superior to clinical examination. In the discussion its diagnostic value is compared with that of other methods. According to most authors, arthrography affords inaccurate results with respect to ligament ruptures. In the literature the author could find only one well conducted study reporting very careful arthrography, with which comparison could be made. However, it clearly showed lower diagnostic predictive values of positive or negative findings than gonylaxometry and also lower than examination under general anaesthesia.

Chapter 7: It is concluded that the gonylaxometric method possesses a very high diagnostic accuracy, higher than other known methods, i.e. good agreement with operative findings. It has a wider spectrum of investigative possibilities than other known methods, affording a possibility of measuring, apart from lateral/ medial instability and anteroposterior instability, also all rotation patterns. It measures in known physical units, mm, by a reproducible and known stress force and a reproducible direction of the X-ray beam. Therefore, it is a good scientific measuring method.

For clinical diagnostic use it is too time-consuming in the form used here as compared with examination under general anaesthesia which has approximately the same predictive values in examining for lateral/medial instability and anteroposterior instability. Accordingly, examination under general anaesthesia, which does not require any special equipment, will presumably be preferred for clinical use in our hospital departments. Ordinary clinical examination is much less reliable than the two methods discussed above.

SUMMARY IN DANISH

Kapitel 1: Arbejdets formål har været at udvikle en metode til pålidelig måling af ligamentært beginget stabilitet i knæleddet. Forfatteren har valgt at videreudvikle den af Kennedy og Fowler (1971) beskrevne metode til stress-radiografisk måling. Gonylaxometri, knæ-løshedsmåling, er en metode, der arbejder efter det stress-radiografiske princip. Den kan måle medial og lateral sidestabilitet, antero-posterior stabilitet og rotationsstabilitet. Det har været formålet at udvikle metoden til videnskabeligt brug med henblik på måling af disse løsheder i mm, samt at afprøve metodens pålidelighed.

Kapitel 2: Der er ud fra litteraturen givet en beskrivelse af metoder til bedømmelse af ligamentært betinget instabilitet i knæleddet. I kapitel 2 a er klinisk instabilitetsbedømmelse historisk belyst og beskrevet, som de seneste årtiers forfattere har redegjort for deres metoder. Under omtalen af de forskellige instabilitetsformer er hovedvægten lagt på Palmers (1938) definitioner af sideinstabilitet og skuffesymptomer. Flere nyere forfatteres systematik ved inddelingen af rotationsinstabilitet er omtalt.

I kapitel 2 b er givet en historisk oversigt over instrumentel måling af knæets stabilitet, dels på humane knæledspræparater, dels in vivo. Måleapparaturer har i videre udstrækning været konstrueret til undersøgelser på præparater, da man her har kunnet fiksere dem direkte i knoglevæv og således opnå nøjagtige resultater. Ved måling in vivo må benyttes udvendigt på underekstremiteten fastspændte apparaturer, hvor unøjagtigheder i målingerne opstår på grund af bløddelsforskydninger over knoglerne. Ved undersøgelser in vivo skelnes mellem ovennævnte form af "extern" måling og radiologisk måling. Den førstnævnte omfatter

1. goniometri, vinkelmåling,
2. måling af antero-posteriore forskydninger i mm,
3. en kombination af 1. og 2. og
4. fotografiske metoder.

Radiologisk undersøgelsesteknik er ligeledes gennemgået historisk. De første metoder indskrænkede sig til påvisning af sideinstabilitet og skuffesymptom; ved de seneste og mest avancerede tilstræbes en måling af disse instabilitetsformer i fysiske enheder. I Kennedy og Fowlers apparatur (1971) benyttes en målelig mekanisk kraftpåvirkning og røntgenoptagelse i standardiserede projectioner herunder; den såkaldte stress-radiografi. Der eksponeres først uden kraftpåvirkning, derefter under en sådan påvirkning. På røntgenfilmen kan direkte måles en afstandsændring mellem leddets knogler, repræsenteret ved nærmere definerede "landmarks" som mål for stabilitet eller instabilitet. Man undgår herved den ovenfor nævnte uberegnelige usikkerhed fremkaldt af bløddelenes forskydning.

Kapitel 3: Knæleddets anatomi belyst ud fra litteraturen. Den ossøse anatomi er behandlet i det omfang, den har betydning for knæleddets røntgenanatomi, herunder de "landmarks", der skal benyttes ved udmåling af parametre på røntgenfilmen.

Knæleddets ligamenter er opbygget af kollagent bindevæv med meget lille elasticitet. Et intakt ligament er derfor et uelastisk organ. En vis lille løshed er til stede i normale knæ for at tillade normale bevægelser. Denne funktion af ligamenterne er omtalt for hvert ligament for sig. Det drejer sig om ligamentum collaterale mediale superficiale et profundum, ligamentum obliquum mediale, ligamentum collaterale laterale og ligamenta cruciata. De sidstnævnte kan hver opdeles i to funktionelt forskellige fiberbundter.

Menisci er omtalt relativt udførligt, idet undersøgelser i de seneste år har vist, at ligamentum collaterale mediales fibre krydses inde i menisksubstansen, således at en menisklæsion eller meniskfjernelse nær meniskens periferi beskadiger ligamentets kollagene fibre. Menisci er intimt forbundet med ligamenterne og har stor betydning for leddets stabilitet.

Knæleddets fibrøse kapsel består fortil lateralt af eet lag, fortil medialt af to lag. Den forreste ca. 10 mm brede del af ligamentum collaterale mediale superficiale glider frit mellem de to lag. Det dybe kapsellag kan på medialsiden inddeles i 3 omtrent lige store dele. Den forreste 1/3 er et tyndt fiberlag adhærent til synovialis; den midterste 1/3 er stærkere og udgør ligamentum collaterale mediale profundum. Den posteriore 1/3 af knæleddets dybe fibrøse kapsel udgøres af ligamentum obliquum mediale plus kapselfibre, der kontinuerligt fortsætter i leddets posteriore kapsel.

Den overordentlige styrke af den posteriore kapsel er fremhævet.

Knæleddets muskler er summarisk omtalt, fordi de kan udøve en aktiv, stabiliserende virkning på leddet. Innervationen er omtalt i forbindelse med refleksbuens betydning for aktiveringen af de musculære stabilisatorer.

Kapitel 4: Egne anatomiske undersøgelser har været påkrævet, idet en klarlæggelse af egnede landmarks i leddet har været nødvendig. Der er fundet uoverenststemmelse med de af Kennedy og Fowler (1971) anvendte landmarks.

Disse fund har ført til korrektion af metoden, specielt hvad angår identifikationen af tibiakondylernes bagkantkonturer på røntgenbilledet.

Kapitel 5 indeholder en beskrivelse af forfatterens stress radiografiske metode, gonylaxometri. Der indledes med de anvendte definitioner af instabilitetstyper og andre anvendte begreber. I 5 b betones det, at gonylaxometeret er et apparat til påvirkning af underekstremiteten med veldefinierede kræfter, ikke et måleapparat i sig selv. En forskydning af bløddelene under fastspændingsapparaturet finder også sted i dette apparat. Det arbejder derfor i forbindelse med røntgenoptagelser under kraftpåvirkningen. Aflæsning af parametrene foregår på røntgenfilmene efter eksponering. Denne teknik sikrer tillige en reproducerbar stråleretning. Trykpåvirkningen sker hydraulisk, og trykgeneratoren er en elektrisk drevet oliepumpe, dobbeltsikret mod for store kraftpåvirkninger. Kraftpåvirkningen foregår langsomt. Der anvendes lokalanæstesi i tilfælde, der er helt akutte eller så friske, at der stadig er smertereaktion fra knæleddet. Patienten er anbragt på en tandlægestol med fastspændte femora og fødder, idet apparaturet kan tilpasses forskellige ekstremitetslængder og forskellige stillinger af knæleddet. Ved abduktions og adduktionsoptagelser benyttes en kraft på 9 kp med angrebspunkt i fodsålens niveau. Der opstår et drejningsmoment, hvor kraftens arm er lig personens cruslængde. Ved optagelser af skuffesymptom er benyttet kræfter på 20 kp og 30 kp med angrebspukt direkte i ekstremitas proximalis tibiae og virkning direkte i displaceringens retning (intet drejningsmoment). De benyttede kræfter ligger betydeligt under ligamenternes tolerance. Ved eksponeringerne er benyttet 50 til 60 kV og 60 mAs.

Ab- og adduktionsmåling foretages med patientens knæ 20° flekterede (160°-positionen). Det er en a-p optagelse af begge knæ dels uden og dels under kraftpåvirkning. Filmen er placeret under personens knæ.

Ved måling af anterior og posterior løshed er patientens knæ flekteret 90°. Anden fodstråle peger direkte fremad "neutral position 90°". Der optages først et billede af det pågældende knæ uden kraftpåvirkning, derefter et med tryk og et med træk. Eventuelt gentages proceduren med foden fastspændt i en roteret position. Herefter gentages proceduren for det modsatte knæ, således at en sammenligning af parametre fra de to knæ bliver mulig.

Udmåling af parametrene på røntgenfilmene foregår på en vandretliggende matglasplade belyst nedefra. Målinger af sideløshed foregår på a-p optagelsen. To grundlinier placeres gennem henholdsvis de mest distale punkter af femurkondylerne og de mest distale konturer af tibiakondylernes ledflader. Medial sideløshed, parameter c, afskæres på en tangent til det mest mediale punkt på tibiakondylen, vinkelret på grundlinien på tibiakondylen, mellem de to grundlinier. Tilsvarende måles parameter d, lateral sideløshed, på en vinkelret til tibia grundlinien, afskåret mellem tibia- og femur-grundlinien. Parametrene for anterior og posterior forskydning udmåles på en grundlinie gennem forreste og bageste punkt af den mediale tibiakondyls ledskål. Herpå nedfældes vinkelrette der tangerer de forreste og bageste punkter på henholdsvis femurkondyler og tibiakondyler. Parametrene afskæres mellem disse tangenter. Der måles en parameter for det laterale kondylpar, en for det mediale. Ved træk mindskes parametrene, idet tibiabagkanterne nærmer sig femurkondylernes forkanter. Ved trykpåvirkning findes det omvendte forhold. Gennemsnittet af forskellene fra det upåvirkede knæled angiver middeldisplacering anteriort eller posteriort: Hvis optagelsen er foretaget i "neutral position 90^{o}", er dette defineret som henholdsvis anterior og posterior displacering; ved patologisk høje værdier henholdsvis anteriort og posteriort skuffesymptom. Forskydes kondylerne ulige meget er der tale om rotation. Formler for beregning af sådanne displaceringer er opstillet. Ved undersøgelser af normale personer er fundet normalområder og 97½% øvre normalgrænser, "critical levels", for disse displaceringsmønstre. Der sammenlignes helst med personens andet knæ og grænser for forskellen mellem de to knæ er ligeledes fundet.

Forstørrelsen er gennemsnitlig 10% på røntgenbilledet. Muligheder for fortegning af de virkelige forhold på røntgenbilledet på grund af forskellig forstørrelse af filmnære og filmfjerne punkter i knæleddet er gennemgået. Det konkluderes, at den langt større bevægelighed af den laterale tibiakondyl ved træk og tryk end af den mediale ikke kan forklares ud fra disse forskelle i forstørrelsen.

Parallaksefejl forekommer ikke ved optagelserne med latero-medial strålegang. Ved a-p optagelserne er muligheden for parallaksefejl så lille, at der i praksis kan ses bort fra den.

Måleusikkerhed ved gentagne fotograferinger og målinger på røntgenfilmene af samme parametre hos de samme forsøgspersoner er undersøgt ved tripple undersøgelser hos 33 personer. Den er med 95% sikkerhedsgrænser < ± 1,2 mm for medial og lateral sideinstabilitet og < ± 2,4 mm for antero-posterior stabilitet. Egentlig aflæsningsusikkerhed fra gang til gang ved aflæsning af samme parameter på samme film har mindre interesse; den er for fire undersøgte parametre ca. 2/3 af den ovenfor nævnte måleusikkerhed.

Som standardprocedure anbefales en serie stress-optagelser bestående af to a-p optagelser og tre sideoptagelser af hvert knæled for sig i "neutral position 90°". Man opnår på a-p optagelserne af de to knæled samtidig: måling af medial og lateral sideløshed. A-P optagelse i ubelastet stilling er fundet overflødig. Ved de seks sideoptagelser opnås måling af anteroposterio løshed samt den overvejende del af rotationsinstabile tilfælde. Antallet af eksponeringer er herved reduceret til otte.

Det findes mest rimeligt at angive resultater i hele mm. Målinger og beregninger udføres med een decimal. Kritisk grænseniveau, "critical level' er 2 mm for sidestabilitet, 3 mm for anterior og posterior displacering i form af differensen mellem patientens læderede og raske knæ. Dette skal forstås sådan, at værdier $\leq$ 2 mm er normale, værdier $\geq$ 3 mm er patologisk forhøjede for medial og lateral stabilitetsmåling. For antero-posterior displacering og rotation gælder, at værdier $\leq$ 3 mm er normale og værdier $\geq$ 4 mm er patologiske.

Kontraindikationer mod undersøgelsen er: livstruende tilstande, læsio arteriae popliteae sive nervi peronei, større fracturer i tilstødende knogler, intraartikulære fracturer, røntgenologisk påviste insertionsafrivninger af ligamenterne.

Kapitel 6: Egne undersøgelser, resultater. Første afsnit omhandler undersøgelser på hundrede normale forsøgspersoner. De omtalte måleusikkerheder og kritiske grænseniveauer er fundet på grundlag af dette materiale. Der er fundet normalområder for parametrenes størrelse, men også for forskellen mellem en persons to knæ for alle parametre. Det har vist sig formålstjenli at benytte denne differens, idet den varierer inden for et meget lille områd medens parameterværdierne selv har meget brede normalområder. Følgelig er det vanskeligere på baggrund af de sidstnævnte normalområder at udtale sig om, hvorvidt en parameter er normal eller ej. Man er imidlertid tvunget til at benytte disse, hvis begge knæ er læderede.

På grundlag af de ved anatomiske og røntgenanatomiske studier fundne landmarks har det været muligt at påvise, at den lateral tibiakondyl under træk eller tryk bevæges omtrent dobbelt så meget som den mediale i normale knæ. Der forekommer altså en rotation indad ved træk, udad ved tryk. Der e også fundet normale grænser for denne bevægelse og for differensen mellem samme persons to knæ. Lignende undersøgelsesrækker er gennemført med forsøg personens fødder fikseret i 15°'s og 30°'s udadrotation og 30°'s indadrotati Der er fundet god overensstemmelse med en række forfatteres undersøgelser af hver deres del af instabilitets-"spektret". Forfatteren er uenig med Markolf et al. (1978) og mener, at deres fund af store differenser mellem samme parametre i en normal persons knæ beror på en unøjagtig metode.

I andet afsnit, kapitel 6 b, er på 153 læderede knæ undersøgt metodens evne til at skelne mellem normale og læderede knæ. Alle undersøgte patienter er opererede, således at gonylaxometrifundet har kunnet sammenlignes med operationsfundet. Man fandt anteriort skuffesymptom, med foden ret fremad, ved læsion af ligamentum cruciatum anterius, posteriort skuffesymptom ved læsion af ligamentum cruciatum posterius. Små positive værdier for medial sideinstabilitet $(c_{syge} - c_{raske}) > 2$ mm til ≤ 4 mm fandtes ved ruptur af ligamentum collaterale mediale profundum og ligamentum obliquum mediale uden samtidig total ruptur af ligemtnum collaterale mediale superficiale. Større positive værdier, $(c_{syge} - c_{raske}) > 4$ mm fandtes ved total ruptur af ligamentum collaterale mediale superficiale; endnu højere værdier når korsbåndsrupturer og ruptur af leddets posteriore kapsel samtidig var til stede. Der er kun få læsioner af ligamentum collaterale laterale i materialet.

Der påvistes i alt 59 tilfælde af forskellige former for abnorme rotationsfænomener. Det drejede sig om simpel medial rotations-instabilitet i 23 tilfælde og kompleks anteromedial rotationsinstabilitet i 20 tilfælde. Det er vist, at der meget vel kan være rotationsinstabilitet i knæ med meget ringe persisterende sideløshed. Udadrotationsinstabilitet, simpel eller kompleks, havde i de fleste tilfælde en fælles traumemekanisme: abduktion-udadrotation i forbindelse med en varierende grad af knæflektion.

Den gonylaxometriske metode er i dette materiale sammenlignet med klinisk undersøgelse og undersøgelse i universel anæstesi. Den fremviste den største diagnostiske sensitivitet og specificitet, dog tæt fulgt af undersøgelse i universel anæstesi. Den var langt bedre end klinisk undersøgelse. I diskussionen er sammenlignet med andre metoder i diagnostisk henseende. De fleste forfattere angiver, at arthrografi giver unøjagtige resultater med hensyn til undersøgelse af ligamentrupturer. Der er i litteraturen kun fundet een velgennemført undersøgelse, med meget omhyggeligt udført arthrografi, med hvilken der kan sammenlignes. Denne fremviser dog klart lavere diagnostisk specificitet og sensitivitet end gonylaxometri og undersøgelse i universel anæstesi.

Kapitel 7: Det konkluderes at den gonylaxometriske metode har en meget høj diagnostisk sikkerhed, højere end andre kendte, d.v.s. god overensstemmelse med operative fund. Den har et større spektrum af undersøgelsesmuligheder end andre kendte, idet den rummer mulighed for målinger af samtlige rotationsmønstre, foruden sideløshed og antero-posterior instabilitet. Den måler i kendte fysiske enheder, mm, med reproducerbar og kendt kraftpåvirkning og reproducerbar røntgenstråleretning. Den er derfor en god videnskabelig målemetode.

Til almindelig klinisk diagnostisk brug er den for tidsrøvende i den her anvendte form i forhold til undersøgelse i universel anæstesi, der for sideløshed og antero-posterior instabilitetsbedømmelse har omtrent samme diagnostiske sensitivitet og specificitet. Undersøgelse i universel anæstesi, der ikke kræver specialudstyr, vil derfor formentlig blive foretrukket i den almindelige klinik på vore hospitalsafdelinger.

ADDENDUM I

ANALYSIS OF GONYLAXOMETRIC RESULTS IN 100 NORMAL SUBJECTS

Addendum I: Contents Page

This Addendum contains documentation and analysis of the results of measurements in stress radiography, gonylaxometry, of normal persons, since the medical journals in which the previous papers have been published have not had space for exhaustive documentation.

Moreover, the material of normal persons was extended from the original 50 to 100, and the measuring results for the 100 normal persons are best presented combined.

The object of the measurements on normal persons was partly to assess the accuracy of the method, i.e. the certainty or uncertainty of the measurement on repeated measurements on the same person (done on the former half of the normal material, subjects C_a1 - C_a50) and to establish the <u>mean magnitude</u> of the knee joint parameters in given positions of flexion and rotation. A further object was to ascertain the <u>standard deviations (SD)</u> and <u>upper normal limits</u>, hereafter called <u>"critical levels"</u> of the same parameters. These investigations were performed on both halves of the normal material. However, the conditions (traction/pressure forces and rotatory position of the foot) were altered in the latter half of the material (subjects C_b51 - C_b100) in order to elucidate also the influence of these alterations. Therefore, the two halves of the material are best presented in the named order.

Normal Material. Admission Criteria

These admission criteria, meaning the conditions for admitting a person to the normal material, were quite unchanged from subject 1 - 100 and will therefore be discussed collectively. Special records have been kept for all the 100 normal subjects, substantiating that they have never had knee injuries, articular diseases, or complaints from the knee joints, and their knees have proved sound at clinical examination. Quadriceps measurements 10 and 15 cm proximally to the base of the patella (as thigh circumference) excluded quadriceps atrophy (the difference between the person's two thighs was to be < 1 cm). Furthermore, I excluded persons with hydrarthrosis, thickening of the joint capsules, restricted mobility in the joint, clinically detectable medial or lateral instability, rotatory instability or drawer sign, tenderness of the joint line, as well as increased laxity of the posterior joint capsule. Thus, I excluded persons who could extend their knee joints beyond the 195° position (measured on the lateral aspect of the leg from the tip of the lateral malleolus to the lateral femoral epicondyle and the tip of the greater trochanter). These measurements were performed with a specially designed goniometer with 50 cm long arms. Persons with valgus position of the knee exceeding 10° were also excluded, seeing that Thestrup Andersen (1955) found the variation of the angle between the femur and tibia in the frontal plane to range from 0° to 10° in a material of 100 persons with sound knees. The length of both lower limbs was measured, from the tip of the lateral malleolus to the proximal margin of the greater trochanter, as the object was to find an expression of the dimensions of the limb itself, not of a lopsided pelvis, valgus deformity of the femoral neck, or the like. Persons in whom the length of the two legs differed by more than 1½ cm were excluded.

No abnormalities were found on the X-ray films of this series.

All the controls were in the age range 20 - 50 years except for one who was 52. This age range was due partly to the possibility of recruiting persons who were willing to participate and partly to my disinclination to expose persons of a younger age to radiation for experimental purposes. Empirically, the age group between 17-18 years and 40 years is particularly prone to sustain ligament injuries in the knee joint (compare (3) Table 1 with (5) Table 1). Thus, the age distribution of the normal material is relevant, i.e. it corresponds to the age of that group of the population which risks sustaining injuries to the knee ligaments. Of course, such injuries occur also in younger and older age groups. In practice, however, the critical levels found can be used for them too (5).

The sex ratio in both parts of the normal material, and thus also in the total normal material, is 1:1. Those who acted as subjects were students, doctors, nurses, nurses' aides, hospital porters, engineers, clerical staff, and teachers, in other words a fairly broad section of the population. A large part of the hospital staff carry out physical work which makes rather great demands on the lower limbs. Nearly all of them went in for some form of sport, but only one man took part in exacting athletic competitions. Technical details and measuring methods have been described.

First Control Group (C_a)

The measurements on the first group of normal healthy controls, C_a1 - C_a25 females and C_a26 - C_a50 males (ratio 1:1), were made in 1973, from February to May incl. All were carried out by the present author as described in (3) and (4). As shown in Table 1, these first 50 normal persons were divided into two groups. In group I the ab- and adduction force was 9 kg, traction and pressure force 20 kg, while other forces were employed in group II. At

Table 1

Age distribution and sex ratio (material C_a)

Age	Females			Males		
Years	total	group I	group II	total	group I	group II
20-30	22	15	7	18	13	5
31-52	3	2	1	7	4	3
20-52	25	17	8	25	17	8

this site there is a need only for emphasizing the statistical analysis of the results in group C_a and the fact that a part of the investigations was performed as a triplicate analysis, not merely a test/retest examination (viz. a duplicate analysis). This triplicate test was carried out on 32 control persons (33 for parameters c and d), 16 females and 16 (17) males, and the statistical analysis was performed as a two-sided variance analysis+).

Let it be stated here that the force used to act upon the knee joint is that reported in paper (3). The movements are performed slowly, and when the hydraulic cylinder which induces the force meets with resistance of the same magnitude to which it is adjusted it stops and thereafter exerts only a static action. The force may also be designated kp, and for conversion to N (Newtons) the conversion factor is 9.81 (Geigy's tables, p. 186), so that 1 kp = 9.81 N. This factor is erroneously lacking in (4). 9 kg pressure force = 9 kp = 9 x 9.81 N = 88.29 N was used in abduction and adduction to act upon the foot. During stress on the 90° flexed knee a force of 20 - 30 kp was used to provoke a possible anterior or posterior drawer sign. When converted it is e.g. 20 x 9.81 N = 196.2 N (in a person weighing 60 kg the force is 3.27 N per kg body weight). This is far below the tensile strength of the ligaments, as was discussed in the main survey.

+) Recommended by Bjørn Andersen, M.D., adviser in medical statistics to the Danish Medical Research Council and carried out by Erik Kousgaard, M.Sc. (stat.).

Evaluating the Accuracy of the Measurement

The test/retest method was used on all the first 50 subjects discussed in papers (3) and (4), and for each parameter the first and second measuring results, x_1 and x_2, were compared as advocated by Therkelsen (1968)+). It applies, then, to the difference $d = x_1 - x_2$:

Variance $= s^2 = \frac{1}{2k} \sum_1^k d^2$. As I have called the standard deviation SD' and the number of duplicate determinations N instead of k, the formula is

$$(SD')^2 = \frac{1}{2N} \sum d^2 = \frac{\sum d^2}{2N} \quad \text{or} \quad SD' = \sqrt{\frac{1}{2N} \sum d^2}$$

which regrettably has been distorted in various ways during the printing of (3) and (4). However, this formula was used in all calculations, also in those tabulated in (3) and (4). The calculations were performed on a table calculator with writer (Compucorp 445, Statistician^R in the laboratory of Dept. C of the Gentofte University Hospital, Copenhagen).

Table 2 gives the standard deviations of the four parameters which had originally been intended for describing medial and lateral stability in the frontal plane: a, b, c, and d.

For comparison, it gives the mean difference between the duplicate measurements of the parameter concerned. This value gives an impression of the measuring accuracy - and of a fairly great accuracy (the mean difference for a, b, c, and d being between 1/4 and 3/4mm).

During the course of the research programme in the gonylaxometer it was observed that the resting position "neutral position 160°" was poorly defined, as each subject felt the knee relaxed at a fairly varying distance of the shoe from the mid-position of the apparatus. For this reason this initial position - and accordingly also parameters a and b - were rejected as inapplicable in the measurements (4). However, they were measured in the first 50 subjects, and from the findings in Table 2 it is apparent that this uncertainty with respect to the position of the foot has not affected the knee parameters a and b. The standard deviation, SD', is even particularly low for a, a little greater for b, but not so great that their use had serious consequences to the measurements.

In fairness, then, it may be said, cf. (4) and Kennedy and Fowler (1971) that a and b (and c-a = medial stability, d-b = lateral stability)

+) Recommended by the adviser in medical statistics to the Research Council and performed by the author.

Table 2

Standard deviation, SD', for the parameters for measuring medial and lateral stability in 34 normal persons (group I). Units: mm. $\bar{x}d$= mean difference in duplicate measurements.

parameter	right		left	
	SD'	$\bar{x}d$	SD'	$\bar{x}d$
a = medial distance, unstressed joint	0.31	0.28	0.31	0.28
b = lateral distance, unstressed joint	0.71	0.74	0.59	0.70
c = medial distance during abduction (valgus stress)	0.53	0.55	0.56	0.62
d = lateral distance during adduction (varus stress)	0.58	0.61	0.59	0.65

were rejected not because they were too inaccurate, but because it is an advantage to use fewer parameters (c = medial stability, d = lateral stability).

The importance of SD' (standard deviation) is as follows: Parameter c in a person (sick or healthy) must be with 95% certainty within the measured c value $\pm\ t_{2\alpha}$ SD' (or in other words: will be within this limit with 95% certainty in a repeated measurement) $t_{2\alpha} = 2.03$ for 34 measurements, and the confidence limits for the measuring method, or in other words the accuracy of the measurement will be ± 2.03 x SD'. ($t_{2\alpha}$ may be read from a table on the t distribution, e.g. Geigy's tables 1960). The values for SD' and ± 2.03 x SD' are shown in Table 3. Thus, the inaccuracy of the measurement will in all cases be less than ± 1.2 mm for medial and lateral stability (c and d) and less than ± 2.4 mm for anteroposterior stability, determined with 95% confidence limits.

When using central points on the tibia (pt. S) the accuracy of the method is seen to become negligibly less (Table 4).

Table 3

Accuracy of method stated in mm (group I)

parameter	letter		SD'	$\pm t_2$ x SD'
medial	c	R	0.53	± 1.05
stability	c	L	0.56	± 1.14
lateral	d	R	0.58	± 1.17
stability	d	L	0.59	± 1.21
anterior displacement	(e-g)	R	0.94	± 1.90
of lateral tibial condyle	(e-g)	L	0.88	± 1.78
anterior displacement	(f-h)	R	0.51	± 1.04
of medial.tibial condyle	(f-h)	L	0.66	± 1.34
posterior displacement	(i-e)	R	1.08	± 2.19
of lateral tibial condyle	(i-e)	L	1.18	± 2.39
posterior displacement	(j-f)	R	0.68	± 1.38
of medial tibial condyle	(j-f)	L	0.70	± 1.42
total displacement of	(i-g)	R	0.97	± 1.97
lateral tibial condyle	(i-g)	L	1.14	± 2.31
total displacement of	(j-h)	R	0.64	± 1.33
medial tibial condyle	(j-h)	L	0.74	± 1.50

Table 4

Accuracy of method on using central points for measuring the displacement of the tibia as a whole.

parameter	letter		SD'	± 2.03 x SD'
anterior displacement of tibia	E - G	R	0.83	± 1.68
(measured by means of point S)	E - G	L	0.63	± 1.28
posterior displacement	I - E	R	0.79	± 1.60
(point S)	I - E	L	1.12	± 2.27
total displacement of	I - G	R	0.79	± 1.60
tibia	I - G	L	1.23	± 2.50

Table 5

Accuracy of method (standard deviation on repeated measurement). Group II (8 males, 8 females)

parameter	letter		SD'	force
medial stability	c	R	0.81	abd. 18 kg
		L	1.05	
lateral stability	d	R	0.53	add. 13 kg
		L	0.68	
anterior displacement of lateral tibial condyle	(e-g)	R	0.99	traction 13 kg
		L	1.14	
anterior displacement of medial tibial condyle	(f-h)	R	0.54	traction 13 kg
		L	0.94	
posterior displacement of lateral tibial condyle	(i-e)	R	0.81	pressure 18 kg
		L	1.20	
posterior displacement of medial tibial condyle	(j-f)	R	0.66	pressure 18 kg
		L	0.63	

With other forces: abduction force 18 kg, adduction force 13 kg, pressure on the proximal end of the tibia 18 kg, and traction (anterior displacement) 13 kg on another 16 persons (8 males and 8 females, group II), the standard deviations (SD') were as shown in Table 5. On the whole, they are somewhat greater than in group I for c and d, but not essentially deviant, while for (e-g), (f-h), (i-e), and (j-f) they do not differ at all from those found in group I.

A standard deviation, SD', on the duplicate measurements from 0.53 mm to 1.23 mm and the corresponding 95% confidence limits: ± 1.2 mm for lateral instability and ± 2.4 for anteroposterior instability immediately raises the question whether it is at all reasonable to state these results with decimal fractions, or whether it would be more reasonable to state them in whole mm. In my opinion, measurements and calculations during the period of testing the method must be stated with decimals, deferring the final decision of this question until the results for normal subjects as well as those for injured persons in a test material have been analysed.

Less interest attaches to actual inaccuracy in repeatedly reading the same parameter on the same film. Therefore, this was tested for only a few parameters: c, d, e, and f. X-ray films of 45 knees from the C_b material were used. Only right-sided parameters were tested. The comparison was blind, with a long interval of time between the two readings. The 2 x 180 readings were compared by the same statistical method that was used in the test-retest investigations of the measuring accuracy. The results of the mean, $\bar{x}$, and the standard deviation, SD'', are shown in Table 6. They constitute about two-thirds of the total inaccuracy of measurement.

Table 6

Inaccuracy of duplikate reading on the same film, unit: mm.

parameter numerical	mean difference $\bar{x}$	standard deviation SD''
$c_1 - c_2$	$0.36 \cong 0.4$	$0.30 = 0.3$
$d_1 - d_2$	$0.37 \cong 0.4$	$0.33 \cong 0.3$
$e_1 - e_2$	$0.63 \cong 0.6$	$0.56 \cong 0.6$
$f_1 - f_2$	$0.49 \cong 0.5$	$0.44 \cong 0.4$

In order to elucidate further the relationship between the accuracy of the method and the size of the parameters needed as well as the magnitude of the variation in these parameters, triple testing was done in 33 cases for parameters c and d, in 32 cases for the other parameters.

Variance analysis was performed on this triple test (performed and measured in a randomized, blind way just like the test-retest method (cf. (3)). In the triple analysis the abduction or adduction force was 9 kg, and in assessing anterior or posterior displacement of the tibia in relation to the femur a traction or pressure force of 20 kg.

The two-sided analysis of variance has been described in most major textbooks of statistics, e.g. in A. Hald: "Statistical Theory", p. 456 ff. (1957).

If the measurements are designated as follows:

	measurement j			
sub-ject i	1	j	3	sum
1	x_{11}	x_{1j}	x_{13}	$x_{1.}$
⋮				
i	x_{i1}	x_{ij}	x_{i3}	$x_{i.}$
⋮				
k	x_{k1}	x_{kj}	x_{k3}	$x_{k.}$
sum	$x_{.1}$	$x_{.j}$	$x_{.3}$	$x_{..}$

the following expressions of the sum of squares of deviations between the subjects are obtained:

$$SSD_p = 3\sum_{i=1}^{k}(\bar{x}_{i.} - \bar{x}_{..})^2 = \sum_{i=1}^{k}\frac{(x_{i.})^2}{3} - \frac{(x_{..})^2}{3k}$$

between measurements

$$SSD_m = k\sum_{j=1}^{3}(\bar{x}_{.j} - \bar{x}_{..})^2 = \sum_{j=1}^{3}\frac{(x_{.j})^2}{k} - \frac{(x_{..})^2}{3k}$$

residual

$$SSD_r = \sum_{i=1}^{k}\sum_{j=1}^{3}(x_{ij} - \bar{x}_{i.} - \bar{x}_{.j} + \bar{x}_{..})^2 = \sum_{i=1}^{k}\sum_{j=1}^{3}x_{ij}^2 - \sum_{i=1}^{k}\frac{(x_{i.})^2}{3} - \sum_{j=1}^{3}\frac{(x_{.j})^2}{k} + \frac{(x_{..})^2}{3k}$$

total

$$SSD_t = \sum_{i=1}^{k}\sum_{j=1}^{3}(x_{ij} - \bar{x}_{..})^2 = \sum_{i=1}^{k}\sum_{j=1}^{3}x_{ij}^2 - \frac{(x_{..})^2}{3k}$$

The degrees of freedom for these four sums of squares are k-1, 2, 2(k-1), and 3k-1. This affords, for the first three sums of squares, the following expressions of variance:

$s_p^2 = SSD_p/(k-1)$, $s_m^2 = SSD_m/2$ and $s_r^2 = SSD_r/2(k-1)$

This presupposes that the mean value $M(x_{ij}) = \alpha + \beta_i + \gamma_j$ can be split up into additive contributions which characterize the subject and the number of the measurement. The hypothesis $\beta_i = 0$ (i.e. no difference between the subjects) can be tested by testing whether $M(s_p^2) > M(s_r^2)$. This is done by an F-test, $F(f_1 = k-1,\ f_2 = 2(k-1)) = s_p^2/s_r^2$. If this ratio significantly exceeds 1, the hypothesis $\beta_i = 0$ has to be rejected. In the same way, $\gamma_j = 0$ (no difference between the measurements) is tested by $F(f_1 = 2,\ f_2 = 2(k-1)) = s_m^2/s_r^2$.

Table 7 gives for the 16 measurements the sums needed to calculate the SSD's which are given, with the corresponding variances, in Table 8. This table also sets out the F values for both tests carried out per measure-

Table 7.

	k	$x_{.1}$	$x_{.2}$	$x_{.3}$	$x_{..}$	$\sum_{i=1}^{k} \sum_{j=1}^{3} x_{ij}^2$	$\sum_{j=1}^{3} x_{.j}^2/k$	$\sum_{i=1}^{k} x_{i.}^2/3$	$x_{..}^2/3k$
c Right	33	273.2	270.0	275.4	818.6	7015.88	6769.1939	6996.3200	6768.7471
c Left	33	271.7	274.7	274.5	820.9	7016.63	6807.0070	6995.6567	6806.8365
d_R	33	433.5	429.6	428.3	1291.4	17126.00	16846.0394	17106.1133	16845.5956
d_L	33	425.6	422.8	426.3	1274.7	16626.41	16412.9361	16610.0233	16412.7282
$(f-h)_R$	32	70.3	68.9	74.8	214.0	678.42	477.6356	658.6133	477.0417
$(f-h)_L$	32	80.6	85.8	84.8	251.2	873.72	657.7825	851.0467	657.3067
$(i-g)_R$	32	240.7	250.8	248.6	740.1	6093.41	5707.4716	6027.1033	5705.7084
$(i-g)_L$	32	245.3	253.2	247.3	745.8	6185.86	5794.9881	6109.0200	5793.9338
$(j-h)_R$	32	124.6	127.7	128.9	381.2	1779.98	1513.9894	1751.7400	1513.6817
$(j-h)_L$	32	130.8	135.8	139.9	406.5	2018.59	1722.5716	1989.4967	1721.2734
$(i-e)_R$	32	99.9	107.6	104.5	312.0	1154.92	1014.9381	1083.8467	1014.0000
$(i-e)_L$	32	99.1	102.9	104.8	306.8	1149.58	981.0081	1065.6467	980.4817
$(j-f)_R$	32	54.3	59.9	54.7	168.9	371.77	297.7684	334.5033	297.1584
$(j-f)_L$	32	50.2	50.0	55.1	155.3	319.15	251.7516	282.3167	251.2301
$(e-g)_R$	32	140.8	143.2	145.0	429.0	2213.16	1917.3712	2156.0133	1917.0938
$(e-g)_L$	32	146.7	150.3	143.5	440.5	2404.67	2021.9759	2353.7900	2021.2526

Table 8.

	c_R				c_L				d_R			
	SSD	f	s^2	F	SSD	f	s^2	F	SSD	f	s^2	F
subjects	227.57	32	7.11	23.70	188.82	32	5.90	18.15	260.52	32	8.14	26.79
measuremts	0.45	2	0.22	<1	0.17	2	0.09	<1	0.44	2	0.22	<1
residual	19.11	64	0.30		20.80	64	0.33		19.44	64	0.30	
total	247.13	98			209.79	98			280.40	98		

	d_L				$(f-h)_R$				$(f-h)_L$			
	SSD	f	s^2	F	SSD	f	s^2	F	SSD	f	s^2	F
subjects	197.30	32	6.17	24.41	181.57	31	5.86	18.91	193.74	31	6.25	17.46
measuremts	0.21	2	0.10	<1	0.59	2	0.30	<1	0.48	2	0.24	<1
residual	16.18	64	0.25		19.21	62	0.31		22.20	62	0.36	
total	213.68	98			201.38	95			216.41	95		

	$(i-g)_R$				$(i-g)_L$				$(j-h)_R$			
	SSD	f	s^2	F	SSD	f	s^2	F	SSD	f	s^2	F
subjects	321.39	31	10.37	9.96	315.09	31	10.16	8.31	238.06	31	7.68	17.05
measuremts	1.76	2	0.88	<1	1.05	2	0.53	<1	0.31	2	0.15	<1
residual	64.54	62	1.04		75.79	62	1.22		27.93	62	0.45	
total	387.70	95			391.93	95			266.30	95		

	$(j-h)_L$				$(i-e)_R$				$(i-e)_L$			
	SSD	f	s^2	F	SSD	f	s^2	F	SSD	f	s^2	F
subjects	268.22	31	8.65	19.29	69.85	31	2.25	1.99	85.16	31	2.75	2.04
measuremts	1.30	2	0.65	1.45	0.94	2	0.47	<1	0.53	2	0.26	<1
residual	27.80	62	0.45		70.14	62	1.13		83.41	62	1.35	
total	297.32	95			140.92	95			169.10	95		

	$(j-f)_R$				$(j-f)_L$				$(e-g)_R$			
	SSD	f	s^2	F	SSD	f	s^2	F	SSD	f	s^2	F
subjects	37.34	31	1.20	2.03	31.09	31	1.00	1.71	238.92	31	7.71	8.41
measuremts	0.61	2	0.30	<1	0.52	2	0.26	<1	0.28	2	0.14	<1
residual	36.66	62	0.59		36.31	62	0.59		56.87	62	0.91	
total	74.61	95			67.92	95			296.07	95		

	$(e-g)_L$			
	SSD	f	s^2	F
subjects	332.54	31	10.73	13.26
measuremts	0.72	2	0.36	<1
residual	50.16	62	0.81	
total	383.42	95		

ment. The significance levels for the F-test - with the present degrees of freedom - will be seen from:

degrees of freedom	significance level		
f_1,f_2	5%	1%	0.1%
32.64	1.63	1.99	2.48
31.62	1.64	2.01	2.52
2.64	3.15		
2.62	3.15		

It is apparent that the variation between the subjects was significant at the 0.1% level in nearly all cases. In 3 cases: $(i-e)_R$, $(i-e)_L$, and $(j-f)_R$ the variation is significant at the 1% level, but for $(j-f)_L$ not until the 5% level. Summing up, the hypothesis $\beta_i = 0$ has to be rejected for all 16 measurements - even very convincingly in most of the cases.

Reversely, the testing of the variation between the measurements gives in practically all cases an F-value lower than 1. F was greater than 1 in only one case $(j-h)_L$, but far from significantly. Thus, the hypothesis $\gamma_j = 0$, which means no difference between the measurements, has to be accepted in all cases.

To the above the following may be added: That the $\beta_i = 0$ hypothesis is rejected means that the subject-to-subject variance is not 0. On the contrary, there are significant differences between the parameters for the various subjects. This "variance between subjects" is abbreviated "subjects" in Table 8. The variance "within subjects" consists of two, viz. the variance between the measurements: "measurements", and a residual variance depending upon the subject, "residual". Reversely, as already stated, there is no significant difference from one measurement to another (or between the three measurements) in the same subject. Accordingly, the method does not have systematic errors. The accuracy of the measurement is satisfactory. s^2 in "measurements" (Table 8) is in the same order of magnitude as $(SD')^2$ in the test-retest investigation, just as they ought to be.

The applicability of the method otherwise must then be assessed according to its applicability in a pathological material once "normal values", upper limits or "critical levels" have been found on the basis of the materials of normal persons.

In the pathological material, Addendum II, there is for each patient - with a couple of exceptions - one sound and one injured leg. Therefore, it might be investigated whether $\bar{x}$ and SD for the parameters from these sound knees accorded with the findings in the normal material. However, the normal material is considered so large and exhaustive that this procedure was deemed superfluous. The idea of the standard procedure in the pathological material is using the parameter in the injured knee less the parameter in the uninjured knee.

Parameter Values in Normal Persons (C_a)

The "standard values" for group I have been reported already in (3) as well as (4), so that here they will be listed only in the form of the mean, $\bar{x}$, and standard deviation, SD, in Table 9. The mean and SD were calculated in the first series of measurements for the right and left leg separately. The values listed in Table 9 are the higher one for each parameter, and thus enable calculations of an upper normal limit, a "critical level". The calculations included 2 decimals, but for the sake of clarity they are rounded to one in Table 9. Testing of a difference, if any, between the parameters in females and males was done for each leg separately, using the Mann-Whitney rank sum test for unpaired data for all parameters of group I (group II being estimated as too small). A significant sex difference (at the 1% level) was found only for paramter c - while in all other cases there was no significant sex difference, not even at the 5% level.

The movement of the central point, S, in the form of E-G (anterior displacement) proved to be practically identical with the calculation $\frac{(e-g) + (f-h)}{2}$ Similar considerations apply to parameters I-E and I-G, cf. Table 9. The accuracy of the method, also when using these central points, is quite close to that found by using the mean of the displacement of the lateral and medial tibial condyles (compare Tables 3 and 4). Then, since the parameters of the displacement of the individual tibial condyles afford the same information when using the mean, and since furthermore they can afford information about the rotation, they were selected. Therefore, E, G, and I were omitted in the standard measurements, although it has been shown that the anteroposterior displacement can be measured by means of central points too. The omission of these measuring points was again done on the basis of the consideration: to obtain the largest possible number of data through the fewest possible parameters. This reasoning was briefly discussed in (4).

Table 9

Normal values in groups I and II, characterized by the mean, $\bar{x}$, and SD for the various parameters. Unit: mm.

parameter		action	(group I)	$\bar{x}$	SD	action	(group II)	$\bar{x}$	SD
c	males	abduction	9 kg	9.0	1.3	abduction	18 kg	9.6	2.8
	females	abduction	9 kg	7.0	1.2	abduction	18 kg	9.6	2.8
d	both sexes	adduction	20 kg	12.9	1.9	adduction	13 kg	14.9	1.8
e-g	both sexes	traction	20 kg	4.4	2.1	traction	13 kg	5.2	2.2
f-h	both sexes	traction	20 kg	2.3	1.5	traction	13 kg	2.1	1.9
$\frac{(e-g)+(f-h)}{2}$	both sexes	traction	20 kg	3.4	1.7	traction	13 kg	3.1	1.8
E - G	both sexes	traction	20 kg	3.4	1.8				
i-e	both sexes	pressure	20 kg	3.1	1.4	pressure	18 kg	3.5	1.5
j-f	both sexes	pressure	20 kg	1.6	0.8	pressure	18 kg	1.7	0.8
$\frac{(i-e)+(j-f)}{2}$	both sexes	pressure	20 kg	2.5	0.8	pressure	18 kg	2.6	0.8
I - E	both sexes	pressure	20 kg	2.6	1.2				
Total a-p displacement:									
i-g	both sexes	pressure & traction	20 kg	7.5	2.2				
j-h	both sexes	pressure & traction	20 kg	4.0	1.8	Not calculated here owing to the difference in the pressure and traction forces.			
$\frac{(i-g)+(j-h)}{2}$	both sexes	pressure & traction	20 kg	5.8	1.8				
I - G	both sexes	pressure & traction	20 kg	6.2	2.0				

As is also apparent from Table 9, the normal ranges of all the parameters stated are very wide, meaning that the subject-to-subject variation of one parameter is marked("variation between subjects" highly significant). It was attempted, therefore, to look for a parameter which remained more uniform from subject to subject, and it was found that the difference between the two legs of the same subject was always very small. - Therefore, all parameters were converted to /right - left/ (numerical difference between the subject's two knees). Corresponding calculations for these differences are shown by the values for group II in Table 10, in which (i-g) and (i-h) are omitted, as they signify nothing, the pressure and traction being exerted with different forces. Where group I is concered, these values were given in (3) Table 2 and in (4) Table 1. It is always an advantage to use them whenever possible (e.g. in a patient with a knee injury whose other leg is uninjured). But in a patient with injury to both knees, the normal range of the parameter has to be used, and it is so wide that doubt may arise as to whether or not the values measured in the patient are pathological.

It will be seen that the actions used in group II are presumably not particularly well-suited, as in this group the 97½% confidence limits for the normal range are higher than in group I (higher than caused by the higher $t_{2\alpha}$ conditioned by the smaller number of persons). In group I 2.0 mm proves to be the upper 97½% confidence limit for normal knees at a 9 kg force of action in adduction as well as abduction, while 3.1 mm is seen to apply in this and all cases of anteroposterior displacement during the action of 20 kg, calculated as the numerical difference between two sound legs (including the inaccuracy of the measurement). For use in comparing with other materials (c-a) is stated for the 34 normal subjects (group C_α, group I) - 68 measurements: range 1.1 mm to 6.1 mm.

Table 10

Standard values for the parameter differences $/P_R - P_L/$ characterized by the mean, $\bar{x}$, standard deviation, SD, and the 97 1/2% upper critical level $\bar{x} + t_2 \times$ SD. Unit mm.
Group: II actions: adduction 13 kg, abduction 18 kg, traction 13 kg, pressure 18 kg.

parameter	$\bar{x}$	SD	$\bar{x} + 2.12 \times$ SD
$/c_R - c_L/$	0.79	0.50	1.85
$/d_R - d_L/$	1.12	0.71	2.62
$^{(e\text{-}g)}/R - L/$	1.56	1.48	4.69
$^{(f\text{-}h)}/R - L/$	0.81	0.76	2.42
$^{(i\text{-}e)}/R - L/$	1.01	0.81	2.72
$^{(j\text{-}f)}/R - L/$	0.97	0.73	2.51

Control Group C_b

This group was added, partly because an investigation of normals during another force of action seemed required. So did an investigation of the role of rotation in the ankle and knee joints during the traction and pressure manoeuvre. Lastly, it was attempted to solve the problem concerning measurement of rotatory instability in the knee joint. The 50 persons of this group were examined from July to December 1977 and received letter-number combinations: Women C_b51 - C_b75 and men C_b76 - C_b100. In all ab- and adduction tests (all in the 160° position) the force used was 9 kg to each foot fixing gear and at all traction (anterior displacement of the tibia) and pressure manoeuvres (posterior displacement of the tibia) 30 kg on the proximal end of the tibia. All 50 subjects had the named measurements, using the stated tractions and pressures from "neutral position 90°", i.e. with foot rotation 0, and also during traction and pressure at an external foot rotation of 15°. The shoes on the floor of the gonylaxometer can be fixed in any rotatory position of the foot. 49 subjects had the abduction and adduction test at the same time. Thirteen, 7 females and 6 males (C_b51 - C_b55 incl., C_b63, C_b64, C_b76 - C_b80 incl., and C_b87) had the pressure and traction test at the same time with 90° flexion in the knee and external rotation of 30° of the foot. Another 10 (C_b56 - C_b60 incl. and C_b81 - C_b85 incl.) were also examined with the foot fixed in 30° internal rotation. The positions of the foot and the degree scale on the floor are shown in the illustrations (Figs. 7, 17 - 22). The age distribution and sex ratio are given in Table 11. All mathematical and statistical analyses of control group C_b were performed in the Computing Centre for the County of Copenhagen+).

Table 11

Age distribution and sex ratio in series C_b. N = 50 persons. Ratio females/males: 1/1.

Minimum age: 20			Maximum age: 50		Mean age: 31		
Fractiles:	5 %	10 %	25 %	Median	75 %	90 %	95 %
	22 years	23 years	26 years	30 years	34 years	40 years	44 years

	females	males
20 – 30 years	13	16
31 – 40 years	9	7
41 – 50 years	3	2

+) Adviser: Leif Mortensen, M.Sc. (Eng.). Location: The Copenhagen County Hospital, Herlev.

This section, then, is in two parts: One part deals with "upper critical levels" for the parameters concerned and the upper limits for the difference between the uninjured, sound legs of the same person with the foot in neutral position during an action of 30 kg pressure and traction. The other part deals with rotation of the tibia, partly during 30 kg action in neutral position and in various positions of rotation of the foot, partly without anteroposterior action forces.

Parameter Values in Normal Persons (C_b)

In group C_b it was investigated whether the parameters were influenced at all by sex, height, weight, and leg length. Moreover, the mutual relationship between sex and height, sex and leg length, and sex and weight was investigated. Such a relationship might easily be the actual cause of a sex dependence of the parameters - the parameters being simply dependent upon the dimensions of the knee joint.

As in the former half of the control material (group C_a) there proved to be a statistically significant difference in parameter c between the two sexes, but none in parameter d. Moreover, e and f are significantly greater in men than in women - and indeed these two parameters represent condylar dimensions, not ligament stability (Table 12). Judging by these findings, therefore, the significantly shorter distance c in women represents a generally smaller dimension in the women. The lacking difference in d must attract more attention, as it indicates greater laxity of the lateral than of the medial ligament, independently of bone dimensions, in the position in which the leg was examined. A similar result of a Spearman rank test for the same parameter, when both sexes are tested together for leg length (mean distance from the trochanter to the malleolus) affords the same impression, viz. that the sex dependence is due to the generally larger dimensions in men. Table 13 demonstrates a definitely significant parameter dependence upon leg length (still with the exception of parameter d) - and this corresponds to a dimension dependence. In particular, the paramters which are so significantly dependent upon leg length (e and f) again represent the dimensions of the knee.

The Spearman rank test on the same parameters against height (in the entire C_b) gives the same result (no dependence of d and dependence of all other parameters). In Table 14 $\bar{x}$ and SD are not repeated, as they do not alter for these parameters.

Table 12

Test of sex dependence of parameters c, d, e, and f. Mann-Whitney test.
Mean, $\bar{x}$, and standard deviation, SD, in mm.

parameter	sex	$\bar{x}$	SD	significance level	significant difference +/–
c_R	males	9.80	1.14	P = 0.0000	+ (highly)
	females	8.12	1.01		
c_L	males	9.80	1.24	P = 0.0000	+ (highly)
	females	8.27	0.86		
d_R	males	12.53	1.82	P = 0.9203	–
	females	12.34	1.48		
d_L	males	12.56	2.14	P = 0.4470	–
	females	12.01	1.51		
e_R-neutral	males	40.92	3.50	P = 0.0000	+ (highly)
	females	34.44	2.72		
e_L-neutral	males	41.20	3.45	P = 0.0000	+ (highly)
	females	34.91	2.76		
f_R-neutral	males	52.45	3.04	P = 0.0000	+ (highly)
	females	45.72	2.12		
f_L-neutral	males	51.00	3.00	P = 0.0000	+ (highly)
	females	45.12	1.85		

Table 13

Spearman rank test for dependence of leg length of parameters d, c (N = 49), and e and f (N = 50).

Leg length: Mean 83.27 cm Range: 75 – 97 cm

parameter (both sexes)	$\bar{x}$	SD	significance level	significant dependence +/– level $p \leqslant 0.05$
c_R	8.98	4.92	p = 0.0072	+
c_L	9.05	1.31	p = 0.0648	– (+ at 6% level)
d_R	12.39	1.65	p = 0.2916	–
d_L	12.29	1.86	p = 0.1822	–
e_R-neutral	37.68	4.51	p = 0.0000	+ (highly)
e_L-neutral	38.05	4.43	p = 0.0000	+ (highly)
f_R-neutral	49.09	4.27	p = 0.0000	+ (highly)
f_L-neutral	48.06	3.86	p = 0.0000	+ (highly)

Table 14

Relationship between height (in cm) and parameters c, d, e and f. Spearman rank test.
Height: Mean 173.80 cm, Range 158 – 196 cm.

parameter (both sexes)	significance level	significant dependence +/–
c_R	p = 0.0004	+ (highly)
c_L	p = 0.0088	+
d_R	p = 0.1381	–
d_L	p = 0.0581	–
e_R - neutral	p = 0.0000	+ (highly)
e_L - neutral	p = 0.0000	+ (highly)
f_R - neutral	p = 0.0000	+ (highly)
f_L - neutral	p = 0.0000	+ (highly)

Table 15

Relationship between body weight (kg) and parameters c, d, e, and f. Spearman rank test.
Body weight: Mean 65.98 kg. Range 46 – 89 kg

parameter (both sexes)	significance level	significant dependence +/–
c_R	p = 0.0000	+ (highly)
c_L	p = 0.0017	+
d_R	p = 0.0377	+ (low)
d_L	p = 0.0165	+ (low)
e_R - neutral	p = 0.0000	+ (highly)
e_L - neutral	p = 0.0000	+ (highly)
f_R - neutral	p = 0.0000	+ (highly)
f_L - neutral	p = 0.0000	+ (highly)

Table 15 presents the relationship to body weight. In this, unlike the other analyses, also parameter d was found to increase in step with the body weight.

Age (Table 16) shows no relationship to the parameters tested. Indeed, this could not be expected, as the age range was fairly narrow (the great majority being from 20 to 40 years), none in childhood or puberty, and none in the senium in which deviant values might be expected. Table 16 also presents the variation of the parameters in the form of the mean, $\bar{x}$, and range in order to give an impression of the great width of the normal range.

Now, it is of interest to ascertain that the Wilcoxon-Mann-Whitney test shows no significant difference in age distribution between the two groups ($p = 0.8383$). The 25 men had a mean age of 30.80, range 21 - 50, and the 25 women a mean age of 31.12 years, range 20 - 46. In other words, a very equal age distribution.

On the other hand, there is a highly significant difference in leg length, height and weight between the male and the female groups, these parameters being significantly greater in the males (Table 17). Accordingly the sex dependence of parameters c, e, and f, found already, must be assumed to be a matter of dimensions.

Table 16

Spearman Rank test for relationship to age for parameters c, d, e, and f.

parameter (both sexes)	Mean	Range	significance level	significant dependence +/–
c_R	8.98	5.70-12.80	$p = 0.9968$	–
c_L	9.05	6.50-12.80	$p = 0.7061$	–
d_R	12.39	9.60-18.40	$p = 0.9734$	–
d_L	12.29	9.50-19.40	$p = 0.5467$	–
$e_{R\text{-neutral}}$	37.68	29.50-48,30	$p = 0.7276$	–
$e_{L\text{-neutral}}$	38.05	28.50-49.20	$p = 0.8188$	–
$f_{R\text{-neutral}}$	49.09	41.10-58.60	$p = 0.5248$	–
$f_{L\text{-neutral}}$	48.06	40.90-55.70	$p = 0.2623$	–

Table 17

Relationship between sex and leg length, height, and weight in group C_b. Mann-Whitney test.

	Leg length in cm		Height in cm		Weight in kg	
Sex	males	females	males	females	males	females
Mean	86.40	80.08	180.04	167.56	74.32	57.64
Range	79-97	75-87	167-196	158-175	59-89	46-66
SD	4.02	3.40	6.11	4.35	7.99	6.11
p = probability	p = 0.0000		p = 0.0000		p = 0.0000	
significant difference +/–	+ (highly)		+ (highly)		+ (highly)	

Testing the secondary (or calculated) parameters, e-g, f-h, etc., for significant sex differences showed a few convincingly significant differences, but as a rule no significant difference at the 5% level (Table 18) or a difference which was barely significant at this level. The reason may be the small displacements in sound knees. However, the differences were in all cases too small to justify separate tabulation of females and males. The same applied when testing against leg length (Table 18). It was estimater, therefore, that in the case of these parameters there was no reason to divide the material into a male and a female group or use any other form of stratification. All the tested persons (N = 50) can be used together for each side and for each parameter.

"Standard values", now, can be defined around the mean value, $\bar{x}$, of the desired parameters, e.g. with an upper 97½% confidence limit $\bar{x}$ + 2 SD (Table 19). For parameter c, $\bar{x}$ and SD should be given separately for each sex, as was done in Table 12. From Table 19 it is apparent also how close are the left and right parameters. Therefore, it is sufficient to use the higher value when seeking the upper normal limit, i.e. the critical level, as is done in Table 19.

If parameter c is not divided by sex, but the right knee is analysed in relation to the left one (50 in each group), the agreement is so close

Table 18

Dependence of secondary parameters on sex and leg length (trochanter - malleolus distance).

parameter (foot$_{\text{neutral}}$)	significant difference females/males +/–	Mann-Whitney p values	significant dependence on leg length +/–	Spearman test p values
(e-g) R	+	p = 0.0012	+	p = 0.0104
(f-h) R	+	p = 0.0488	–	p = 0.2020
$\frac{(e-g)+(f-h)}{2}$ R	+	p = 0.0042	+	p = 0.0363
(e-g) L	+	p = 0.0174	+	p = 0.0517
(f-h) L	–	p = 0.3768	–	p = 0.3987
$\frac{(e-g)+(f-h)}{2}$ L	–	p = 0.0727	–	p = 0.0862
(i-e) R	+	p = 0.0488	–	p = 0.4558
(j-f) R	–	p = 0.3220	–	p = 0.3784
$\frac{(i-e)+(j-f)}{2}$ R	–	p = 0.4096	–	p = 0.8731
(i-e) L	+	p = 0.0055	+	p = 0.0411
(j-f) L	–	p = 0.8460	–	p = 0.7234
$\frac{(i-e)+(j-f)}{2}$ L	–	p = 0.1623	–	p = 0.4852

Table 19

Mean, SD and upper critical levels (97 1/2 %) for the parameters of anterior and posterior displacement. Traction and pressure forces: 30 kg. Neutral position 90° (rotation of foot 0). Both sexes, (N = 50).

Displacement	parameter	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$ + 2 SD
ant. displacement lat. condyle	(e-g) R	5.26	1.85	5.3	1.9	9.1
	(e-g) L	5.30	1.89			
ant. displacement med. condyle	(f-h) R	2.89	1.75	2.9	1.8	6.4
	(f-h) L	2.92	1.66			
ant. displacement mean of both	$\frac{(e-g)+(f-h)}{2}$	R 4.07	1.66	4.1	1.7	7.4
		L 4.11	1.64			
post. displacement lat. condyle	(i-e) R	4.21	1.89	4.2	1.9	8.0
	(i-e) L	4.11	1.68			
post. displacement med. condyle	(j-f) R	1.82	1.26	1.8	1.3	4.3
	(j-f) L	1.72	1.24			
post. displacement mean of both	$\frac{(i-e)+(j-f)}{2}$	R 3.02	1.20	3.0	1.2	5.4
		L 2.91	1.13			
total displacement lat. condyle	(i-g) R	9.48	2.74	9.5	2.7	15.0
	(i-g) L	9.41	2.58			
total displacement med. condyle	(j-h) R	4.71	2.47	4.7	2.5	9.5
	(j-h) L	4.64	2.42			
total displacement mean of both	$\frac{(i-g)+(j-h)}{2}$	R 7.09	2.29	7.1	2.3	11.7
		L 7.02	2.27			

that the upper limit at the 97½% level, viz. the critical level, in the form of $\bar{x}$ + 2 SD, is 11.7 for both.

As to parameter d, the same level is 15.7 mm for the right and 16.0 mm for the left knee. Parameter e-g shows a critical level of 9.0 mm for the right and 9.1 mm for the left knee.

For ((e-g) + (f-h))½ the 97½% critical level is 7.39 mm for both knees. In other words, there is no systematic difference between the right and left knee.

These "critical levels" are a bit higher when the pressure and traction force is 30 kp than 20 kp (compare Table 19 with Table 2 in (3)). The SD *proved a little lower for anterior displacement (tenths of a mm) and a little* higher for posterior and total displacement.

The use of side difference, meaning $/P_R - P_L/$, i.e. the numerical difference between the two knees for the parameter concerned, P, is preferable as stated in the section on control group C_a, since this makes the normal range much narrower and easier to handle in relation to the pathological findings. The characteristics of the parameter variation ($\bar{x}$ and SD) and upper 97½% critical levels for this normal material are given in Table 20.

Table 20

Mean, SD and upper 97 1/2% critical levels for parameters c and d and the parameters for anteroposterior displacement, /R – L/. Traction and pressure force 30 kg. Neutral pos. N = 50.

Displacement	parameter	$\bar{x}$	SD	$\bar{x}$ + 2 SD
Valgus gap	c	0.49 ~ 0.5	0.42 ~ 0.4	1.33 ~ 1.3
Varus gap	d	0.53 ~ 0.5	0.37 ~ 0.4	1.27 ~ 1.3
Anterior displacement				
lateral condyle	e-g	1.12 ~ 1.1	0.85 ~ 0.9	2.82 ~ 2.8
medial condyle	f-h	0.82 ~ 0.8	0.73 ~ 0.7	2.28 ~ 2.3
mean	$\frac{(e-g)+(f-h)}{2}$	0.85 ~ 0.9	0.58 ~ 0.6	2.01 ~ 2.0
Posterior displacement				
lateral condyle	i-e	1.10 ~ 1.1	0.75 ~ 0.8	2.60 ~ 2.6
medial condyle	j-f	0.81 ~ 0.8	0.63 ~ 0.6	2.07 ~ 2.1
mean	$\frac{(i-e)+(j-f)}{2}$	0.72 ~ 0.7	0.48 ~ 0.5	1.68 ~ 1.7
Total anteropost. displacement				
lateral condyle	i-g	1.48 ~ 1.5	1.01 ~ 1.0	3.50 ~ 3.5
medial condyle	j-h	1.24 ~ 1.2	0.94 ~ 0.9	3.12 ~ 3.1
mean	$\frac{(i-g)+(j-h)}{2}$	1.16 ~ 1.2	0.84 ~ 0.8	2.84 ~ 2.8

The standard deviations do not differ from those shown for traction and pressure forces of 20 kg shown in Table 2 of paper (3). Nor do the upper limits exceed those found in (3) and (4) or in (5) and (7), in the latter two called critical levels. However, the total anteroposterior displacement of the lateral tibial condyle - and only this parameter - proved to exceed a critical level of 3 mm (after rounding), being 3.5 mm. It will be seen, as already mentioned, that the lateral tibial condyle becomes more displaced, both anteriorly and posteriorly. This is apparent in particular from the mean values, $\bar{x}$, in Table 19. At anterior or posterior displacement alone the critical level of 3 mm is not exceeded (Table 20).

Summary: The critical levels of 2.0 mm for medial and lateral instability and of 3.0 mm for anterior or posterior drawer sign for both pairs of condyles, or the mean thereof (viz. the difference between two sound knees in the same person including the measuring error) which have been used already, proved to remain unchanged from a 20 kg traction and pressure to a 30 kg traction and pressure. This manner of calculation renders the values independent of sex, body height, leg length, and body weight which do affect the upper 97½% critical levels for the parameter excursions of each leg separately. This is caused by a greater knee dimension, resulting in a higher upper critical level. The difference between the two sexes is due to a difference in knee dimension.

Rotation and Rotatory Instability

That rotatory movement is not only possible, but that it does occur during stress radiography, even with the foot in the neutral position, was discussed already above in connection with Fig. 12. This figure clearly showed that rotation in the intact joint takes place with greater movement in the lateral than in the medial joint chamber.

Rotatory instability, therefore, must be defined as rotation exceeding the normal rotation in a given position of the knee and foot during a given action.

Consequently, normal limits have to be fixed also for the rotatory movement with a 90° flexed knee joint during traction and pressure - and a wish for an examination with the foot fixed in different degrees of rotation was inspired particularly by Slocum and Larson's study from 1968.

Slocum and Larson described their clinical test position with 90° flexed knee and "with the foot and leg in 15 degrees external rotation". However, the foot and tibia do not rotate equally. Therefore, a parallel, less extensive study was made of some of the subjects in order to elucidate the relationship between the rotation of the foot and the simultaneous rotation of the proximal end of the tibia, presupposing that the thigh is fixed and the knee in 90° flexion. This was done by an external examination, not radiographically.

Thereafter, gonylaxometric measurements were made on the 50 normal subjects C_b51 - C_b100, both with the foot in neutral position and with the foot 15° externally rotated (and fastened in that position) in all 50 subjects. Thirteen of them also had measurements in 30° external rotation and another ten in 30° internal rotation of the foot.

Study of the Relationship of Foot Rotation to Rotation of the Tibial Condyles (Proximal End of the Tibia) at External Examination

The investigations were performed on a small series of subjects (C_a29 and C_b51, 52, 53, 54, 55, 56, 57, 62, 77, 78, 87 - 4 males and 8 females).

The procedure is simple, and the investigations were performed in connection with the stress radiographic measurements of the subjects concerned. The set-up is shown in a series of photos:

Fig. 7 shows the subject in the gonylaxometer chair, with the piston shaft intended for traction and pressure actions fastened around the proximal part of the lower leg, at the site of the proximal end of the tibia. Foot position neutral. In Fig. 17 the piston shaft has been exchanged with a plaster bandage furnished with a pointer. This bandage envelops the tibial tuberosity and half the circumference of the lower leg at that level. It is kept taut against the tibial tuberosity by a strong rubber band. As previously, the thigh is fixed with an inflated rubber cuff. The pointer from the tibial tuberosity ends above the shoe in a small black indicator. The foot rest ends in a pointed tip. Both pointers are placed at 0, i.e. neutral starting position (Fig. 18). Then, the foot is gradually rotated outwards Figs. 19 - 21) and inwards (Fig. 22), and readings are made on the common grading scale on the floor. The tibial pointer is read with the shoe in 15°, 30°, and 45° external and internal rotation. It is apparent that the pointer fixed on the tibia gives excursions which are only about one-third of those of the foot. The means and ranges of the measurements on all 12 subjects are listed in Table 21. The maximum rotation of the foot and knee were not systematically investigated.

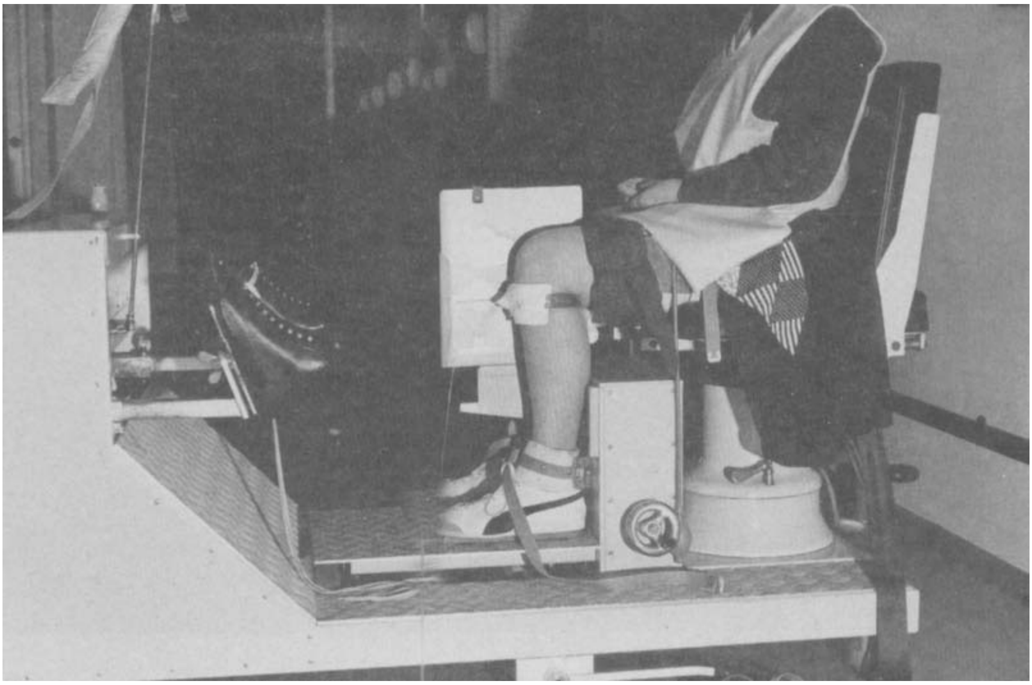


Figure 17: External rotation measurement; unit: degrees. The same set-up as in Fig. 7. The piston shaft has been exchanged with a plaster brace around the tibial tuberosity and anterior semi-circumference of the tibial head. The plaster brace is fastened by a rubber band around the hollow of the knee. The metal pointer from the plaster brace down to the level of the toe of the shoe is visible.

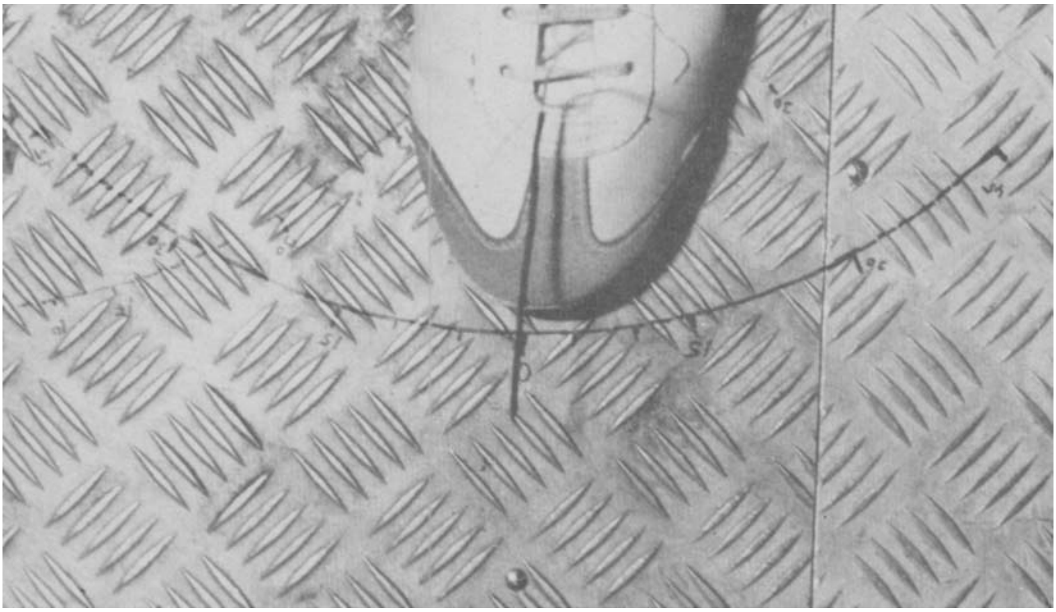


Figure 18: The position of the tibial metal pointer above the grading scale of the floor and just above the shoe. Both the pointer and the tip

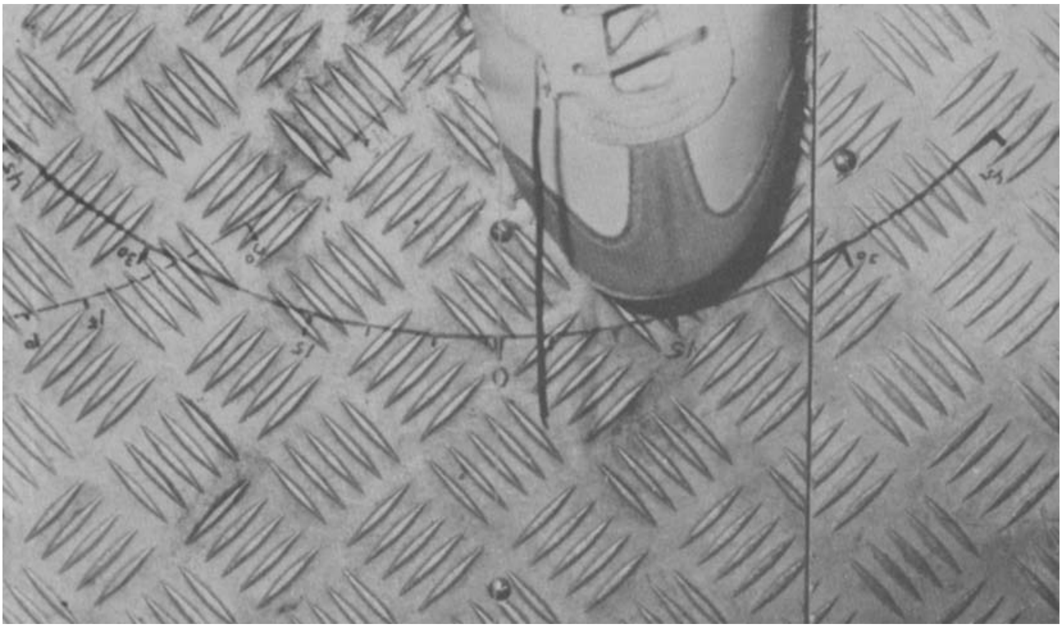


Figure 19: Left foot in 15° external rotation. The pointer mounted against the tibial tuberosity is only 4° externally rotated.

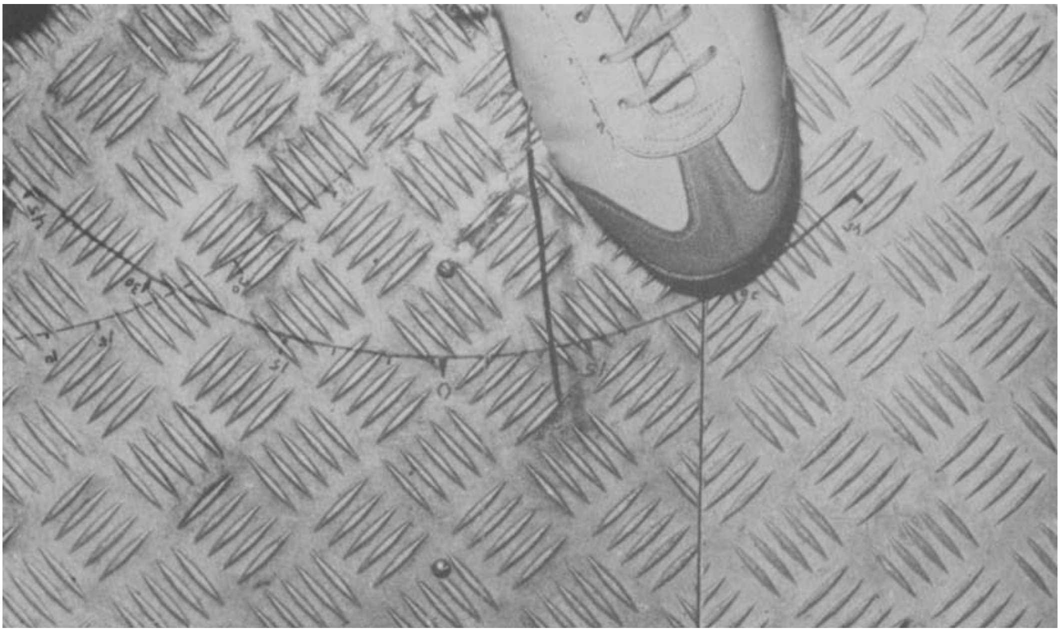
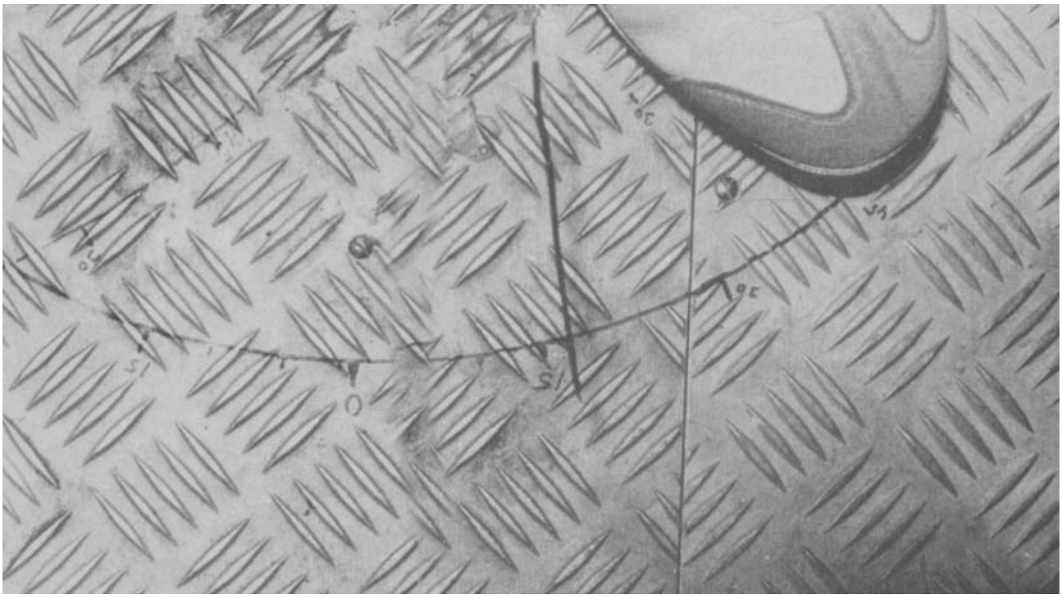
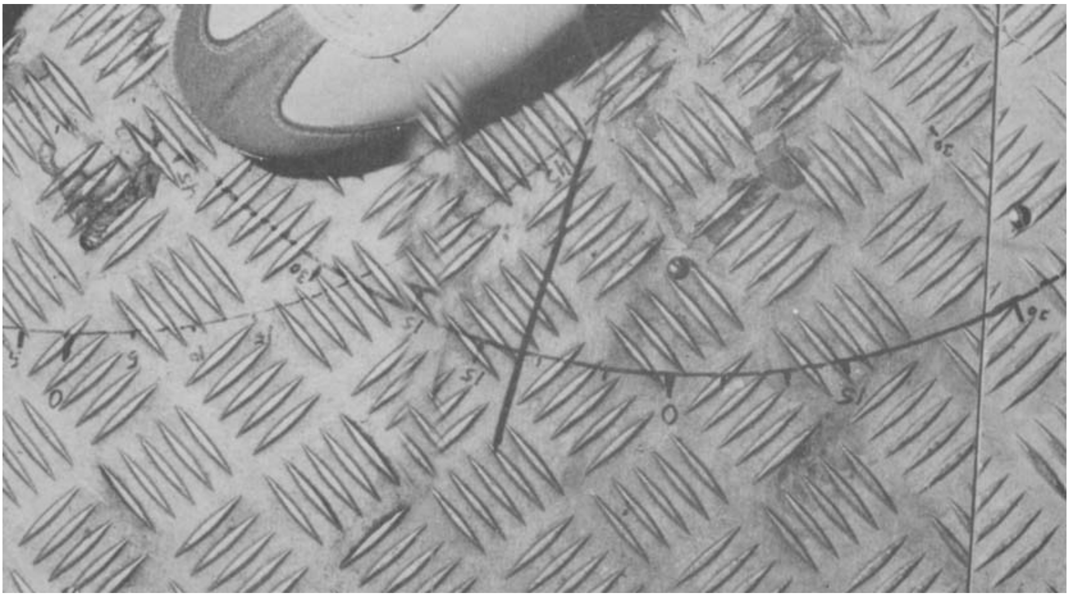


Figure 20: Left foot in 30° external rotation, the tibial tuberosity in 12° external rotation.



<u>Figure 21:</u> Left foot in 45° external rotation, the tibial tuberosity, and thereby also the tibial condyles, in only 17° external rotation.



<u>Figure 22:</u> Left foot in 45° internal rotation, the tibial tuberosity in 12° internal rotation.

This method of measurement of course involves the sources of error which have been discussed already (3), primarily soft-tissue shifts in the skin and subcutis which may make the tuberosity move underneath the skin, and thus underneath the plaster cuff, so that the pointer shows less rotation of the tibial tuberosity than the true one. However, this series was included to show that about half or more than half of the rotation in "the foot and leg" occurs in the ankle joint in this set-up. Thus, without purporting to be exact, the measurements do indicate that the clinical investigation advocated by Slocum and Larson can hardly be particularly well-defined in its starting position and hardly causes much rotation of the tibia. This renders the choice of foot rotation in stress radiographic standard exposures of the knee joint difficult. Slocum and Larson seem to have used 15° rotation of the foot. Therefore, this was selected as the standard position for exposures with rotated foot, and all the subjects (C_b51 - 100) were thus examined, while smaller groups, as already mentioned, were examined also with the foot in 30° external or internal rotation. Examination with the foot in 15° rotation causes the subject practically no discomfort, while greater rotation may do so.

Rotation in the Knee on Rotation of the Foot Without Simultaneous Stress Action - Assessed Radiologically

To find an expression of rotation in the knee during rotation of the foot from the neutral position (i.e. rotatory position 0°), a varying number of degrees outward or inward, let us consider what happens to the original parameters e and f on the lateral view. Having no interest at the moment in rotation during traction or pressure, we can disregard the other parameters on the lateral view. Fig. 13 shows the same knee joint in "neutral position 90°", in a position in which the foot is 15° externally rotated, and in a position in which the foot is 30° internally rotated. The rotation can be directly seen from the location of the head of the fibula in relation to the tibial condyles, the former moving backward on external and forward on internal rotation in relation to the tibial condyles. This can also be measured and seen from the plotted parameters.

In external rotation, in which the head of the fibula - and simultaneously the posterior margin of the lateral tibial condyle, viz. the landmark for the most posterior end of distance e - moves backward in relation to the femoral condyles, distance e will be increased. In other words, $e_{\text{neutral}} < e_{15^\circ\text{external}}$ or $e_{\text{neutral}} < e_{30^\circ\text{external}}$. Thus, calculation of

$e_{neutral} - e_{15^o external}$ or $e_{neutral} - e_{30^o external}$ gives a negative expression (Table 22). The medial tibial condyle, on the other hand, moves forward in relation to the immovable femoral condyles in such an external rotation, and consequently distance f is decreased. $f_{neutral} - f_{15^o external}$ and $f_{neutral} - f_{30^o external}$ will become positive. If an expression for rotation is desired, the sum of the two opposite movements should be included, so that both contribute to increasing the numerical value of the expression. Therefore, a numerical calculation could be performed, as in the last column of Table 22. However, it is possible also to set up a formula which acquires the same numerical value, but maintains the sign (last but one column in the table). When defining $k_1 = e_{neutral} - e_{15^o ext.}$ and $l_1 = f_{neutral} - f_{15^o ext.}$ and in the same way k_2 and l_2 at a 30° external rotation of the foot and k_3 and l_3 at a 3o° internal rotation of the foot, k - l may be used in general as an expression of rotation (without traction or pressure).

From Table 22 it will be seen how, in that case, the expression is always negative on external rotation (but acquires numerically a maximum value) and positive on internal rotation. Thus, the sign may be used for distinguishing between internal and external rotation. Numerically the value will become the larger, the greater the rotation.

In Table 22 the mean, $\bar{x}$, of measurements on a major number of persons is used for calculating k - l, but when considering for instance the range values it will be seen that the signs are always as just stated.

In Table 23 the upper critical level of this rotatory movement is calculated from $\bar{x}$ of (k - l) and 2 SD of (k - l). It will be seen that this makes the values very high when compared e.g. with the total anterior or posterior movement of the tibial condylar massive - but these latter quantities represent the mean, while the rotatory movement is represented by a sum. Let it be mentioned that the 99% fractiles in the small materials for 30° external rotation (N = 13) and 30° internal rotation (N = 10) are within the limits stated in Table 23.

Trigonometric Calculation of Approximate Rotation in the Knee Joint at Rotation in the Foot Without Traction or Pressure

To relate the rotation found radiologically, expressed as $e_{neutral} - e_{rotated}$ and $f_{neutral} - f_{rotated}$ (mm), to the external measurements of degrees, a trigonometric, approximated conversion of these distances to degrees of rotation can be performed. An exact conversion is not possible, because the centre of rotation is not known, and the accurate distance between the two posterior landmarks on the tibia is also unknown. However, it is an advantage to use an approximated value of the distance between the named landmarks rather than an approximated value of a radius, as the former is independent of the situation of the centre - and thus does not alter if the location of the rotation centre changes, as e.g. in ligament tears. In such injuries the location of the centre alters to an entirely unknown site.

On Fig. 23 the tibia is seen from above, schematically, viewed as a rectangular figure (e.g. the left tibia from above). The posterior corners of the figure are used for "landmarks" when it is rotated. If the hatched position is considered the starting position, or neutral position, and the non-hatched one the position after external rotation, the angle v is equal to the rotation angle. This is a consequence of the elementary geometrical sentences: 1. an angle at the centre is measured by the arc over which it extends and 2. an inner angle is measured by half the sum of its own and its vertical angle's arc (both arcs are equally large in our example). The rotation is equal to the angle of the centre. The sinus to angle v, sin v, is equal to the opposite cathetus divided by the hypotenuse in a right-angled triangle, viz.

$\sin v = \frac{a}{x} = \frac{b}{y}$; x and y are not known, but x + y (the short side of the rectangle) are known (with approximation, vide infra). This approximate measure is called RT (reduced transverse measure)

of $\frac{a}{x} = \frac{b}{y}$ gives $y = \frac{b}{a}x$ and of

$RT = x + y = (\frac{a}{a})x + (\frac{b}{a})x = (\frac{a+b}{a})x \qquad x = \frac{RT.a}{a+b}$

$$\underline{\sin v} = \frac{a}{x} = \frac{a(a+b)}{RTa} = \underline{\frac{a+b}{RT}}$$

When imagining parallel X-rays directed from the top of the figure towards its bottom at right angles to the neutral position of the rectangular object (hatched), a measurement on the X-ray film at right angles to the beam will give the result shown at the bottom of the figure. In this case line segments e and f are equally long, making up the long sides of the rectangle. Measurements are made before and after the rotation from the static line sl, which corresponds to the normal measurement on the basis of the static femoral condyles - which are used as the "immovable" reference points on the X-ray films in stress radiography.

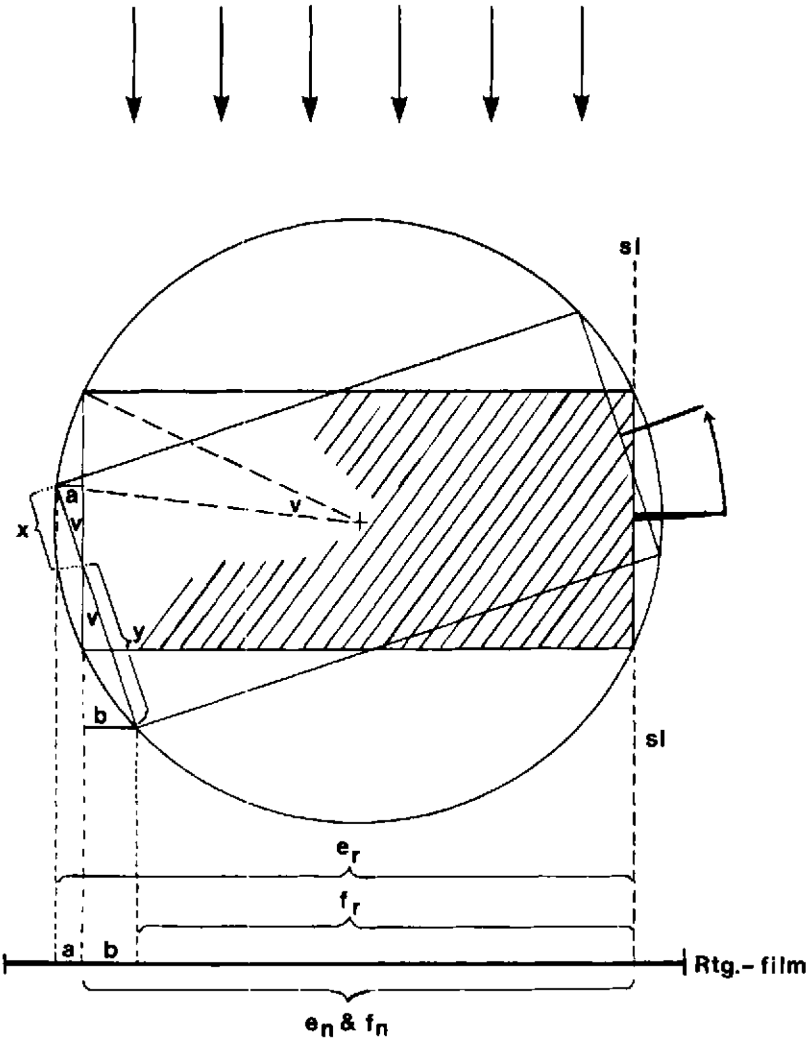


Figure 23: Schematic drawing of the left tibia viewed from above during rotation. The tibial condyles are taken to be a rectangular body. Anterior aspect on the right, at the arrow. Lateral aspect upwards, toward the beam. Medial side toward the film. The posterior side of the rectangle $= x + y$. In the neutral position the rectangle is hatched. The common, static reference line, sl, whence the measurement is made on the X-ray film, and which corresponds to the anterior margins of the femoral condyles, is placed for clarity - at the anterior side of the rectangle. The long sides of the rectangle, then, will be e_n laterally and f_n medially, corresponding to the parameters of the same designation in stress radiography. It is apparent that in rotation e_n increases by a, while f_n decreases by b. $a = /e_n - e_r/$, $b = f_n - f_r$, then, are the changes measured on the X-ray film and thus known quantities.

In external rotation e will be larger than before, $e_r = e_n + a$, $a = e_r - e_n = /e_n - e_r/$, and f will be smaller, $f_n = f_r + b$ or $b = f_n - f_r$. Only numerical values are used.

However, this is a highly simplified model - and any departure from it entails errors in the calculation. For instance, the position in a frontal plane of the posterior side of the rectangle at the beginning of the exposure is a presupposition for the appearance of right-angled triangles - and if the formula is used nevertheless a deviation will arise. So it will, if the two points which make up the posterior landmarks, called on Fig. 24 LL (lateral landmark) and ML (medial landmark), rotate on separate circle arcs. And it is probable that a circle having the rotation centre of the tibia as centre can include only one of the two points. Thus, the points usually rotate on two concentric circles. The error of the calculation increases when the rotation angle, v, increases. The rotating chord (x + y), moreover, can for several reasons only be calculated with wide approximation, partly because LL and ML are not fixed points, but contours which no doubt change somewhat in the course of the rotation during the X-ray exposure. In other words, the measurement is made only with approximation from point to point. Secondly, the distance has to be measured on the anteroposterior exposure, and this makes it a cathetus (x + y) instead of a hypotenuse (ML - LL) in a right-angled triangle (illustrated in Fig. 24), and thus somewhat shorter than ideally, ML-LL. Thirdly, the distance cannot be measured directly in each individual subject, but has to be calculated on the basis of the largest transverse measure of the proximal end of the tibia, T, on the anteroposterior exposure. On a preparation the points ML and LL were marked by needles, and the ratio between the distance ML - LL on the a-p view and the largest transverse measure of the head of the tibia on the film proved to be 48.0/92.2. This ratio will be used for calculating the following "reduced" transverse measures, RT: $x + y = RT = T \cdot (\frac{48.0}{92.2})$.

Thus, the calculation carries such inaccuracy that it can only be used as an estimate. It was performed only for a few subjects in whom an "external" measurement of degrees was available for comparison. Table 24 illustrates the inaccuracy of the calculation. In broad outline, however, there is agreement between the two measurements (mean difference 2^o).

Since, as already mentioned, the calculation of degrees, by means of the sinus of angle v carries a number of inaccuracies apart from that which is inherent in the primary measurement, it will be left out of account in the following.

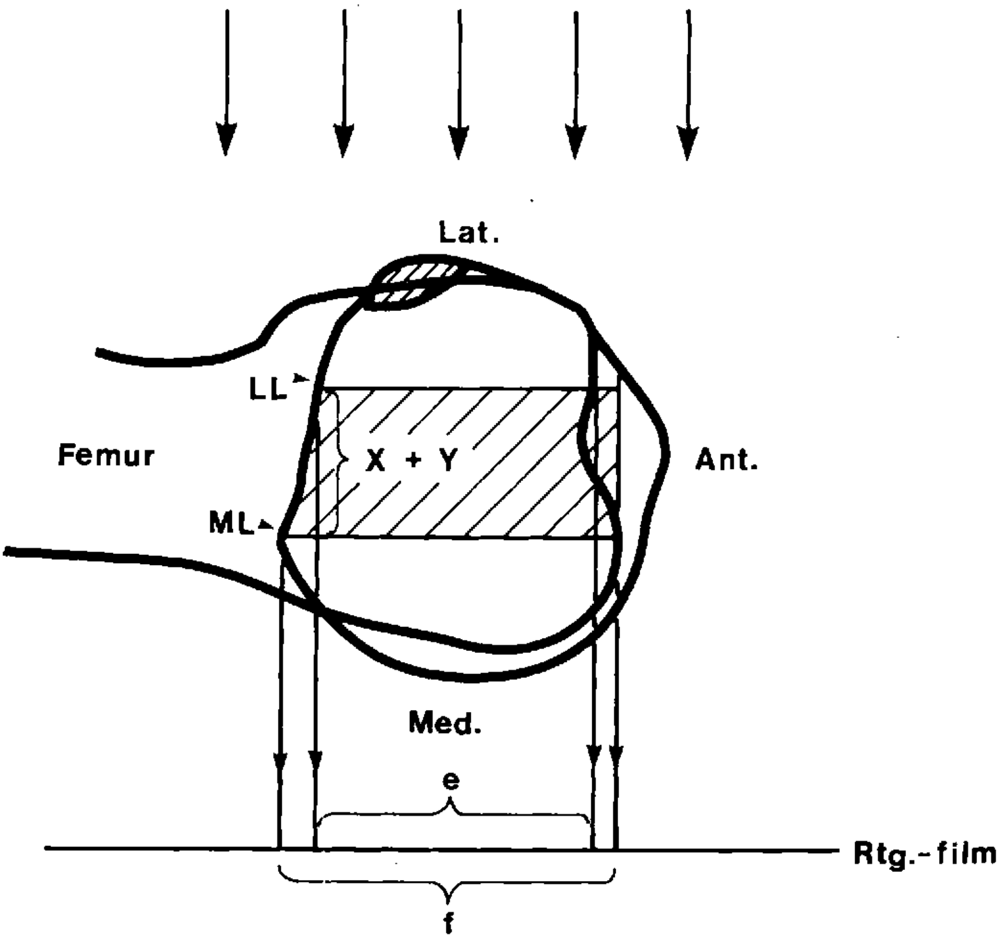


Figure 24: Contours of the 90° flexed knee joint viewed from above. Fibula hatched. The contour of the femur may be followed forward from the shaft. LL: lateral landmark on the tibia to which e is measured from the anterior margin of the lateral femoral condyle, as shown. ML: medial landmark on the tibia (posterior edge of medial tibial condyle). The measurement of f on the X-ray film is also shown. If, instead of a lateral radiation source, an anterior one is used, $(x + y)$ may be measured (on a preparation) and used as the approximated value for the line segment ML - LL. A corresponding rectangular area on a level with these points is hatched on the tibial condyle, where it takes part in the rotation and can be compared with the idealized Figure 23.

Summary: It has been demonstrated above, both by "external measurement" in degrees, by means of a pointer fixed against the tibial tuberosity, and by an approximated trigonometric calculation, that the foot rotates considerably more than does the knee, when it is attempted to induce rotation by means of a shoe which can be kept fixed in a desired position of rotation. The thigh is still fastened. Both the methods, although agreeing in broad outline, must be considered to carry such marked sources of error that the author prefers using the linearly measured parameters in mm, also to express rotation. The formula k - 1, where $k = e_{neutral}$ less $e_{rotated}$ and $1 = f_{neutral}$ less $f_{rotated}$ is well-suited for this purpose.

Normal Parameter Values at 15° and 30° Externally Rotated and 30° Internally Rotated Foot

Table 25 gives the mean values, $\bar{x}$, the standard deviation, SD, and the upper 97½% levels for the parameters of anteroposterior displacement, the foot fixed in 15° external rotation. Comparison with Table 19, in which the foot was fastened in the neutral position, shows that now the lateral tibial condyle is more forward displaced on traction, but less backward displaced on pressure - corresponding to that part of the rotation which has taken place already while the foot was being rotated without traction or pressure on the tibia. In other words: During the initial rotation from the neutral position to 15° external rotation of the foot, the lateral tibial condyle has already moved somewhat backward. Therefore, upon an action from this'new initial position it can be pulled farther forward - and will be less backward displaced than under "neutral" conditions. The mobility of the medial tibial condyle has changed very little (the rotation centre being apparently closer to the medial structures).

Tables 26 and 27 present the characteristics of the same parameters with the foot fastened in 30° of external rotation and in 30° of internal rotation. In accordance with the previous section, anterior displacement on traction of the lateral condyle is significantly greater when the foot is in external than when it is in internal rotation ($p = 0.004$ for the right-sided values in MannWhitney's rank sum test and $p = 0.003$ for the left-sided values). The explanation is the same as in the previous section.

On pressure there is, during internal rotation, greater mobility of the lateral tibial condyle than during external rotation ($p = 0.002$ on the left and $p = 0.08$ on the right). Moreover, there is significantly less backward displacement of the medial tibial condyle at internal rotation of the foot as the initial position than at external rotation ($p = 0.01$ for the right as well as left side).

Total mobility is less in the medial joint chamber (j-h) than in the lateral one (i-g), regardless of the position in which the foot is fastened.

In Table 28 it is investigated whether the rotation of the foot has any influence upon the critical levels in the form of 97½% upper critical levels. Realizing that such levels are probably somewhat dubious in dealing with small materials (13 and 10 examinations), the author has listed also the highest values measured in these series. The numerical difference between the two knees of healthy persons is used. At a 15° rotation of the foot the upper limits are unchanged from the examination with the foot in a neutral position, but at a more extreme position of rotation in the foot the possibilities of differences in mobility appear to increase - in particular for the lateral tibial condyle. Nevertheless, in rotatory examinations too it appears to be an advantage to use the narrower limits to the difference between the parameters of a subject's two knees rather than the limits to the parameters themselves which are quite wide (Tables 25, 26, and 27).

Just as $(k-l) = e_{neutral} - e_{rotated}) - (f_{neutral} - f_{rotated})$ was used to express rotation without anteroposterior stress action upon the joint, the expression (e-g) - (f-h) may be used for rotation during traction and the expression (i-e) - (j-f) for possible rotation during pressure.

Table 29 sets out the findings during traction with a force of 30 kg in which anterior displacement of the tibia is attempted. Normally, this will induce slight anterior displacement of both condyles and internal rotation. This is illustrated graphically in Fig. 25, the situation on the right. But what is shown on the left may happen too: merely an internal rotation. This occurs when the lateral condyle becomes forward displaced while the medial condyle is forced backward. From the figure it may be seen that (f-h) on the left becomes negative, (e-g) positive, and (e-g) - (f-h) positive in the form of the total of the two small, thick line segments. On the right another situation, in which (e-g) - (f-h) becomes positive, is shown as the difference between two line segments. The resulting line segment (measured on the X-ray film) is shown thicker than the rest. Both these situations occur in the normal material on traction. The one on the left may also represent internal rotation which occurs merely on rotation of the foot. In that case e is merely exchanged by e_n, f by f_n, g by e_r, and h by f_r, where n signifies neutral and r rotated position. The expression, then, is $((e_n - e_r) - (f_n - f_r)) = (k-l)$. The expression ((e-g) - (f-h)) may even become negative, with a numerically low

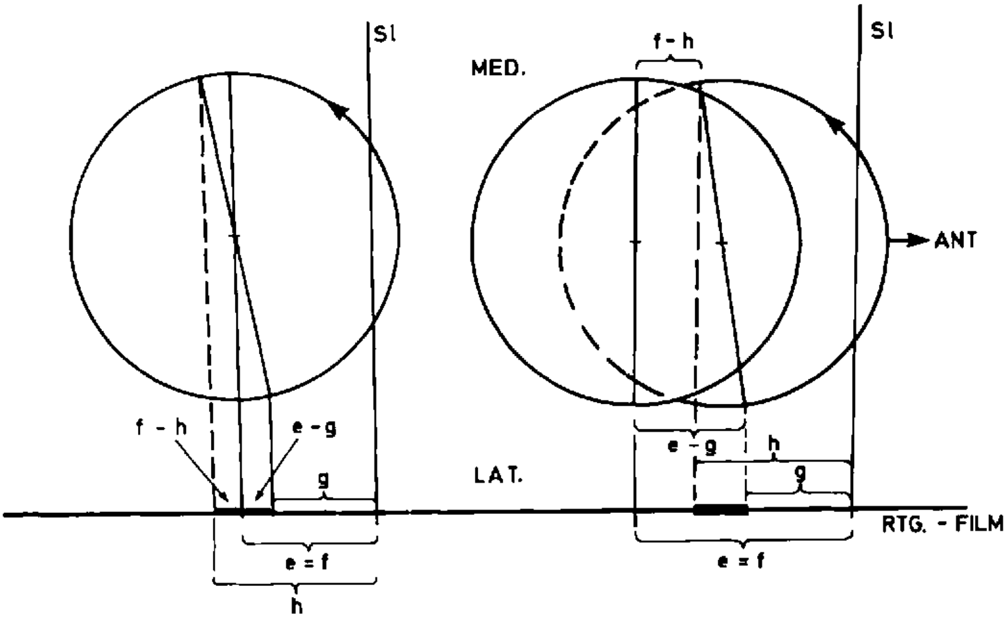


Figure 25: Graphic illustration of the rotation in the right tibial condyle, viewed from above. In the situation on the right the tibia moves a little forward on traction as compared with the static reference line sl (cf. Fig. 23). For the sake of clarity the landmarks whence the parameters are measured on this diagram have been moved to the periphery of the circles (corresponding to the points of intersection with the diameter). The medial parameters are f and h, the lateral ones e and g. In both cases rotation occurs. The line segment which represents rotation is thick in both situations. The X-ray (RTG) film on which all measurements are made is indicated. Cf. also the text.

value in a few cases, as is apparent from the first column of figures in Table 29. In that event, the explanation is a very slight external rotation upon traction.

As regards the mean values, $\bar{x}$, it will be seen, firstly, in each column that traction causes increasing internal rotation the more the foot has been externally rotated in the initial position, while rotation has almost ceased when a 30° internally rotated foot is used as the initial position. It is apparent also that the expression ((e-g) - (f-h)), like the expression (k-l) is positive during internal rotation. It is negative during external rotation. The latter is seen in approximately the same number of cases as internal rotation at an initial position with 30° externally rotated foot.

The bottom of each column in Table 29 gives the numerical difference between the two knees of normal persons; for this expression the upper 97½% critical level does not exceed 3.0 mm.

Fig. 26 demonstrates that the expression ((i-e) - (j-f)), which occurs on pressure upon the anterior part of the proximal end of the tibia, becomes positive on external rotation and negative on internal rotation. This is unlike the previous expressions. Table 30 lists the results of the calculation of this expression during a 30 kp pressure upon the tibia when the foot is in neutral position, 15° externally rotated, 30° externally rotated, and 30° internally rotated. As all mean values are positive, it is evident that in practically all cases the rotation is external. This is most obvious when the initial position of the experiment is with the foot in 30° internal rotation. Since in that case the lateral aspect of the tibia is forward-inward rotated already in the initial position, external rotation would also be expected on pressure. As may be seen from $\bar{x}$ in the columns of Table 30, external rotation is still appreciable at neutral position of the foot, but becomes lesser when the foot is fixed, before the experiment, in 15° or 30° external rotation. From the lowest "range" values, however, it will be seen that in all initial positions there occurred cases of internal rotation (negative values for the expression). In cases with 30° external rotation of the foot, internal rotation often occurred. The numerical difference between the persons' two legs are shown in the bottom columns of Table 30. No upper limit or maximum value exceeded 3.4 mm.

It has been found that $(e_n - g_{15}) - (f_n - h_{15})$ may be useful as an expression of rotation at traction. Thereby, the movement of the lateral tibial condyle from the neutral position without any force action, e_n, to the final position in which the foot is 15° externally rotated, and during 30 kg traction, g_{15}, is examined together with the corresponding rotatory movement for the medial pair of condyles $(f_n - h_{15})$. The values for the expression for the right and left leg and the numerical difference are given in Table 31. This table also presents an expression for rotation

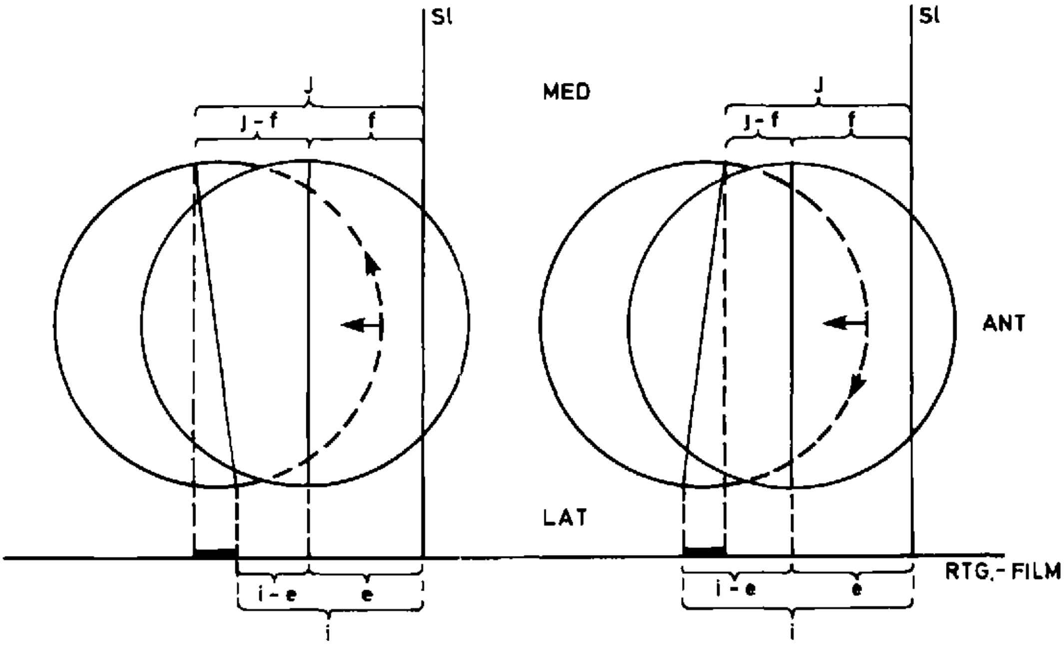


Figure 26: Pressure on the proximal end of the right tibia (viewed from above) which is pressed backward. The medial parameter changes from being f in the neutral position without pressure to being j, the lateral one from e to i. When external rotation occurs as well (on the right in the figure), the expression ((i-e) - (j-f)), represented by the thick line segment, becomes positive, on internal rotation (the situation on the left) it becomes negative.

during pressure from the neutral position without a force action: $(i_{15} - e_n) - (j_{15} - f_n)$. The mean values for condylar movements in the two situations were also calculated (the last two columns of the table).

Corresponding numerical differences between the right and left knee are calculated in the following tables, for rotation without traction or pressure actions, but an action through rotation of the foot only. Table 33 lists the movements of the lateral and medial tibial condyle separately. Only in one case of rotation did the numerical difference exceed 3.0 mm - and this was a difference in the displacements of the medial condyles $(f_n - f_{30^\circ ext.})$ during 30° external rotation of the foot (in one case 3.2 mm). As to the expression (k-l) the upper limit to the side difference of 3.0 mm also seems applicable (Table 32), although a few values are beyond it.

Summary and Conclusion

In a number of tables it has been demonstrated that even in normal knees the two tibial condyles move a great deal, on traction and pressure, in relation to the respective femoral condyles. Which condyle is most displaced depends upon the initial position in which the foot has been fastened (abbreviated foot rotation), cf. Tables 19, 25, 26, and 27. The total anteroposterior displacement is always less in the medial joint chamber, regardless of the foot rotation. The anterior displacements may amount to as much as 10-12 mm for each condyle - up to 17 mm total anteroposterior displacement. On the other hand, the anterior or posterior displacement, expressed as the difference between a person's two knees, never exceeds 3.0 mm in the neutral position, 3.1 mm in 15° external foot rotation or 30° internal rotation. At 30° external rotation the limit was exceeded (3.8 mm in one case). At the different forms of rotation the upper limit of 3.0 mm was not exceeded by the expression (k-l) or ((e-g) - (f-h)), but by the expression ((i-e) - (j-f)) when pressure was exerted upon the knee, there being a 3.4 mm difference between a healthy person's two knees. All of this heavy documentation, then, serves the purpose to reduce the parameter investigation needed in patients with unilateral traumatic injuries to the knee ligaments. It may be concluded that a reasonable limit or "critical level" in comparing the same parameter for a person's two knees in order to distinguish between normal and abnormal conditions must be 3.0 mm for parameters e, f, g, h, i, and j and parameters derived from them, while 2.0 mm is a reasonable "critical level" for c and d.

In dealing with patients having bilateral knee injuries, it is still necessary to use the wide limits of normal movements and thus look up the tables in this Addendum (Tables 9, 10, 19, 23, 25, 26, 27, 29, and 30).

In the survey it was discussed whether a "critical level" in whole, rounded figures would not be most reasonable, measuring with one decimal and then rounding the final result.

Table 21

Rotation of pointer on the tibial tuberosity at given foot rotation. Mean and range in 12 subjects (4 males and 8 females). Knee rotation follows the direction of the foot rotation.

Foot rotation		15° ext.	30° ext.	45° ext.	15° int.	30° int.	45° int.	T
Right	Mean:	5.5°	10,5°	15.3°	4.4°	8.8°	13.3°	28.6°
knee	Range:	5° - 8°	7° - 14°	12° - 17°	0° - 6°	5° - 10°	10° - 15°	24° - 30°
Left	Mean:	5.3°	9.8°	14.9°	4.3°	8.2°	12.9°	27.8°
knee	Range:	4° - 7°	7° - 12°	12° - 17°	0° - 7°	4° - 10°	7° - 15°	20° - 30°

T = "total rotation" of the knee = /knee rotation at a foot rotation of 45° int./+/knee rotation 45° ext./. Forced ext. and int. rotation of the foot were not attempted, so there is no question of an actual maximum rotation.

Table 23

Lower critical levels (for external rotation) and upper critical levels (for internal rotation) of 97 1/2 % to the total expression of rotation, k – l.

Right/ Left	Parameter (k – l)	$\overline{X}_{(k-l)}$	$SD_{(k-l)}$	$(\overline{X} \pm 2\ SD)_{(k-l)}$
Right	$k_1 = e_{\text{neutr.}} - e_{15^\circ\text{ ext.}}$ $l_1 = f_{\text{neutr.}} - f_{15^\circ\text{ext.}}$	– 3.90	1.50	– 6.90 = – 6.9
Left	$k_1 = e_{\text{neutr.}} - e_{15^\circ\text{ext.}}$ $l_1 = f_{\text{neutr.}} - f_{15^\circ\text{ ext.}}$	– 3.82	1.34	– 6.50 = – 6.5
Right	$k_2 = e_{\text{neutr.}} - e_{30^\circ\text{ ext.}}$ $l_2 = f_{\text{neutr.}} - f_{30^\circ\text{ext.}}$	– 7.83	2.11	– 12.05 = – 12.1
Left	$k_2 = e_{\text{neutr.}} - e_{30^\circ\text{ext.}}$ $l_2 = f_{\text{neutf.}} - f_{30^\circ\text{ext.}}$	– 6.82	1.68	– 10.18 = – 10.2
Right	$k_3 = e_{\text{neutr.}} - e_{30^\circ\text{int.}}$ $l_3 = f_{\text{neutr.}} - f_{30^\circ\text{int.}}$	5.33	1.07	7.47 = + 7.5
Left	$k_3 = e_{\text{neutr.}} - e_{30^\circ\text{ int.}}$ $l_3 = f_{\text{neutr.}} - f_{30^\circ\text{int.}}$	5.89	1.54	8.97 = +9.0

Table 22

Knee rotation on mere foot rotation. Traction and pressure: 0. Measured on the basis of alterations in parameters e and f. Unit mm.

No. of subjects N	Foot rotation from neutral	R/L	Parameter	Range	$\overline{X}$	SD	Expression of rotation $\overline{X}\,k - \overline{X}\,l$	 numerical
50	15° ext.	Right knee	$e_{\text{neutr.}} - e_{15^\circ\,\text{ext.}} = k_1$	− 5.9 → − 0.20	− 2.39	1.12	$\overline{X}\,k_1 - \overline{X}\,l_1 =$	3.89
			$f_{\text{neutr.}} - f_{15^\circ\text{ext.}} = l_1$	+ 0.2 → + 4.30	+ 1.50	0.75	− 3.89	
		Left knee	$e_{\text{neutr.}} - e_{15^\circ\text{ext.}} = k_1$	− 5.3 → + 0.5	− 2.71	1.05	− 3.81	3.81
			$f_{\text{neutr.}} - f_{15^\circ\text{ext.}} = l_1$	− 0.9 → + 2.7	+ 1.10.	0.85		
13	30° ext.	Right knee	$e_{\text{neutr.}} - e_{30^\circ\text{ext.}} = k_2$	− 7.5 → − 2.1	− 4.78	1.39	$\overline{X}\,k_2 - \overline{X}\,l_2 =$	7.83
			$f_{\text{neutr.}} - f_{30^\circ\text{ext.}} = l_2$	+ 1.2 → + 7.7	+ 3.05	1.74	− 7.83	
		Left knee	$e_{\text{neutr.}} - e_{30^\circ\text{ext.}} = k_2$	− 7.4 → − 2.2	− 4.75	1.38	− 6.82	6.82
			$f_{\text{neutr.}} - f_{30^\circ\text{ext.}} = l_2$	+ 0.4 → + 4.5	+ 2.07	1.09		
10	30° int.	Right knee	$e_{\text{neutr.}} - e_{30^\circ\text{int.}} = k_3$	+ 1.6 → + 4.1	+ 2.86	0.94	$\overline{X}\,k_3 - \overline{X}\,l_3 =$	5.33
			$f_{\text{neutr.}} - f_{30^\circ\text{int.}} = l_3$	− 3.5 → − 2.0	− 2.47	0.51	+ 5.33	
		Left knee	$e_{\text{neutr.}} - e_{30^\circ\text{int.}} = k_3$	+ 1.1 → + 5.5	+ 3.56	1.48	+ 5.89	5.89
			$f_{\text{neutr.}} - f_{30^\circ\text{int.}} = l_3$	− 3.6 → − 1.0	− 2.33	0.89		

Table 24

Calculation of knee joint rotation during foot rotation on the basis of sin. v.
For comparison, the angulations found by "external measurement". Unit: degrees.

Control No.		Foot 15° ext. rotated		Foot 30° ext. rotated		Foot 30° int. rotated	
		calculated v	external measurement	calculated v	external measurement	calculated v	external measurement
51	R	3°	5°	7°	10°		
	L	4°	6°	8°	10°		
52	R	6°	5°	10°	10°		
	L	6°	5°	10°	10°		
57	R	5°	8°			6°	5°
	L	6°	5°			7°	5°
62	R	4°	5°				
	L	3°	7°				
78	R	9°	5°	9°	10°		
	L	8°	5°	10°	8°		
80	R	9°	5°	15°	10°		
	L	5°	5°	11°	10°		

Table 25

Characteristics and upper critical levels (97 1/2 %) of parameters for anterior or posterior displacement. Traction and pressure: 30 kg.
Foot fastened in 15° external rotation. N = 50.

Displacement	parameter		$\bar{X}$	SD	$\bar{X}$	SD	$\bar{X}$ + 2 SD
ant. displ. lat. condyle	(e-g)	R	6.23	2.21	6.3	2.2	10.7
	(e-g)	L	6.27	2.07			
ant. displ. med. condyle	(f-h)	R	2.69	1.63	3.1	1.7	6.5
	(f-h)	L	3.13	1.70			
ant. displ. mean of both	$\frac{(e-g)+(f-h)}{2}$	R	4.46	1.76	4.5	1.8	8.1
		L	4.70	1.64			
post. displ. lat. condyle	(i-e)	R	3.42	1.65	3.2	1.8	6.9
	(i-e)	L	3.16	1.85			
post. displ. med. condyle	(j-f)	R	2.44	1.17	2.4	1.2	4.8
	(j-f)	L	2.21	1.25			
post. displ. mean of both	$\frac{(i-e)+(j-f)}{2}$	R	2.93	1.08	2.7	1.3	5.2
		L	2.68	1.26			
total displ. lat. condyle	(i-g)	R	9.65	2.50	9.7	2.5	14.7
	(i-g)	L	9.43	2.57			
total displ. med. condyle	(j-h)	R	5.13	2.12	5.3	2.0	9.3
	(j-h)	L	5.34	2.04			
total displ. mean of both	$\frac{(i-g)+(j-h)}{2}$	R	7.39	2.04	7.4	2.0	11.4
		L	7.38	2.01			

Table 26

Characteristics of parameters for anterior or posterior displacement. Traction and pressure: 30 kg. Foot fastened in 30° external rotation. N = 13: 7 females and 6 males. Unit mm.

Parameter		$\bar{X}$	Range	SD	Used $\bar{X}$	Used SD	Upper critical level $\bar{X}$ + 2.2 x SD
(e-g)	R	6.87	3.60 – 11.80	2.39	7.1	2.4	12.4
(e-g)	L	7.12	3.00 – 12.40	2.43			
(f-h)	R	3.51	0.70 – 7.10	1.99	3.9	2.2	8.7
(f-h)	L	3.87	1.20 – 9.50	2.20			
$\frac{(e-g)+(f-h)}{2}$	R	5.19	2.45 – 9.45	2.09	5.5	2.2	10.3
	L	5.50	2.10 – 10.95	2.23			
(i-e)	R	2.97	0.00 – 7.20	1.71	3.0	1.7	6.7
(i-e)	L	2.37	0.50 – 7.20	1.83			
(j-f)	R	2.66	0.70 – 4.30	1.10	2.7	1.1	5.1
(j-f)	L	2.47	1.10 – 4.40	1.05			
$\frac{(i-e)+(j-f)}{2}$	R	2.82	1.25 – 5.00	1.04	2.8	1.3	5.2
	L	2.42	1.05 – 5.70	1.26			
(i-g)	R	9.84	6.60 – 17.40	3.32	9.8	3.3	17.1
(i-g)	L	9.49	5.40 – 16.70	3.29			
(j-h)	R	6.17	2.30 – 10.90	2.49	6.2	2.5	11.7
(j-h)	L	6.34	3.80 – 11.60	1.98			
$\frac{(i-g)+(j-h)}{2}$	R	8.00	4.45 – 12.80	2.77	8.0	2.8	14.1
	L	7.92	5.20 – 12.85	2.43			

Table 27

Characteristics of parameters for anterior or posterior displacement. Traction and pressure: 30 kg. Foot in 30° internal rotation. N = 10 (ratio females/males: 1/1). Unit mm.

Parameter		$\bar{X}$	Range	SD	Used $\bar{X}$	Used SD	Upper critical level $\bar{X}$ + 2.2 x SD
(e-g)	R	3.81	0.80 – 7.50	1.98	3.8	2.0	8.2
(e-g)	L	3.62	0.30 – 5.30	1.64			
(f-h)	R	3.78	0.70 – 9.10	2.57	3.8	2.6	9.5
(f-h)	L	3.61	0.90 – 6.90	2.09			
$\frac{(e\text{-}g) + (f\text{-}h)}{2}$	R	3.79	0.75 – 8.30	2.25	3.8	2.3	8.9
	L	3.61	0.70 – 6.10	1.74			
(i-e)	R	4.47	1.40 – 8.60	2.16	4.9	1.6	8.4
(i-e)	L	4.90	3.10 – 8.30	1.64			
(j-f)	R	1.29	0.10 – 3.10	0.93	1.3	0.9	3.3
(j-f)	L	1.28	0.50 – 2.20	0.66			
$\frac{(i\text{-}e) + (j\text{-}f)}{2}$	R	2.88	1.50 – 4.90	1.21	3.1	0.9	5.1
	L	3.09	1.80 – 4.65	0.92			
(i-g)	R	8.28	5.10 – 13.90	2.50	8.5	2.5	14.0
(i-g)	R	8.52	5.40 – 10.70	1.65			
(j-h)	R	5.07	1.40 – 11.00	2.54	5.1	2.5	10.7
(j-h)	L	4.89	1.50 – 9.00	2.36			
$\frac{(i\text{-}g) + (j\text{-}h)}{2}$	R	6.67	4.45 – 12.45	2.25	6.7	2.3	11.6
	L	6.70	3.15 – 9.60	1.74			

Table 28

Characteristics for parameters of anteroposterior displacement /right-left/. Traction and pressure force: 30 kg.
Foot in different positions of rotation. Max.: maximum value measured.

	Foot rotation 15° ext. N = 50			Foot rotation 30° ext. N = 13			Foot rotation 30° int. N = 10		
Displacement, parameter	$\bar{X}$	SD	$\bar{X}$ + 2 SD	$\bar{X}$	max.	$\bar{X}$ + 2.2 SD	$\bar{X}$	max.	$\bar{X}$ + 2.2 SD
anterior:									
lateral condyle e-g	1.25	0.94	3.13 ~ 3.1	1.08	4.6	3.8	1.05	3.00	3.0
medial condyle f-h	0.98	0.77	2.52 ~ 2.5	1.16	3.4	3.1	0.91	2.30	2.7
mean $\frac{(e-g)+(f-h)}{2}$	0.94	0.79	2.52 ~ 2.5	0.98	4.0	3.2	0.86	2.65	2.6
posterior:									
lateral condyle i-e	1.15	0.84	2.83 ~ 2.8	0.89	2.00	2.3	0.89	3.60	3.1
medial condyle j-f	1.12	0.70	2.52 ~ 2.5	0.88	1.90	2.4	0.69	2.50	2.2
mean $\frac{(i-e)+(j-f)}{2}$	0.85	0.64	2.13 ~ 2.1	0.85	1.70	1.8	0.66	2.05	2.0
total anterior posterior:									
lateral condyle i-g	1.21	0.98	3.17 ~ 3.2	0.95	3.10	2.9	1.72	4.80	4.9
medial condyle j-h	0.95	0.74	2.43 ~ 2.4	1.25	2.40	2.6	1.16	2.40	3.1
mean $\frac{(i-g)+(j-h)}{2}$	0.84	0.75	2.34 ~ 2.3	0.77	2.30	2.4	1.12	2.85	3.3

Table 29

Knee rotation during traction of 30 kg in normal persons expressed as ((e-g) – (f-h)) and as the numerical value of the difference in this quantity between the right and left knee.

Side	Characteristics	Foot neutral, N = 50	Foot 15° ext., N = 50	Foot 30° ext., N = 13	Foot 30° int., N = 10
Right	range	– 0.4 → + 5.3	+ 0.5 → + 7.6	+ 1.7 → + 6.0	– 1.6 → + 1
	$\bar{X}$	2.38	3.54	3.36	0.03
	SD	1.39	1.64	1.37	0.85
				$\bar{X} \mp 2.2$ SD	$\bar{X} \mp 2.2$ SD
	X ∓ 2 SD	– 0.4 → 5.16 ~ 5.2	+ 0.26 ~ 0.3 → 6.82 ~ 6.8	+ 0.34 ~ 0.3 → 6.37 ~ 6.4	– 1.8 → + 1.9
Left	range	– 1.3 → + 5.1	– 2.3 → + 7.8	+ 1.0 → + 5.4	– 2.3 → + 2.3
	$\bar{X}$	2.38	3.15	3.25	0.01
	SD	1.36	1.88	1.23	1.39
				$\bar{X} \mp 2.2$ SD	$\bar{X} \mp 2.2$ SD
	$\bar{X} \mp 2$ SD	– 0.34 ~ 0.3 → 5.10	– 0.61 ~ – 0.6 → 6.91 ~ 6.9	0.54 ~ 0.5 → 5.96 ~ 6.0	– 3.0 → + 3.1
/Right – left/	range	+ 0.1 → + 2.9	+ 0.1 → + 3.1	+ 0.1 → 2.7	0.0 → 2.1
	$\bar{X}$	1.24	1.14	1.20	0.78
	SD	0.72	0.82	0.75	0.59
	$\bar{X} + 2$ SD	2.68 ~ 2.7	2.78 ~ 2.8	2.70 ~ 2.7	2.07 ~ 2.1

Table 30

Knee rotation during pressure of 30 kg in normal persons as ((i·e) – (j·f)) and as the numerical value of the difference in this quantity between the right and left knee.

Side	Characteristics	Foot neutral, N = 50	Foot 15° ext., N = 50	Foot 30° ext., N = 13	Foot 30° int., N = 10
Right	range	– 2.6 → + 7.40	– 3.0 → + 5.1	– 4.3 → + 4.4	– 0.2 → + 8.2
	$\bar{X}$	2.39	0.98	0.31	3.18
	SD	2.13	1.89	1.97	2.28
	$\bar{X} \pm 2$ SD	– 1.87 ~ – 1.9 → 6.65 ~ + 6.7	– 2.8 → 4.76 ~ + 4.8	$\bar{X} \pm 2.2$ SD: – 4.0 → + 4.6	$\bar{X} \pm 2.2$ SD: – 1.8 → + 8.2
Left	range	– 1.1 → + 7.7	– 3.1 → + 5.4	– 3.3 → + 3.0	+ 2.3 → + 7.3
	$\bar{X}$	2.39	0.95	– 0.10	3.62
	SD	1.90	1.89	1.59	1.71
	$\bar{X} \mp 2$ SD	6.19 ~ 6.2 → – 1.41 ~ – 1.4	4.73 ~ 4.7 – 2.83 ~ – 2.8	$\bar{X} \mp 2.2$ SD: – 3.6 → + 3.4	$\bar{X} \mp 2.2$ SD: + 0.1 → + 7.4
/Right – left/	range	+ 0.1 → + 3.40	+ 0.1 → + 3.30	+ 0.0 → + 1.90	+ 0.4 → + 3.1
	$\bar{X}$	1.33	1.44	0.88	1.14
	SD	0.95	0.96	0.59	0.92
	$\bar{X} + 2$ SD	3.23 ~ 3.2	3.36 ~ 3.4	2.18 ~ 2.2	3.16 ~ 3.2

Table 31

Rotations calculated from the neutral foot position without any application of force, e_n and f_n, to 15° external rotation in the foot and 30 kg traction, g_{15} and h_{15}, and 30 kg pressure i_{15} and j_{15}.

Side	Characteristics	$(e_n \cdot g_{15}) - (f_n \cdot h_{15})$	$(i_{15} \cdot e_n) - (j_{15} \cdot f_n)$	$\frac{(e_n \cdot g_{15}) + (f_n \cdot h_{15})}{2}$	$\frac{(i_{15} \cdot e_n) + (j_{15} \cdot f_n)}{2}$
Right	range	– 1.20 → 8.60	0.60 → 8.30	0.85 → 7.95	1.10 → 6.80
	$\bar{X}$	– 0.36	4.88	4.02	3.37
	SD	1.50	1.99	1.71	1.23
	$\bar{X} \mp 2$ SD	– 3.36 ~ – 3.4 → + 2.64 ~ + 2.6	0.90 ~ 0.9 → 8.86 ~ 8.9	0.60 ~ 0.6 → 7.44 ~ 7.4	0.91 ~ 0.9 → 5.83 ~ 5.8
Left	range	– 5.80 → 2.70	– 0.20 → 9.60	1.10 → 8.20	1.25 → 7.10
	$\bar{X}$	– 0.67	4.77	3.89	3.49
	SD	1.90	2.01	1.53	1.25
	$\bar{X} \mp 2$ SD	– 4.47 ~ – 4.5 + 3.13 ~ + 3.1	0.75 ~ 0.8 → 8.79 ~ 8.8	0.83 ~ 0.8 → 6.95 ~ 7.0	0.99 ~ 1.0 5.99 ~ 6.0
/Right – left/	range	0.00 → 4.70	0.00 → 4.70	0.05 → 3.55	0.00 → 2.00
	$\bar{X}$	1.27	1.76	0.83	0.73
	SD	1.01	1.06	0.66	0.57
	$\bar{X} + 2$ SD	3.29 ~ 3.3	3.88 ~ 3.9	2.15 ~ 2.2	1.87 ~ 1.9

Table 32

$/(k-l)_{R-L}/$. Difference in rotation between a person's two knees.

Rotation	N	Range	$\bar{X}$	SD	$\bar{X}$ + 2 SD
0 – 15° ext.	50	0.0 – 4.3	0.98	0.92	2.82 ~ 2.8
0 – 30° ext.	13	0.6 – 4.0	1.61	0.97	
0 – 30° int.	10	0.0 – 3.0	1.14	0.93	

Table 33

Knee rotation at different foot rotations. Traction and pressure = 0. Numerical difference between the right and left knee. Measured by simpler parameters: $/(e_n - e_r)\ R-L/$ and $/(f_n - f_r)\ R-L/$.

Rotation	N	Parameter	Range	$\bar{X}$	SD	$\bar{X}$ + 2 SD
0 – 15° ext.	50	$/(e_n - e_{15})(R-L)/$	0.1 → 2.8	0.89	0.70	2.29 ~ 2.3
		$/(f_n - f_{15})(R-L)/$	0.0 → 2.2	0.90	0.62	2.14 ~ 2.1
0 – 30° ext.	13	$/(e_n - e_{30})(R-L)/$	0.1 → 2.7	1.29	0.81	
		$/(f_n - f_{30})(R-L)/$	0.3 → 3.2	1.64	0.86	
0 – 30° int.	10	$/(e_n - e_{30})(R-L)/$	0.2 → 1.5	0.98	0.48	
		$/(f_n - f_{30})(R-L)/$	0.1 → 1.5	0.90	0.45	

ADDENDUM II

ANALYSIS OF STRESS RADIOGRAPHIC MEASUREMENTS OF MEDIAL, LATERAL, ANTEROPOSTERIOR, AND ROTATORY INSTABILITY AND COMPARISON WITH OPERATIVE FINDINGS IN 153 KNEE INJURIES

Addendum II: Contents Page

Patient Material. Survey

The classification in papers (5) and (6) was used, the cases being reported in numerical order. Group 1 comprises cases of fresh knee injuries, meaning that the interval between the trauma and operation was 14 days or less, group 2 cases in which this interval was 15 days to 3 months, and group 3 cases in which it exceeded 3 months.

The group of fresh injuries is made up of 90 knee joints. Local anaesthesia (lidocaine chloride) was used in the measurements, adding noradrenaline into collateral ligaments and capsule, but not into the joint space (5 ml, after aspiration of hyd- or haemarthrosis). The fresh cases are particularly well-suited for observing the extent of the damage in the course of surgery, as there is not yet any blurring scar formation in the collateral ligaments and capsule or atrophy of injured cruciate ligaments. However, the pain reaction may be violent in this group, and in three of the 90 cases this prevented measurement of the drawer sign.

Group 2 comprises only 26 knee joints. In this group too local anaesthesia had to be applied at the stress radiographic measurement. The pathological appearance of the injuries proved partly blurred by scar formation and cruciate atrophy.

Group 3 comprises 37 knee joints. In this group there was no pain reaction during the measurements, and local anaesthesia was not used. The original pathological anatomy of the collateral ligaments and capsules proved to have been almost totally transformed by scar formation. Injuries to the cruciate ligaments could be assessed only as partial or total atrophy (in some cases as the presence of ligament remnants). Possible healing with lengthening of cruciate ligaments is difficult to evaluate.

In all, 153 knee injuries in 151 patients will be reported, as two patients were examined, and operated upon, twice on the same knee. They were a patient listed first as Case 50 and later as Case 101 and another one listed first as No. 60 and later as Case 148. In both cases there was a question first of a fresh injury and later of a new trauma presented late for treatment. Thus, the pathological anatomy was quite clear and easy to describe in Cases 50 and 60, while in Case 101 it was as in other cases of group 2 and in Case 148 as in other group 3 cases. Therefore, the two repeated operations on the same knee joint do not influence the analysis.

A total survey on the composition of the clinical material by age and sex has been given in Table 1 of (5), a total survey on the "cause" of the trauma in Table 2 of the same paper. "Cause" is taken to mean the activity in which the patient was involved when the accident occurred. An attempt was always made to elucidate the pathogenesis of the injury, meaning the mechanism of the trauma, and it will be tabulated below. It is of importance to which types of instability are expected to be found in the joint concerned. The patients were examined during the period January 1974 to November 1975.

Lastly, true negative, TN, true positive, TP, false negative, FN, and false positive, FP, findings of instability will be analysed, considering the operative finding the decisive factor. Thereafter, the results of stress radiography, clinical examination (by another surgeon, i.e. the Head or Senior Registrar), and examination under general anaesthesia were compared (cf. (5)). This was done by calculating the PV_{pos} and PV_{neg} of the named TN, TP, FN, and FP values (Wulff 1973 a). In considering the importance of rounding the stres radiographic measuring results to whole figures (mm), it must be taken into account whether these expressions are affected by such rounding.

Operative Method

Operation was initiated in all cases by a vertical incision anterior to the medial collateral ligament and continued as arthrotomy opening the joint capsule anterior to the named ligament up to the vastus fibres. The vastus medialis muscle was incised only in major procedures. This gave such good access to the joint that the cruciate ligaments and the medial collateral ligaments could be inspected, and so could a large part of the articular cartilage, the medial meniscus, and the anterior horn of the lateral meniscus. In other or simultaneous injuries, further incisions were applied over the lateral collateral ligament, into the popliteal space, etc. In the medial incision the infrapatellar branch of the saphenous nerve was always exposed, covered with tape, and spared. Secondary rupture of this nerve branch during the operation sometimes occurred in major procedures involving suture of the cruciate ligaments etc. A more detailed description of the technique of ligament suture is outside the scope of the present paper.

All the cases are tabulated, while particularly interesting or complicated cases will be described in the text.

Rules of Calculation:

From Addendum I, in particular, the last summary, and from definitions and findings in (3), (4), and (5), the following calculation rules can be summed up:

Expressions of rotation:

1. H: $k - l = (e_{\text{neutral}} - e_{\text{rotated}}) - (f_{\text{neutral}} - f_{\text{rotated}})$. This expression is positive on internal rotation of the tibia (and negative on opposite rotation). No stress action.
2. F: $(e - g) - (f - h)$ expresses rotation during traction in neutral position e_n, g_n, etc.; in 15° external rotation e_{15}, g_{15}, etc.; in 30° external rotation $e_{30^\circ\ \text{ext.}}$, $g_{30^\circ\ \text{ext.}}$, etc., and in 30° internal rotation of the foot: $e_{30^\circ\ \text{int.}}$, $g_{30^\circ\ \text{int.}}$, etc.

   The expression is positive in internal rotation of the tibia (and negative in the opposite rotation.
3. G: $(i - e) - (j - f)$ expresses rotation during pressure (posteriorly directed force). The same sub-expressions of the parameters are used as in rule 2 to designate the position of the foot during the force action. Expression 3 is positive in external rotation of the tibia and negative in the opposite rotation.
4. /Parameter of injured knee - that of the uninjured knee/ > 3.0 mm to be abnormal. However, to all foot positions concerning expression 3, and in 30° external or internal rotation of the foot concerning expression 1 there is a limit > 3.4 mm.

Expressions of medial and lateral instability:

5. A: $(c_{\text{injured}} - c_{\text{uninjured}}) > 2.0$ mm: medial instability.
6. B: $(d_{\text{injured}} - d_{\text{uninjured}}) > 2.0$ mm: lateral instability.

Expression of anteroposterior displacement:

7. C: $\frac{(e - g) + (f - h)}{2}$ (injured - uninjured) > 3.0 mm: anterior drawer sign.
8. D: $\frac{(i - e) + (j - f)}{2}$ (injured - uninjured) > 3.0 mm: posterior drawer sign.
9. E: $\frac{(i - g) + (j - h)}{2}$ (injured - uninjured) > 3.0 mm: abnormal total anteroposterior displacement (applies to neutral position and 15° externally rotated foot, while a few values are 3.2 and 3.3 in further internal or external rotation of the foot).

Combinations of anteroposterior instabilities and rotatory instabilities do occur (6). The three expressions of rotation subtract the greater part of any anterior or posterior displacement, as is apparent from Figures 25 and 26. They are then, correctly, multiplied by a factor 2, as a perpendicular line from the new centre will divide the line segment concerned into two halves, and the new centre represents total displacement. However, this does not acquire any practical importance, as the numerical values were calculated on

Table 1

Algebraic formulae for calculation of instability:

A: Medial instability: $c_{inj.} - c_{uninj.}$
B: Lateral " : $d_{inj.} - d_{uninj.}$
C: Anterior displacement (drawer sign): $\frac{(e-g) + (f-h)}{2}$ n (inj. - uninj.)
D: Posterior " " " : $\frac{(i-e) + (j-f)}{2}$ n (inj. - uninj.)
E: Total anteroposterior displacement: $\frac{(i-g) + (j-h)}{2}$ n (inj. - uninj.)
where n = neutral, inj. = injured, uninj. = uninjured.
C, D, and E can also be calculated for foot in 15° ext., 30° ext., and 30° int. rotation.
F: Rotation on traction ((e-g)) - (f-h)) n_{15° ext. (inj. - uninj.)
30° ext.
30° int.
G: Rotation on pressure: ((i-e) - (j-f)) n_{15° ext. (inj. - uninj.)
30° ext.
30° int.
H: Rotation without pressure or traction: $(k-l)_{(inj. - uninj.)} = (e_n - e_{15}) - (f_n - f_{15})$.

H can also be calculated for 30° of external or internal rotation in which 15° ext., 30° ext., and 30° int. designate foot rotation.

$H_{n15^\circ ext.}$, $H_{n30^\circ int.}$, $H_{n30^\circ ext.}$ designate knee rotation when the foot is rotated from the neutral position 15° externally, 30° internally, or 30° externally. $C_{n15^\circ ext.}$, $D_{n15^\circ ext.}$, $F_{n15^\circ ext.}$, $G_{n15^\circ ext.}$ are the corresponding designations.

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the basis of the normal material (Addendum I). Thus, although the general use of the halved expressions, e.g. ½ ((i - e) - (j - f)) does mean halved critical levels, they also halve the values with which they are to be compared in abnormal cases. Therefore, factor ½ can just as well be excluded, i.e. multiplied by 2.

Table 1 is a survey on a set of formulae deduced from the calculation rules, using constantly the difference (injured - uninjured). The formulae are stated in capital letters to save space in the following tabulations in which they will be used. It is the intention to use these formulae as a screening of the calculated values for the different forms of instability, the numerical critical level of the expressions being known: 2.0 mm for A and B, 3.0 mm for C, D, E, F, and $H_{n - 15^{o}ext.}$, and 3.4 mm for G and $H_{n - 30^{o}int.}$, and $H_{n30^{o}\ int.}$. Where these numerical values are exceeded, the sign must be observed, and a more detailed analysis of the movements in the condyles of the injured and uninjured knee instituted.

The procedure may seem complicated, but it was felt to be indicated for scientific reasons. When the possibilities have been investigated, it is planned to simplify both the number of measurements and calculations by picking out the simplest ones for routine use. In the injured material it was not possible to carry out all the examinations on each patient. Therefore, some spaces in the tables will be empty.

Patient Group 1

Table 2, in which the above system is used, presents the outcome of the calculations in Cases 1 to 11. Among these patients none exhibited medial or lateral instability at gonylaxometry, i.e. none exceeded the critical level of 2.0 mm for A and B (Table 2).

Nor did any of them have a positive drawer sign, as none had C or D values exceeding the critical level of 3.0 mm, cf. Fig. 2 in (5). Note that the clinical examination in all these cases presented FP findings (in 9 cases medial laxity, in 2 cases drawer sign (Table 3)). Examination under general anaesthesia presented only one FP and gonylaxometry none. On the other hand, there is reason to comment on the values for rotatory instability in some of these patients. Clinical evaluation of rotatory instability has proved so difficult that no comparison was made of the findings at gonylaxometry, at clinical evaluation, and at examination under general anaesthesia as done for medial and lateral instability and for the drawer signs.

Case 1:

This case has been reported in (6), Table 1 and Fig. 3, and in the text of the present survey under "findings" and "discussion".

A 29-year-old man sustained an injury during flexion-external rotation of the left lower leg in relation to the thigh while skiing. Stress radiography did not demonstrate any medial instability, $(c_{inj.} - c_{uninj.})$ being < 2.0 mm (= 1.8 mm). Examination under general anaesthesia also did not demonstrate medial instability. Anterior displacement of the lateral tibial condyle (traction 30 kg) in the neutral position was for

the injured knee (e - g): 7.2 mm,
uninjured knee (e - g): 8.6 mm
(injured - uninjured = -1.4 mm).
Anterior displacement of the medial tibial condyle was for
the injured knee (f - h): 8.2 mm
uninjured knee (f - h): 5.9 mm
injured -uninjured: + 3.2 mm

Thus, when considering the medial tibial condyles, it will be seen that the displacement of the "injured condyle" is greater than that of the uninjured one (indicating external rotation), and when considering the lateral condyles, that of the injured knee is less anteriorly displaced than that of the uninjure knee, i.e. relatively posteriorly, also indicating external rotation. The difference between $(f - h)_{inj.}$ and $(f - h)_{uninj.}$ is sufficiently great to afford the sole documentation of this external rotation. The difference between the injured and uninjured knee for the lateral pair of condyles (e - g) is negative and the total difference therefore 4.6 mm.

It is this way of calculation, totalling the movements of both tibial condyles, which is collected algebraically in expression F in Table 1:

$$((e - g) - (f - h))_{inj.} - ((e - g) - (f - h))_{uninj.},$$

and the calculation gives:

$$(7.2 - 8.2) - (8.6 - 5.0) = (- 1.0)-(3.6) = - 4.6 \text{ mm},$$

which is numerically equal to the above result, while the sign, cf. calculation rule 2, indicates external rotation. This rotation exceeds the critical level of 3.0 mm.

Regarding the expressions for the injured and the uninjured leg isolated, it will be seen that $((e - g) - (f - h))_{inj.}$ becomes negative, i.e. indicating external rotation, while the same expression for the uninjured leg is positive, indicating internal rotation, as normally found on traction.

Operative findings: Isolated, partial rupture of the SMCL, the long anterior fibres being ruptured. In extension and in slight flexion the intact, posterior fibres prevent medial instability. In 90° flexion, in which examination for anterior displacement is performed, these fibres are lax and permit abnormal external rotation, Fig. 3 in (6).

Case 2:

While playing football the patient had been hit by an opponent's boot anteromedially on the tibia. This was, then, a posteriorly directed abduction trauma to the (hyper ?)-extended knee.

Operative findings: Fraying of the anterior fibres of the SMCL superiorly at the medial femoral epicondyle, but without a complete interruption of continuity. Rupture also of the posteromedial capsule. This case is analogous to Case 1.

The calculations in Case 2 were carried out as follows:

A: $(c_{inj.} - c_{uninj.}) = 11.2 - 11.2 = 0.0 \text{ mm} < 2.0 \text{ mm}$

B: $(d_{inj.} - d_{uninj.}) = 14.4 - 14.1 = 0.3 \text{ mm} < 2.0 \text{ mm}$

C_n: $\frac{(e-g) + (f-h)}{2} \text{ (inj.- uninj.)} = \frac{2.9 + 6.4}{2} - \frac{7.0 + 3.4}{2} = - 0.6 \text{ mm}.$

The only abnormal finding on stress radiography was abnormal external rotatory instability on traction in the neutral position of the foot as well as with the foot fastened in 15° external rotation.

F_n: $((e_n - g_n) - (f_n - h_n))_{inj.} - ((e_n - g_n) - (f_n - h_n)_{uninj.} =$

$((42.1 - 39.2) - (55.1 - 48.7)) - ((45.0 - 38.0) - (51.8 - 48.4))$

$= (2.9 - 6.4) - (7.0 - 3.4) = (- 3.5) - (3.6) = \underline{- 7.1 \text{ mm}},$

while F_{n15} was performed in a somewhat different way, the entire rotation being included at the same time:

F_{n15}: $((e_n - g_{15^\circ ext.}) - (f_n - h_{15}))_{(inj. - uninj.)} = \underline{- 7.2 \text{ mm}}$

Case 3:

In this case there were no abnormal values for medial/lateral instability or drawer sign. The values for rotation were calculated:

$F_n = ((e_n - g_n) - (f_n - h_n))_{(inj. - uninj.)} = 1.6 \text{ mm} < 3.0 \text{ mm}$

$F_{15^\circ ext.} = ((e_{15} - g_{15}) - (f_{15} - h_{15})) \text{ (inj. - uninj.)} = 0.8_{\ inj.} - 4.4_{\ uninj.}$

$= - 3.6$ mm, which is numerically > 3.0.

This means external rotation of the injured knee as compared with the uninjured one on traction, both rotating inward (being positive) - and this relative rotation has to be investigated in more detail.

When the foot is rotated from the neutral position into 15° external rotation, without force upon the tibia:

$(k - 1)_{uninj.} = ((e_n - e_{15\ ext.}) - (f_n - f_{15\ ext.})) =$

$(41.9 - 45.6) - (51.2 - 46.8) = - 8.1 \text{ mm}$

$(k - 1)_{inj.} = (44.0 - 45.2) - (52.5 - 50.6) = - 3.1 \text{ mm}$

The uninjured knee, thus, shows marked external rotation (which is normal) when the foot is rotated from 0° to 15° external rotation, whereas the injured knee shows an inhibition of this rotation so marked that $(k - 1_{(inj. - uninj.)}) = 5.0$ mm by far exceeds the critical level. This inhibition of normal external rotation is presumably due to a reflex muscle protection of the injured joint. The external rotation found in the calculation of F_{15^o} indicates that part of this rotatory inhibition is overcome by the forward traction on the tibial condyle. However, as the inhibition was 5.0 mm, and the rotation caused by the traction only 3.6 mm, there obviously still remains resistance to rotation in this case.

Operation showed, at the medial femoral epicondyle, a very slight fraying of a small part of the long fibres of the SMCL. This fraying was not visible until the intact layer of connective tissue, peritendineum, investing the ligament had been split in the direction of the fibres. The DMCL was completely intact. The inhibition of rotation must be assumed to have been due to intact nerve fibres close to the injured tissue which tried, via the reflex arc, to protect the ligament from further destruction (Palmer 1938).

Case 7:

Measurement of F_n = - 3.2 just exceeded the critical level of 3.0 mm, but the difference was so slight that a possible rounding to whole figures would include it in the "normal findings". Operation disclosed the sequelae of dislocation or subluxation of the patella.

Case 10:

Here G was 3.4 mm, which is just the critical level of G, which was not exceeded, cf. calculation rules 3 and 4.

$H_{n30^o\ int.}$: Considerably less internal rotation in the knee joint at 30° internal rotation of the foot (without pressure or traction) in the injured than in the uninjured knee (difference 3.7 mm).

Operative findings: A bucket-handle injury of the lateral meniscus which has prevented this internal rotation, as it has blocked the anterior movement of the lateral tibial condyle during traction. This phenomenon was not disclosed during clinical examination or during examination under general anaesthesia.

Thus, as also emphasized in (5) and (6), there is agreement between the parameters measured and the operative findings in the 11 cases of this group in which there was not total rupture of any ligament and in which only the medial ligament was involved, or in which the injury was of tissues other than ligaments (Table 3).

In Cases 2, 3, and 9 examination under general anaesthesia also showed no medial instability. Thus, in the 11 cases of this group the measurements were true negatives, TN.

Cases 12 - 24 incl. make up a sub-group characterized by isolated injury to the medial collateral ligament, including the deep layers of this ligament, and at the same time slight medial instability, nearly always less than 4 mm. As is apparent from Table 5, the operative findings are characterized by rupture of the DMCL and OMCL, possibly combined with partial rupture of the SMCL, but never total rupture of this structure. In many cases these partial ruptures were so slight that the peritendineum, the connective tissue membrane investing the parallel fibres of the ligament, had not been torn, and the injury presented itself merely as a small haematoma beneath it. Any minor defect in the ligament could be palpated, but in some cases it did not appear until after incision of the connective-tissue membrane along the ligament fibres. Some ruptures of this type are illustrated in Figure 27.

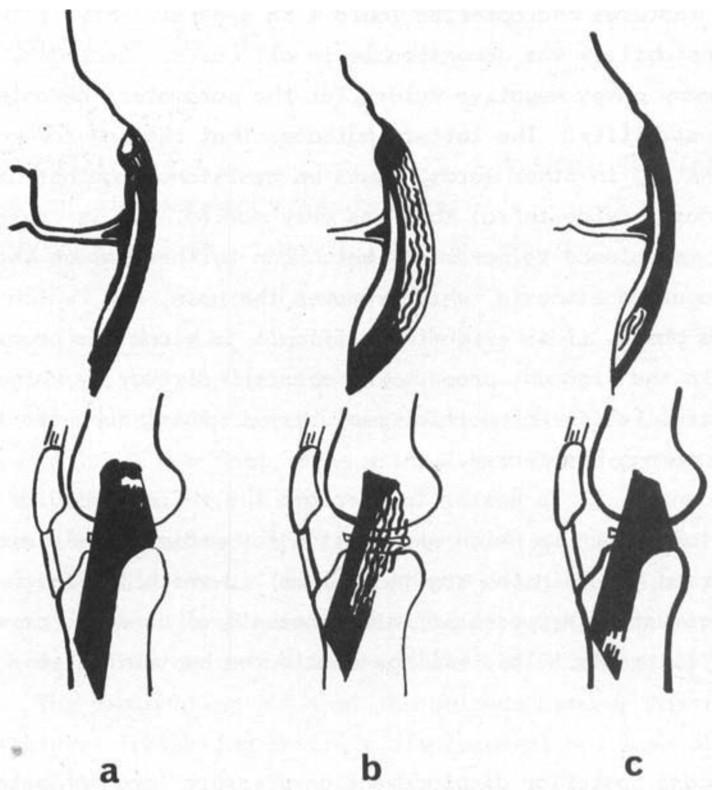

Figure 27: Sketches of partial ruptures of the SMCL

a Case 20
b Case 16
c Case 21.

In connection with Table 5 it must be mentioned, also, that only positive operative findings are listed. Thus, where the table states "partial rupture of the SMCL", this implies that the DMCL and OMCL were completely intact.

On scrutiny of Table 5 it is striking that the mechanism of trauma in practically all these cases consisted in abduction and external rotation of the tibia in relation to the femur and some degree of knee flexion. The same mechanism may be seen in Table 3, in Cases 3 and 9, in which operation also revealed small, partial ruptures of the medial collateral ligaments. As is apparent from Table 3, the same mechanism may sometimes lead to dislocation of the patella. It might be assumed, therefore, that it would be possible to demonstrate external rotatory instability by traction (or rotation of the foot), and in Table 4 special attention should be given to the F values.

Two features characterize Table 4 in general: First, that positive medial instability was demonstrable in all cases. Secondly, the very low and in many cases negative values for the parameters of anteroposterior or rotatory stability. The latter indicates that the injured knee moves less on actions or, in other words, puts up resistance against displacements. In some cases (vide infra) this was very marked. It is caused by reflex muscular resistance to movements which can further damage the ligament. During local anaesthesia, which removes the pain, and which was used in all these cases, it is evidently difficult to block the proprioceptive receptors in the ligament proper. As observed already by Palmer (1938), this is a special feature of partial ruptures; in total ruptures the resistance to displacement has ceased.

Evidently, it is easier to overcome the reflex muscular resistance in the frontal plane, in which examination for medial and lateral instability is performed, than in the sagittal plane, in which the thigh and lower-leg muscles resist anteroposterior displacements of condyles carrying partially ruptured ligaments. This will be elucidated by the following cases.

Case 18:

In this case posterior displacement on pressure (mean of both condyles) in the injured knee as compared with the uninjured knee was D = -4.4 mm, i.e. definitely reduced. This indicates a reflex muscle spasm. Before local anaesthesia was applied, it had manifested itself as a contraction state with the knee in about 60° flexion. Under general anaesthesia the muscle spasm completely disappeared, and the flexion defect was abolished.

Case 22:

Here nearly all parameters bear witness to muscular "locking" of the injured knee. Anterior as well as posterior displacement in the neutral position is less than in the uninjured knee, but without exceeding the critical level which, however, is greatly exceeded by parameter E representing the total anteroposterior displacement (5.4 mm less in the injured than in the uninjured knee).

Rotatory Findings, Cases 12 - 24

Case 22, continued: $G_n = -4.4$ indicates marked internal rotation in the neutral position on pressure, and in other words injury to the medial collateral ligamentous apparatus. $H_{n15^{o}\ ext.} = 3.2$ represents reduced external rotation of the injured knee on external rotation of the foot without any force applied, probably due to muscular defence. Operation revealed partial rupture only of the SMCL.

Case 16:

Medial instability: $A = (c_{inj} - c_{uninj.}) = 4.6$ mm. 30^{o} internal rotation of the foot and simultaneous pressure gives:

for the injured knee: $((e_n - g_{30^{o}\ int.}) - (f_n - h_{30^{o}\ int.}))_{inj.} = 5.3$ mm,
positive, int. rot.
for the uninjured knee: $((e_n - g_{30^{o}\ int.}) - (f_n - h_{30^{o}\ int.}))$ uninj. = 8.9 mm,
positive, int. rot.

Both values are within the normal range for rotation of the knee joint in internal rotation of the foot, even without any force applied, cf. Addendum I, bottom of Table 23.

As traction is applied, the uninjured knee rotates more inward than the injured knee (difference (injured - uninjured) = -3.6 mm = $F_{n30^{o}\ int.}$). In other words, the injured knee is externally rotated as compared with the uninjured knee. This accords with the magnitude of the figures and with the signs. The explanation is that the balance between passive lateral and medial structures inhibiting anterior displacement has been altered by the medial rupture.

Characteristics of Sub-group Cases 25 - 57

All but one showed medial instability exceeding 4 mm, and all had rupture of the anterior fibres, about 10 mm in width, of the SMCL. Within this group there was one partial subsynovial rupture of the ACL (Case 37, Fig. 28). No injuries to the menisci were found in this group, thus not from Case 1 - 57, when disregarding Case 10 and the fact that the anchoring of the meniscus has been detached as soon as the deep collateral ligament has ruptured. Thereby, the mobility of the meniscus at long sight will be altered, if the deep ligament does not heal in some way or other. There was one false positive, FP, value for lateral instability (Case 32).

Case 28:

This case showed external rotation on traction. Parameter F_n = -3.5 mm, indicating abnormal external rotation.

In this case there was total rupture of the SMCL as well as of the DMCL.

Case 33:

In this case there was greatly restricted anterior displacement in the injured knee as compared with the uninjured one on traction (C = -4.9 mm). This also entailed total anteroposterior displacement (E = -5.5 mm). Considering that the operation disclosed partial rupture of the DMCL, it is reasonable to imagine, in this case too, a reflex muscular resistance to the movement. The SMCL was totally ruptured.

Case 35:

Operation revealed total rupture of the SMCL, DMCL, and OMCL at the distal attachment on the tibia. Thus, in wriggling movements the meniscus went along with the femur, being lifted from the tibia.

On pressure on the tibia in the neutral position, internal rotation of the injured leg (-0.3 mm) was found, and the difference from the opposite knee (which rotated outward) clearly exceeded the critical level of 3.4 mm, being G_n = -4.8 mm. This rotation was not found until after the introduction of the algebraic formulae for rotation.

Case 37:

Neither clinical examination, gonylaxometry, nor examination under general anaesthesia could reveal any drawer sign. Operation revealed a small subsynovial rupture of the ACL with subsynovial haemorrhage. In the critical count of positive and negative findings in the calculation of Table 3 in (5) the evaluation is designated FN, marked by an asterisk in Table 7 of this Addendum. However, it is probably more reasonable to designate the finding TN. In the subsequent total analysis of the material ((5) pp. 307 - 308), therefore, the measurement is taken to be TN. The small injury which cannot be expected to give rise to a drawer sign, is depicted in Fig. 28.

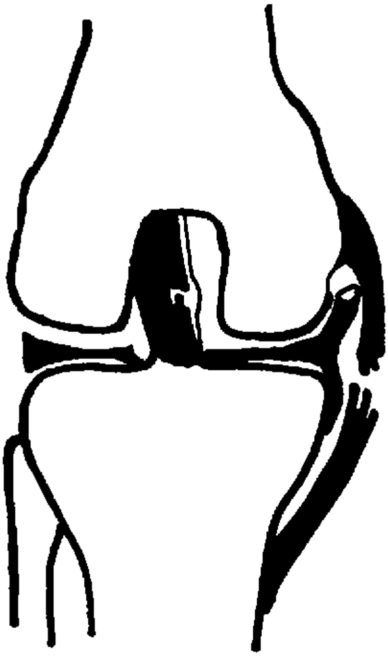

Figure 28: Sketch of the injury in Case 37. Partial injury to the ACL, the anteromedial fibres having burst subsynovially - and at operation the injury was primarily visible only as a subsynovial haematoma. The SMCL was totally ruptured, showing a frayed tear in the middle. The DMCL and OMCL had been torn off the attachment on the distal part of the epicondyle where there was a denuded bony area. The intact PCL is not depicted in order not to disturb the impression of the injured ACL.

Case 38:

This case, showing isolated total rupture of the SMCL, was previously (6) recorded as having a positive internal rotation of the injured knee during pressure of 30 kg. The difference between the posterior displacement of the injured and uninjured tibial condyle on pressure in the neutral position was:

for the medial condyles: 4.0 mm (injured > uninjured)
for the lateral condyles: 1.3 mm
Difference 2.7 mm

Whether this is to be considered positive rotation depends upon the critical level chosen, viz. whether it is felt reasonable to use 90% or 95% or an even higher upper confidence limit for normal values. The 90% confidence limit for normal values of G_n may be found in Addendum I, Table 30 in which $\bar{x} = 1.33$ and SD = 0.95 mm. Geigy's tables (1960) show $t_{2\alpha} = 1.2991$ for $P = 0.1$ ($2P = 0.2$) and degrees of freedom $N - 1 = 49$. The named 90% limit, then, will be: $\bar{x} + t_{2\alpha}$ SD $= 1.33 + 1.2991 \times 0.95 = 2.56$ mm. Calculated in the same way the 95% upper limit will be: 2.92 mm. Thus, the value for rotation of 2.7 mm is between 90% and 95% upper confidence limit. If this is felt to be acceptable, there is positive rotation. In paper (6) it is included as positive. But when using the somewhat stricter limits suggested in Addendum I, 97½%, the value has to be rejected as a representative of established rotatory instability.

Case 39:

Operation disclosed distraction of the fibres in the entire width of the SMCL, but the continuity of the ligament was preserved by the peritendineum. There was total rupture of the DMCL and OMCL, continuing backward into the posteromedial capsule. The rupture in the SMCL must be said to be a borderline case between partial and total rupture. The medial instability was quite marked, and a slight, further action would have entirely interrupted the continuity (Fig. 29) A = 4.6 mm.

Calculation of rotation for each knee separately:

injured knee: $(e - g) - (f - h) = 4.5 - 5.3 = -0.8$ mm, negative, which means external rotation,
uninjured knee ....$= 8.3 - 5.6 = 2.7$ mm, positive, which means internal rotation,

shows in the injured knee external rotation of slight extent due to an altered ligament balance. In the uninjured knee there is internal rotation like that expected in normal knees. The difference between the two knees, $F_{n15^\circ \text{ ext.}} = (-0.8) - (2.7) = -3.5$ mm. This is, even after rounding to whole figures, un-

Figure 29: Sketch of the rupture in Case 39. At the top the rupture in the SMCL as well as of the DMCL and OMCL. At the bottom only the rupture in the DMCL and OMCL and in the posteromedial capsule. The SMCL is greatly distended and shows a frayed tear, but the continuity is preserved. This is midway between partial and total rupture. This figure is representative also of Case 41.

Case 41:

Marked negative values, in particular for C, viz. anterior displacement, indicate that the injured leg is fixed, while the uninjured leg moves forward. The same applies when calculating rotations. In other words, local anaesthesia was not sufficient to abolish this spasm.

Case 43:

In this case external rotation without traction just exceeded the critical level. The difference was eliminated on traction (Table 6).

Case 45:

In this case $G_n = -3.7$ represents internal rotation on pressure.

Case 49

exhibited marked external rotation of the injured knee, the position of the foot altering from 0° to 15° external rotation, calculated by $H = -4.0$ mm. This was due, almost exclusively, to anterior displacement of the right medial tibial condyle of the injured knee, because of total rupture of the SMCL, DMCL, and OMCL.

Case 50:

Two months previously this patient had sustained a football trauma, consisting in abduction and external rotation of the tibia with flexed knee. He sustained a new, entirely analogous trauma immediately before admission. Operation revealed an older rupture of the SMCL as well as the DMCL and OMCL. All were retracted and rolled-up, club-shaped, and the fragments were displaced far from each other. In other words, there was no healing. Instead, thin, plaque-shaped cicatricial tissue had grown over the injury on the medial aspect of the knee, and this tissue had ruptured at the latter, fresh injury. The patient was classified among the fresh injuries, because the pathology was so clear. At gonylaxometry he had $F_n = -2.5$ mm and $F_{15^o\ ext.} = -2.1$ mm, and on this basis he has previously (6) been designated as positive rotation. However, these values are clearly below the critical level fixed in Addendum I, so that this finding will hereafter be designated negative.

Case 52:

There was abnormal external rotation on rotating the foot 15° outward from the neutral position without applying force: $H_{n15^o} = -3.6$ mm.

When the individual components are considered, the expression $H_{n15^{o}}$ is made up of:

$(k - l)_{inj.}$ = -7.2 mm: marked external rotation,
$(k - l)_{uninj.}$ = -3.6 mm: moderate external rotation.
This rotatory instability was not mentioned in (6).

Case 54:

In this case there was abnormal internal rotation on pressure on the injured knee:

$G_n = ((i - e) - (j - f))_{(inj. - uninj.)} = (-0.2)_{inj.} - (+4.1)_{uninj.} = -4.3$ mm.

Normally the knee rotates outward on pressure and gives a positive value like that found for the uninjured leg. In the injured leg there is a negative value, viz. internal rotation which becomes really marked on the background of the marked external rotation in the uninjured leg. This case was also not recorded in (6).

Injuries to the Lateral Collateral Ligament

Partial injuries to this ligament were found in two cases of fresh joint traumas, Cases 58 and 59. Neither of them exhibited lateral instability. In both cases operation showed rupture in the form of fraying of about one-third of the fibres, with completely preserved continuity of the ligament. In one case the localization was distal, in the other at about the middle. The measurements must be said to be TN, true negatives, also with regard to lateral instability.

Summary of Cases 25 - 59:

The most marked medial instabilities, when not comparing with the uninjured leg as in the standard method, were in Case 38: 20.2 mm and in Case 43: 19.8 mm. In the last six columns of the tables the results are listed as TN, TP, FN, etc. These designations apply also in Cases 58 and 59 who had partial ruptures of the lateral collateral ligament, only to medial instability and the drawer sign.

Seven new, not previously recognized rotatory instabilities were found, Cases 16, 22, 35, 39, 45, 52, and 54, exceeding the new, higher critical levels.

In cases showing partial ruptures at operation - and in cases in which the ligament fibres had ruptured but were situated beneath the intact connective-tissue membrane of the ligament - gonylaxometry often showed inhibition of the a-p mobility of the condyle which carried the injured ligament. This inhibition must be assumed to be reflex, muscular and due to unbroken nerve fibres in the otherwise destroyed tissue - or perhaps in the preserved connective-tissue membrane ensheathing the ligament.

Possibly, further rotatory instabilities would be disclosed if the patients were examined under general anaesthesia, as most of the trauma mechanisms include a rotation component. On the other hand, there would no doubt be a risk of further rupture of partially injured ligaments. In this connection, it should be mentioned that gonylaxometry performed with local anaesthesia, as done in the present series, does not convert a partial rupture into a total one. This is evidenced by the numerous findings of partial ruptures at subsequent operation.

An attempt at <u>analysing the operative findings in relation to the mechanism of the injury</u> shows that in the most common mechanism, viz. abduction-external rotation flexion, there occur total as well as partial ruptures of the SMCL as well as partial or total ruptures of the DMCL and OMCL, and lastly various combinations thereof. This is no doubt due to the numerous possibilities of combination inherent in the named mechanism of injury in the degree of flexion or rotation, or anteroposterior forces, or abduction. Accordingly, there is a possibility of total ruptures of the DMCL or OMCL without rupture of the SMCL and reversely of total ruptures of the SMCL without rupture of the DMCL and OMCL.

<u>Cases 60 - 90:</u>

These cases represent injuries in which operation disclosed involvement of the cruciate ligaments.

Therefore, they have a drawer sign, defined by $\frac{(e-g) + (f-h)}{2} > 7.4$ mm, or the difference (injured - uninjured) > 3.0 mm for the anterior drawer sign and $\frac{(i-e) + (j-f)}{2} > 5.4$ mm or the difference (injured - uninjured) > 3.0 mm for posterior drawer sign.

If, apart from a drawer sign, there is rotation, this is called complex rotation. If the difference between the injured and uninjured joint is used, the above-mentioned expressions have to be fulfilled, and the displacement of one condyle must exceed that of the other one by a given number of mm (still in relation to the uninjured knee). In (6) 2 mm were chosen, as this is equivalent to the inaccuracy of the measurement.

It is possible also to employ the expressions used so far for simple rotation (F, G, and H) and demand that their critical level has been exceeded to talk about rotation in connection with a drawer sign. Then, the critical levels will be 3.0 mm and 3.4 mm in certain cases. They correspond to simple comparison of condylar movements like that done in (6).

Whether the higher critical level used here is to be applied in the evaluation is a matter of estimate, as there is no "normal value" in the proper sense with which to compare (the normal subjects did not have a "drawer sign without abnormal rotation"). However, it must be reasonable to use the same critical level for the terms relating to simple and complex rotatory instability.

Case 60:

This patient was admitted with a fresh haemarthrosis of the knee, and this is why he was assigned to this group. However, he had a history of an untreated posttraumatic haemarthrosis 2 months previously. The operation showed a fresh injury of the MM which had been avulsed from the capsule posteriorly and from the DMCL and OMCL which were totally ruptured. The MM was displaced into the joint chamber anterior to the medial femoral condyle, and it locked the knee. This is the explanation of the absence of a drawer sign. The SMCL and the LCL were exposed, but both proved intact.

Table 8 shows how stress radiography revealed a slight drawer sign when the patient was examined with 15° external rotation of the foot. From Fig. 30 it will be seen how it may be imagined that the medial femoral condyle, and thereby an anterior drawer sign, is blocked in the neutral position, while external rotation of the foot and knee can partially loosen this locking mechanism.

The antero-medial two-thirds to three-quarters of the ACL proved to be ruptured, and were lying, already atrophic, at the bottom of the joint - indicating that the cruciate ligament injury must have occurred at the former trauma two months previously.

The clinician found at admission positive medial instability and a positive anterior drawer sign, listed in the respective columns of Table 9 as TP. In an examination under general anaesthesia both had been found to be negative, and in the calculation of the PV_{pos} and PV_{neg} they were listed as FN, as the assessment has to be strict and because they are in contrast to the clinician's positive findings. The same applies to the stress radiographic evaluations. The asterisk at the TN in the last column, however, indicates that in analysing the PV_{pos} and PV_{neg} in the total material, as already stated in (5), a negative drawer sign at gonylaxometry in the neutral position is classified as TN, as it had been demonstrated that in general partial ruptures of the cruciate ligaments gave negative results in anteroposterior measurements. The positive finding of an anterior drawer sign in the externally rotated position did not alter this classification which is strictly reserved for measurements with the foot in a neutral position.

Suffice it here to establish that the measurement became positive in external rotation of the foot, presumably indicating anterior instability after partial abolition of the meniscal blocking.

Case 61:

Gonylaxometry revealed a slightly abnormal external rotation on pressure with the foot in a neutral position ($G_n = 4.8$). This has not been demonstrated previously. Operation disclosed total or practically total, rupture of the ACL with a taut, intact synovial fold posteriorly, possibly containing ligament fibres. The "negative anterior drawer sign" (C_n) was presumably due to nerve fibres in this synovial fold. Moreover, the operation showed rupture of the DMCL and OMCL which had also not been demonstrated by the stress radiography or by the other examinations done.

Case 64:

The critical level for anterior drawer sign (3.0 mm) was only just exceeded ($C_n = 3.2$ mm). On the other hand, the critical level or total anteroposterior displacement in the neutral position (3.0 mm) was clearly exceeded: $E_n = 5.1$ mm. This means a positive anterior drawer sign. $G_n = -4.1$ signifies internal rotation on pressure. In fact, this is relative, as external rotation occurs, but less than in the uninjured knee, presumably because of inhibitory impulses from the partial injury to the iliotibial tract (avulsed with a small chip of bone from Gerdy's tubercle).

Case 65:

This patient exhibited, in the same way, reduced external rotation in the injured knee on pressure, and thus a relative internal rotation ($G_n = -5.1$ mm). The asterisk in the last column of Table 9 signifies the same as in the previous cases (TN drawer in partial rupture). Operation revealed partial ACL rupture.

Case 66:

As in Case 60, it was not possible to demonstrate a drawer sign in the neutral position from which the PV_{pos} and PV_{neg} were calculated. The asterisk at TN, at the bottom of the last column, indicates, as in Case 60, that the case was later considered TN, because normally it is not possible to demonstrate a drawer sign in the neutral position in cases with partial rupture of the ACL. Again in analogy with Case 60, the sign was demonstrated on measurement with the foot in 15° external rotation. There was no injury to the meniscus.

Case 68:

exhibited a fresh injury in the right knee (the injury with which we are now dealing) and a four-year-old injury to the left knee with persistent instability medially as well as anteroposteriorly, the latter marked. This rendered it difficult to perform the examinations, both the clinical, the one under anaesthesia, and the gonylaxometry, as a comparison of the two knees was inapplicable. Instead, each knee had to be assessed separately, and the findings were then compared with the normal range stated in Addendum I.

The stress radiographic measurements are as follows:

Anterior instability, calculated as the mean of the displacements of the medial and lateral condyle:

right knee (fresh injury):		8.6 mm > 7.4 mm	
left knee (old injury)		15.7 mm > 7.4 mm.	
Posterior displacement, right knee:		4.5 mm < 5.4 mm	
left knee:		9.5 mm > 5.4 mm.	
Total anteroposterior displacement:	right	13.1 mm > 11.7 mm	
	left:	25.2 mm > 11.7 mm	
Rotation on traction ((e-g) - (f-h)),	right:	4.2 mm < 5.9 mm	
	left:	4.2 mm < 5.9 mm	
Rotation on pressure ((i-e) - (j-f)),	right:	-1.4 mm	within critical limits: -1.9 - 6.7.
	left:	2.4 mm	

The column of figures on the right constitutes the 97½% confidence limits, as stated in Addendum I, Tables 19, 29, and 30. A comparison shows that the right knee exceeds the limits in measurement of the anterior and total displacement. In other words, an anterior drawer sign has been demonstrated in the right knee.

As regards the left knee, both an anterior and a posterior drawer sign have been demonstrated. Rotatory instability was not demonstrable on either side.

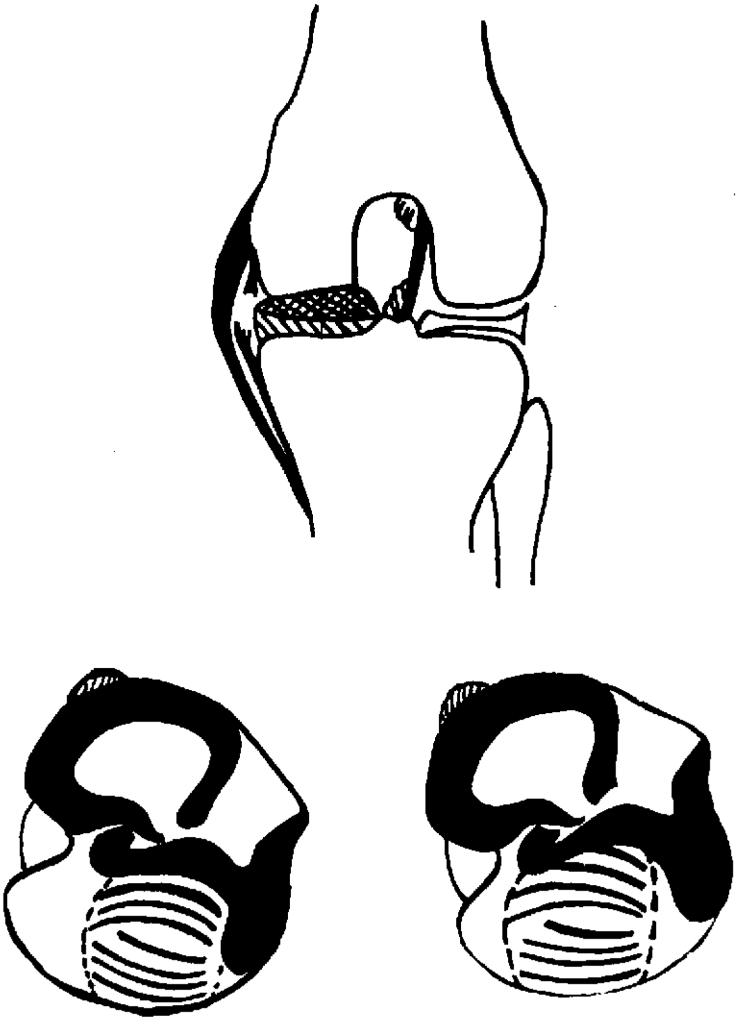

Figure 30: Case 60: Injury to the left knee. At the top the knee is shown from the anterior aspect. There is total rupture of the DMCL and OMCL, but no injury to the SMCL. The anteromedial fibres of the ACL are ruptured in about two-thirds of its width, and the fragments are atrophic.

Legend to Fig. 30 contd.

The MM has curled up in front of the medial femoral condyle (hatched and cross-hatched, the latter indicating the curled-up posterior part). The bottom part of the drawing illustrates this on the left tibia viewed from above. The LM is in situ. The MM is curled-up in front of the contact area between the medial tibial condyle and the medial femoral condyle with the knee in 90° flexion. The contact area is framed by broken lines and indicated by curved hatching. Most posteriorly the neutral position (foot straight forward), anteriorly (to the right on the paper) the foot, and tibia, in external rotation.

That this position of the meniscus should prevent anterior displacement of the tibia in the neutral position on traction is not directly evident, as blocking of the medial condylar movement sets in when an attempt is made to press the condyle backward against the femoral condyle. This is clearly shown by the figures from the stress radiography: pressure 30 kp:
posterior instability for the left (injured) knee:
medial condyle (j - f): 1.1 mm
for the right medial condyle (j - f): 3.4 mm.
The right and left lateral tibial condyles move equally on pressure, viz. 4.6 and 4.7 mm.

The explanation of the blocking on traction lies in rotatory movements and is given below:
On traction 30 kp:
the medial condyle moves more on the injured side (7.1 against 4.1 mm), and so does the lateral tibial condyle (7.7 against 5.8 mm).
However, this is not sufficient for the difference between the mean values to exceed the critical level of a positive drawer sign. Under normal conditions the lateral tibial condyle moves more than the medial one. In other words, an internal rotation normally occurs. Such a rotation was inhibited by the curled-up meniscus in front of the medial femoral condyle. From the bottom drawing on the right, where external rotation has been performed and traction can be applied, it will be seen that now the blocking has been unlocked, and on traction an internal rotation ought to occur: the lateral tibial condyle ought to be able to move particularly far. And indeed it does in this case:
Anterior displacement:
in injured knee: L. lateral condyle: 11.1 mm
L. medial condyle: 7.0 mm
(mean 9.1 mm)
in uninjured knee: R. lateral condyle: 6.2 mm
R. medial condyle: 3.7 mm

It will be seen that if comparison between the patient's two knees had been made, the right-sided, fresh anterior drawer sign would have been completely "drowned" in the very marked, old left-sided drawer sign. Thus, the drawer sign was estimated as negative at the clinical examination.

For the medial and lateral instability the differences between the right and left knee are stated (Table 8), but they do not exceed any critical level for medial or lateral instability. Neither do the right or left medial and lateral instability measurements when each is compared with normal values. Thus, the negative finding is a bit uncertain, as always when using such wide normal ranges.

It turned out that the stress radiographic analysis for drawer sign on the freshly injured right side was correct, the operation showing total rupture of the ACL superiorly in the fibrous substance. On the other hand, a total rupture of the DMCL and OMCL, extending posteriorly into the posteromedial capsule, was not, as already stated, disclosed by the stress radiography. The result is therefore listed as FN in the last but one column of Table 9.

The findings relating to the old injury in the left knee were confirmed by records borrowed from another hospital, but they are not included in the present analysis.

Case 70:

In the course of a football match this patient was hit by a direct trauma (kick) on the medial aspect of the knee, while the knee was lifted high from the ground and 90° flexed. At admission the patient had a total peroneal paralysis, but with neuropraxia, as operation did not show interruption of continuity in the nerve. There was total rupture of the ACL and PCL, the LCL, the popliteal tendon, the biceps femoris tendon, the posterior and lateral capsule, plus partial rupture of the iliotibial tract and of the DMCL as well as the SMCL (of minor extent).

This patient was reported in (6) as a case of combined anterolateral complex rotation and posterolateral complex rotation. Anterior and posterior drawer signs were present (Table 8, C, D, E). The component of internal rotation on traction, anterolateral instability, is 2.8 mm (F_n), well above the critical level of 2.0 mm from (6) and a bit below the level of 3.0 mm used in the present Addendum. On the other hand, the value for external rotation on pressure (here posterolateral instability) is 1.6 mm, and this is far below both levels. Thus, the case can be accepted as anterolateral complex rotation, while there is only a hint of a posterolateral rotation - but it is obvious that the severity of the injury justifies its presence (Fig. 16).

Case 71

represents the prototype of an injury which causes complex anteromedial rotatory instability: Total rupture of the ACL, DMCL, OMCL as well as SMCL.

Case 72:

A violent trauma with a complicated mechanism. In jumping up while playing volley ball, the patient sustained dislocation of the right patella, so that the leg became fixed in an acute-angled flexion. In this position she fell, hitting the floor with this leg. This increased the abduction, and external rotation of the tibia resulted. Operation revealed total rupture of the ACL, partial rupture of the PCL, total rupture of the SMCL, DMCL, and OMCL, continuing in a tear of the posterior capsule. Throughout the length of the medial patellar aspect there was a large capsular tear caused by the patellar dislocation. Furthermore, there was total avulsion of the posterior horn and the entire medial attachment of the MM. The latter, moreover, showed a large bucket-handle injury enveloping the medial femoral condyle. The last-mentioned injury is held responsible for the inability to demonstrate a drawer sign or rotatory instability by clinical examination, examination under general anaesthesia, or gonylaxometry.

Case 75:

Mild external rotatory instability of the injured leg was demonstrated (F_n = 4.2 mm). There was also an increased total anteroposterior mobility, interpreted preoperatively as an anterior drawer sign, as its major part was anterior displacement. Operation disclosed total rupture of the ACL and a very slight, partial rupture of the SMCL on a level with the articular line.

Case 76

exhibited the marked medial instability which is seen only in the presence of rupture of the medial structures, both cruciate ligaments, and the posterior capsule (Fig. 14). Indeed, these injuries were found at operation, and so was a tear of Robert's ligament which attaches the posterior horn of the LM to the medial femoral condyle. The SMCL as well as the DMCL and OMCL were totally ruptured, and this rupture continued in a capsular tear behind the medial femoral condyle. There were sequelae of a simultaneous (presumably initial) patellar dislocation, viz. a small osteochondral fracture on the medial edge of the patella and an osteochondral fracture on the lateral femoral condyle as well as total rupture of the medial capsule of the knee joint along the medial edge of the patella. The injury had occurred during water-skiing in an abrupt turn at high speed, in abduction, external rotation, and flexion. At gonylaxometry there occurred no rotation during traction straight forward, and at pressure there was but a hint of internal rotation, -2.1 mm, posteromedial instability, practically all structures giving way, and pronounced drawer signs appearing.

Case 78:

There was an increased anterior drawer sign at 15° external rotation of the foot, of an extent that can be seen only in the presence of a severe injury to the medial collateral ligaments. According to Slocum and Larson (1968) and (6), this may be taken to indicate anteromedial instability. This was confirmed by the operative findings: total rupture of the SMCL, DMCL, as well as the OMCL, with a posterior capsular rupture and total rupture of the ACL. The LM had been torn off the anterior horn and along the greater part of its circumference (abduction, external rotation, flexion injury in the down-jump from a smash in badminton).

Case 80:

Unchanged from Table 2 in (6) in which the external rotation was found ($F_{15ext.}$ = -3.5) and the sign merely indicates the direction of rotation. H_{n15} = 5.7 signifies internal rotation, the injured medial compartment accompanying the movement of external rotation (foot 15° externally rotated) until stress was applied.

Case 82:

Knee injury in a fall while skiing at high speed on a steep hill. Operation disclosed subsynovial (intrasynovial), partial rupture of the ACL (its posterolateral fibres). Total rupture of the SMCL as well as the DMCL and OMCL, and capsular tear continuing posteriorly. The MM had become detached throughout its circumference and had become dislocated into the joint (it was removed). In the neutral position it was not possible to demonstrate a drawer sign. It is not known whether the marked drawer sign demonstrated with the foot in 15° external rotation is to be taken as a sign of external rotatory instability due to the large medial rupture or of a locking mechanism (due to the injured meniscus) being unlocked in external rotation - cf. Case 60 (Fig. 30).

Case 83:

A pronounced anterior drawer sign on traction with the foot in 15° external rotation ($C_{15\ \text{ext.}}$ = 13.4 mm) was accompanied by a slight internal rotation ($F_{15\ \text{ext.}}$ = 4.1 mm).

The totally ruptured medial collateral structures would be expected to permit external rotation. In the presence of the marked anterior displacement of both condyles in the injured leg, apparent from the calculations below, it is not possible to explain exactly why the medial condyle was arrested in its anterior displacement before the lateral one, but the movement is dependent upon the total remaining capsular and ligamentous apparatus.

$$F_{15^\circ\ \text{ext.}} = ((e-g) - (f-h))_{(\text{inj.} - \text{uninj.})} = (18.9 - 15.4)_L - (3.6 - 4.2)_R = 4.1.$$

This sign of rotation diminishes if the calculation is based upon the values for e and f in the "neutral position 90°" and the total condylar movement is calculated on that basis:

$$F_{n15^\circ\ \text{ext.}} = ((e_n - g_{15}) - (f_n - h_{15}))_{(\text{in.} - \text{uninj.})} = 3.3\ \text{mm},$$

whereby the critical level is just touched (Addendum I, Table 31).

Cases 86 - 90 incl.

and the above-mentioned Cases 70 and 76 exhibited ruptures of the PCL. In yet another case of rupture of the ACL and PCL the measurement of anteroposterior displacement was given up because of pain, whereas the medial and lateral stability could be measured (Case 74).

Case 86:

In this case a posterior drawer sign and external rotatory instability were demonstrated on pressure, viz. posterolateral rotatory instability and lateral instability, in conformity with the findings at operation.

Case 87

exhibited only medial instability and posterior drawer sign in the neutral position. In this position no critical levels of rotatory instability were exceeded. But with the feet 15° externally rotated there was a mean anterior displacement of the tibial condyles in the injured knee exceeding that in the uninjured knee by 4.2 mm on traction, the medial one 2.2 mm more than the lateral. This must be interpreted as external rotation due to instability of the medial structures (cf. Slocum and Larson's test). In particular, it is worth noting the absence of an anterior drawer sign in the neutral position. Operation revealed total rupture of the SMCL, DMCL, and the PCL.

Case 88:

In this case gonylaxometry revealed a pronounced total anteroposterior displacement. As the calculation of anterior displacement as well as of posterior displacement by far exceeded the critical levels, the case was interpreted preoperatively as representing both anterior and posterior drawer sign.

However, operation showed only rupture of the PCL and of the DMCL and OMCL as well as of the fibrous capsule posteriorly. The SMCL and the ACL were intact.

On the X-rays it is possible to observe the position of the proximal end of the tibia on the injured knee as compared with the uninjured one. This shows that on the injured leg the tibia had become displaced 2.3 mm posteriorly already in the unstressed, neutral position. However, this cannot quite place the anterior drawer sign below the critical level.

At clinical examination and at examination under general anaesthesia too there was doubt about the direction or directions of the drawer sign, but all examinations definitely indicated operation.

The pressure procedure resulted in external rotation of the injured knee G_n = 5.9 mm. The explanation may be: Since the SMCL as well as the LCL were intact, it had to be the, also intact, ACL which determined the direction of rotation.

This ligament slackens when the tibia is posterolaterally pressed, but tightens when the tibia is posteromedially pressed in relation to the femoral condyles. This must favour a posterior movement of the lateral tibial condyle and thus an external rotation (Fig. 31). It must be borne in mind, however, that this rotation is determined by a complicated interaction of intact and injured structures. For instance, the intact SMCL contributed to preventing the internal rotation shown in an extreme example in the middle situation in Fig. 31.

Case 89

is illustrated in Fig. 5 in (6) as a representative of posteromedial complex rotatory instability. This can be confirmed by calculation using the formulae set up here: G_n = -4.6 mm, signifying internal rotation on pressure. At the same time, there is a posterior drawer sign of 6.2 mm. This is fully compatible with the injury, cf. Table 9.

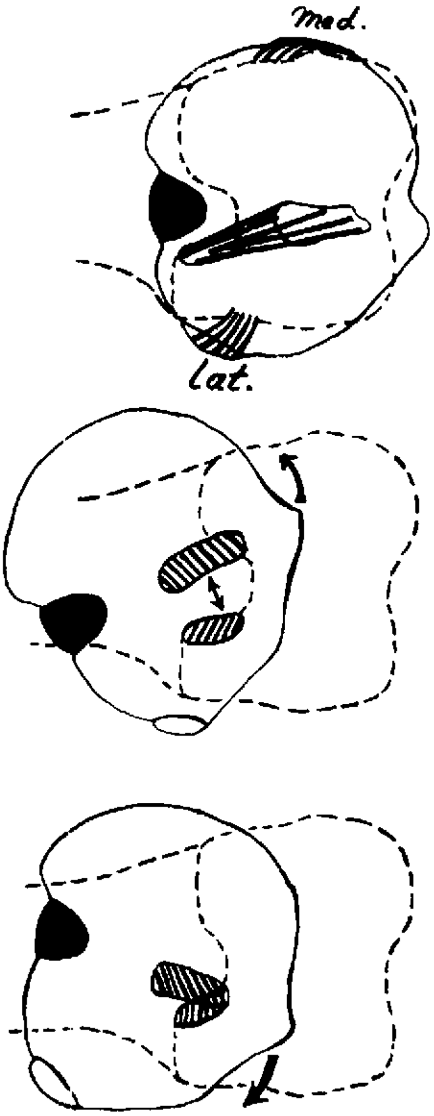

Figure 31: Diagram of the right knee viewed from above. The tibial plateau is indicated by a solid line, the femur by broken lines. At the top the knee joint in its normal position. The medial collateral ligament (med.) is shaded, and so is the lateral collateral ligament (lat.). The origin and insertion of the ACL are indicated on all three drawings, shaded on the two at the bottom, connected with the ligament fibres on that at the top. The insertion of the PCL on the posterior intercondylar area on the tibia is black. The latter ligament is ruptured in this case (Case 88), so that no further regard is paid to it. It may be seen how the distance between the origin of the ACL on the lateral femoral condyle and the insertion on the anterior intercondylar area on the tibia lengthens on attempts at internal rotation (middle) and shortens on external rotation, both in connection with a posterior drawer sign, permitted by the ruptured PCL. Thus, both the SMCL and the ACL prevent internal rotation and permit a complex external rotation on pressure.

Case 90

showed on gonylaxometry only a posterior drawer sign, and operation disclosed total rupture of the PCL and the posterior joint capsule.

On the X-ray films there is a small bone chip anteriorly, medially on the tibia at the site of the digital impression of the area intercondylaris anterior where the anterior horn of the MM is attached. The bone chip is evidently a shearing fracture, there being correspondingly, far anteriorly on the medial femoral condyle, an impression fracture. All the findings suggest a hyperextension trauma, cf. Fig. 15 which also shows the posterior drawer sign.

Summary: Cases 60 - 90, and Addition

In general, an anterior drawer sign in the neutral position is not demonstrabl in partial rupture of the ACL (Cases 62, 65, 66, 79, and 81) or in intrasynovial rupture (Cases 61 and 84). Radiological demonstration of these types of ruptures can hardly be expected either, and this is indicated in the colum concerned by TN^+ below the FN used for calculating the predictive values among the fresh ruptures. TN^+ is used in the subsequent total calculation in (5). In one instance, Case 88, it was difficult to interpret the direction of an otherwise striking drawer sign, since injury to the PCL evidently displaces the tibia backwards, also in the "neutral resting position". This gave rise to a false anterior drawer sign on traction.

Posterior drawer signs were found in 7 cases: Nos. 70, 76, 86, 87, 88, 89, and 90. In an additional case with total rupture of the ACL as well as PCL the measurements were given up because of pain (Case 74). In Case 72, who had partial rupture of the PCL and total rupture of the ACL, the anteroposterior displacement was blocked by a bucket-handle injury of the medial meniscus.

In the present study, the difference between the injured and uninjured knee was always used. Concerning a comparison with other materials, however, it must be mentioned that the highest value for anterior drawer sign in the neutral position measured in the present material, without deduction of the value for the uninjured knee, was 17.2 mm and for the medial condyle 18.2 mm (Case 71). Expressed in the same way, the greatest posterior drawer sign measured was 21.3 mm, in Case 76 who also exhibited a total anteroposterior mobility of 36.6 mm, having simultaneously an anterior drawer sign of 15.3 mm. He also exhibited the maximum medial instability of the whole group, viz. 29.9 mm. Case 70 had the greatest unilaterally measured lateral instability, 27.8 mm.

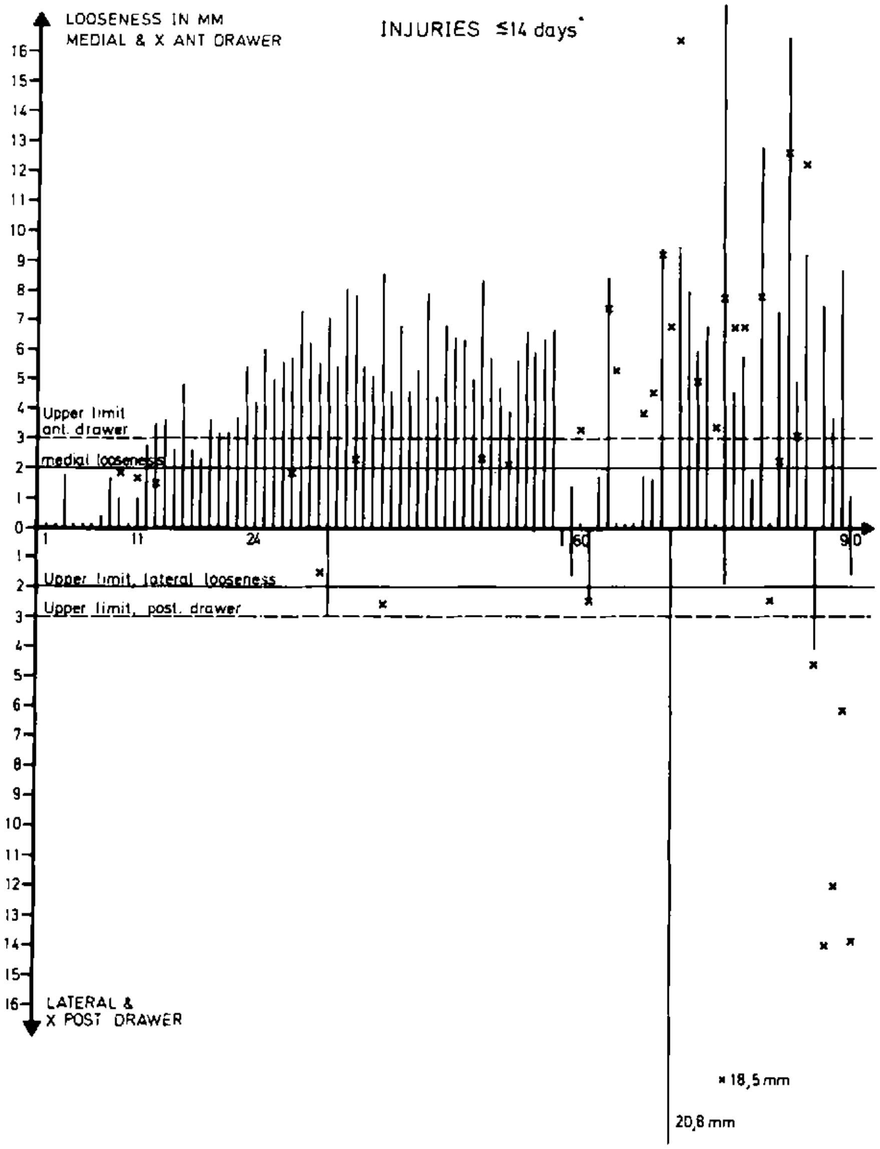

Figure 32: Diagram showing stress radiographically measured instabilities in group 1. Differences between injured and uninjured knee. Medial collateral instability: Columns above the axis of the abscissa, lateral instability: columns below the axis, anterior displacement or drawer sign as an x above the axis, and posterior drawer sign as an x below the axis (values below the axis are thus also positive). Every column and cross show measurements on one patient, the patient number being shown on the abscissa. The relationship between marked medial/lateral instabilities and drawer signs in this group is evident. (From Acta orthop. Scand. 48, 301-310, 1977).

Anteromedial complex rotatory instability was demonstrated in eight cases (Cases 71, 75, 78, 80, 82, 83, 84, 85), posteromedial complex rotatory instability unmistakably in only one patient (Case 89) (and with less strict demands in Cases 76 and 87), posterolateral complex rotatory instability in Case 86, and anterolateral complex rotatory instability in Case 70.

In two patients, Cases 61 and 88, pressure caused an external rotation which could only be classified with some uncertainty. As also shown on Fig. 31, the question of rotation is a more complicated one, as the movements of the joint on traction and pressure are guided by a great number of components, some of which are injured.

Possibly, the approach would be simplified, also in the case of complex rotations, if the examination were carried out under general anaesthesia, as in that event any active or reflex muscular guidance would be completely eliminated. But even though all the present clinical cases do not appear to be explicable with equal ease, it must primarily be established that it proved possible to demonstrate these rotations objectively and measurably and to give a satisfactory explanation of the majority.

Patient Group 2. Injuries Sustained 15 Days to 3 Months Previously

These patients made up the smallest group (26 knee joints) and also the least valuable one, portly because it is too small for a separate statistical analysis and partly because a comparison of the results of the measurements with the injuries blurred by scar tissue can only be accepted with reserve. Moreover, some patients had a history of even older knee injuries.

During this phase the patients still had pain and tenderness at the site of the injured tissue, so that local anaesthesia had to be applied in the stress radiographic examination. Nevertheless there occurred, as in group 1, muscular defence reaction during examination for anteroposterior displacement (Cases 96, 98, 114).

The first seven cases of group 2, Cases 91 - 97, had no measurable medial/lateral instability or drawer sign on gonylaxometry, in accordance with the findings under general anaesthesia. The operative findings were, as shown in Table 11, in one case a loose body in the knee, in three meniscal injuries, and in two cases scanty cicatricial tissue left by small ruptures of the collateral ligaments. The findings at clinical examination in these cases differed a great deal from those of the other two diagnostic procedures - and from the operative findings as well. This was characteristic of group 2 as a whole. The clinical examiner had difficulty in decid-

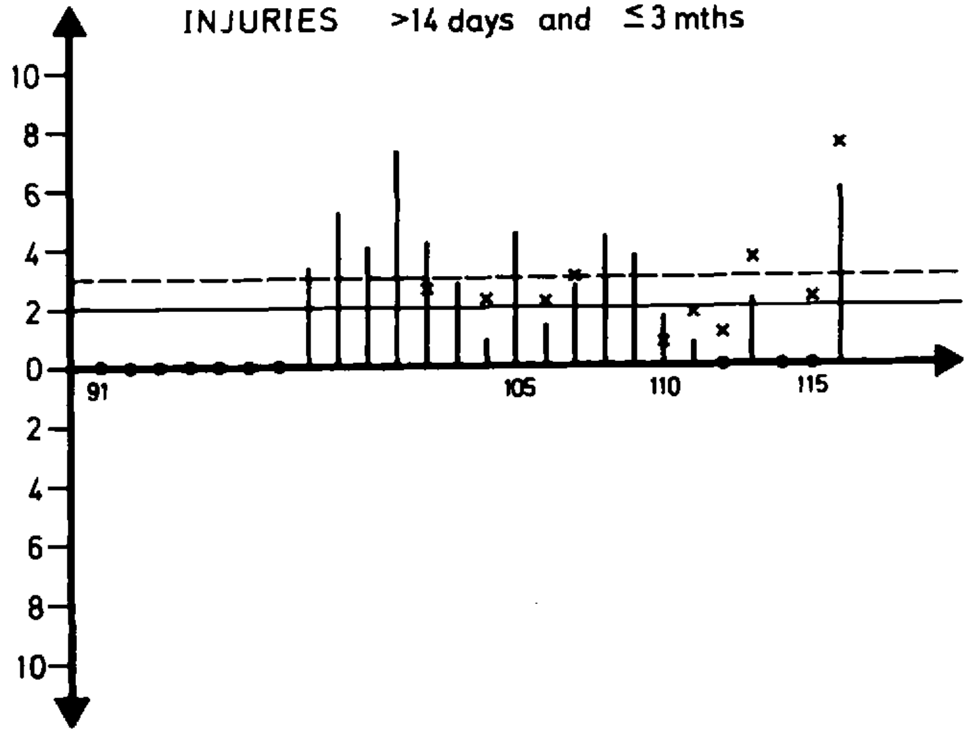

Figure 33: Stress radiographically measured instabilities in group 2.
No lateral or posterior instabilities in this group.
(From Acta orthop. Scand. 48, 301-310, 1977).

ing whether a rotation factor was involved, both when examining for the drawer sign and for medial/lateral instability.

In cases with fairly old and old injuries it is difficult to distinguish at operation the structures which have been injured, and especially to what degree. Therefore, it is difficult also to use the operative findings as a basis for assessment concerning the various forms of instability. In columns 6, 7, 8, and 9 in Tables 11 and 13, therefore, it is stated from Case 105 and onwards only that the finding was positive, P, or negative, N. Evaluation of the PV_{pos} and PV_{neg} for the total material of patients was performed only for the gonylaxometric findings of medial/lateral instability and anteroposterior instability. In groups 2 and 3, unlike group 1, no comparison was made with the manual, clinical assessment, or the assessment under general anaesthesia.

In the following 19 cases different degrees of medial instability were found at stress radiographic measurement, but at most $A = c_{inj.} - c_{uninj.} =$ 7.3 mm or $c_{inj.}$ 17.2 mm. Accordingly, there was at operation cicatricial tissue, of fairly loose or firmer consistency, in the collateral ligaments.

There were no cases of injuries to the LCL or to the PCL. Also no cases of false positive or false negative measurements of medial instability.

Four cases with operatively confirmed partial ruptures of the ACL (Cases 110, 111, 112, 114) had no measurable drawer signs. This accords with the examination under general anaesthesia, while a clinical examiner (not the author) could easily find a positive drawer sign in one of these cases (Case 110, Table 11). All proved to have rupture of the posterolateral fibres of the ligament, so that a demonstration of drawer sign at gonylaxometry could not even be expected - cf. (5) "Discussion" (pp. 308 - 309).

Case 105:

Subsynovially in the ACL there was an area with firm scar tissue, but no visible elongation or thinning of the ligament. Stress radiography did not show a drawer sign, the difference from the uninjured knee being 0.9 mm. At increasing external rotation of the foot, however, there was a continuously increasing anterior displacement: $C_{15^\circ \text{ ext.}} = 3.7$ mm and $C_{30^\circ \text{ ext.}} = 6.6$ mm.

This may signify a drawer sign, but sooner the form of external rotation described by Slocum and Larson (1968) and demonstrated in the position of the foot described by them as a sign of medial collateral ligament instability. And indeed, it was found to be so (A = 4.5 mm). Operation showed, apart from the above-mentioned special injury to the ACL, scar tissue in the DMCL as well as SMCL.

Only 3 cases exhibited total rupture of the cruciate ligaments (Cases 113, 115, 116). At stress radiography a positive drawer sign was found in the neutral position in Cases 113 and 116 and not until in 15^o external rotation of the foot in Case 115. Therefore, the latter case was classified as FN in analysing the predictive value. However, it may represent anterior drawer sign. It may also represent external rotatoryinstability (Slocum and Larson type) - which was indeed demonstrated also by the formula: $F_{15^o \text{ ext.}}$ = 3.1 mm. The most pronounced anterior drawer sign, in Case 116, amounted to 11.8 mm in the neutral position, without subtraction of the measuring result for the contralateral knee.

Rotatory Instability in Group 2:

Simple rotatory instability was found in seven cases. In four of them simple external rotatory instability could be demonstrated by the method of Slocum and Larson. As stated in (6), this finding is a sign of insufficiency of the medial collateral ligaments. When the patient is examined with 90^o flexed knee the injured knee must not be forward displaced on traction when the foot is in the neutral position, but must be forward displaced when the foot is in 15^o external rotation (or more) and maintained in that position. This was found in Cases 101, 105, 106, 107.

Simple rotatory instability was demonstrated in the neutral position in three cases, Nos. 95, 108, and 114:

Case 95:

G_n = -4.5 mm, which means internal rotation on pressure, and $H_{n15^o \text{ ext.}}$ = -7.3 mm, meaning pronounced external rotation with rotated foot. Both findings consistently indicate injury to the medial collateral ligaments. Operation showed no injury to the cruciate ligaments, but also no fresh injury to the medial ligaments. The instability must be derived from an injury to the last-mentioned ligaments in a trauma sustained one year previously.

Case 108

exhibited internal rotation, F_n = 3.9 mm. The rotation was a true one, the injured knee having the value 4.9 mm for rotation on traction and the uninjured knee 1.0 mm. The operation showed scar tissue of relatively soft consistency on a level with the articular line, in the DMCL as well as SMCL.

Case 114

showed on pressure internal rotation, G_n = -4.6 mm.

Two cases of complex anteromedial instability were discovered, Cases 155 and 116. They have been described previously in (6). However, Case 116 only just touches the critical level for F_{15^o} ext.

Group 3: Patients with Injuries Older Than 3 Months

In these patients there is no pain reaction during the measurements which thus can be performed, without using local anaesthetics, on completely relaxed knees. Therefore, entirely correct instability measurements may be expected. One meniscal locking was observed in this group.

The most remarkable finding is that in such old injuries the medial/lateral instability is quite modest. In 23 out of 37 cases (62%) the medial instability was below the critical upper limit of 2 mm. On the other hand, rotatory instability of some form or other was found in 11 of these 23 cases: 121, 124, 127, 129, 130, 133, 137, 139, 140, 141, 151 (vide infra). In 22 of these 23 cases subsequent operation showed no sequelae at all of rupture of the medial collateral ligamentous apparatus. All the others, with medial instabilities between 2.1 and 4.6 mm (before subtraction of the value for the uninjured knee: 13.6 mm in Case 125, 14.9 mm in Case 123), showed changes in the form of firm or somewhat looser scar tissue.

Three patients of this group had been admitted for instability in the lateral part of the joint. In Case 121 the value for lateral instability was B = 1.9 mm, i.e. not exceeding the critical level. On the other hand, the F_n value was 3.1 mm, viz. positive, meaning internal rotation on traction. The pronounced forward movement of the lateral condyle in the injured knee on traction (4.6 mm as compared with 1.5 mm of the medial condyle) was the reason why the critical level for total anteroposterior displacement was exceeded. Even before the operation, this was realized, and the result had been interpreted as a purely rotatory movement indicating a lateral injury. Operation revealed normal cruciate ligaments, absence of the LM, and loose scar tissue at the insertion of the LCL on the lateral femoral epicondyle. The original injury 4 years previously had been treated immediately by lateral meniscectomy elsewhere. In other words, an example of simple lateral rotatory instability.

Case 124:

Special views of the right knee joint showed an old depression fracture of the right lateral tibial condyle. In stress radiography it caused very marked lateral instability, B = 6.0 mm, but after correcting for the fracture there

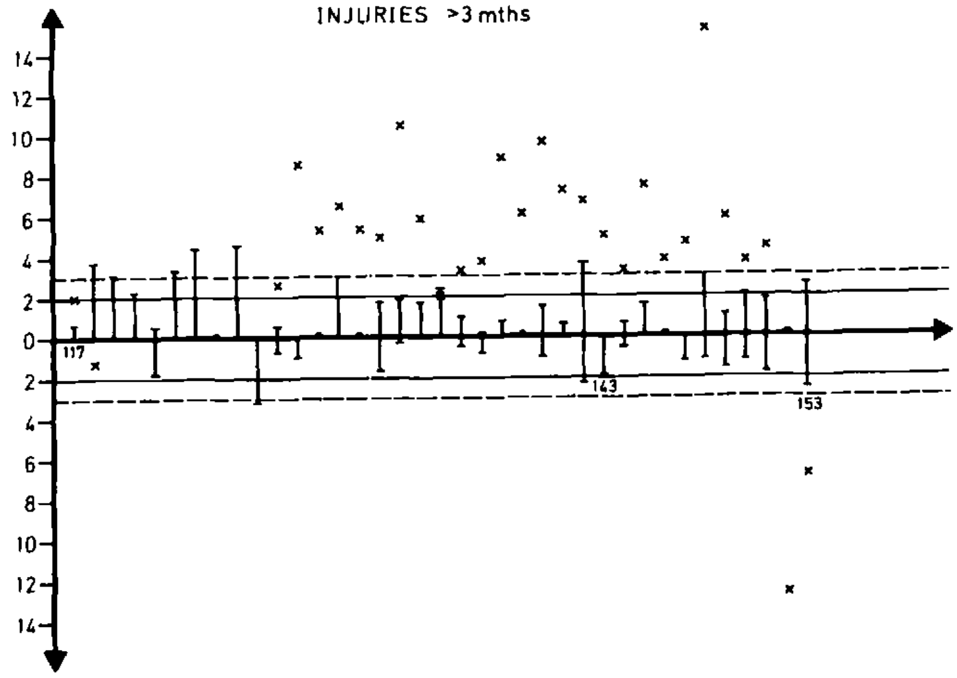

Figure 34: Stress radiographically measured instabilities in group 3. Note: In these old injuries the medial/lateral instability is rather slight, even in the presence of major drawer signs. (From Acta orthop. Scand. 48, 301 - 310, 1977).

was no difference between the sides on a-p views in adduction, B = 0.1 mm. The values for anteroposterior instability, C_n and $C_{15^\circ \text{ ext.}}$ (Table 12) showed a drawer sign. However, this was due primarily to a very marked anterior displacement of the lateral tibial condyle on traction in the neutral position: anterior displacement (injured - uninjured) of the lateral tibial condyle: 8.6 mm, of the medial condyle: 2.6 mm.

The terms F_n and $F_{n15^\circ \text{ ext.}}$ show marked internal rotation on traction, while G_n signifies internal rotation on pressure. Operation revealed the named depression fracture of the lateral tibial condyle of wide extent, but no injuries to ligaments or menisci. Preoperatively too, the measurement had been interpreted as rotatory instability. This case is interesting in elucidating how loss of substance in the condyles may give rise to pronounced instability in several planes.

Case 125:

Table 12, listing the results of the measurements, shows only medial instability and a total anteroposterior displacement on traction and pressure in the neutral position exceeding the normal critical level. This case is best elucidated when regarding the displacements separately (injured - uninjured):

Ant. displ. lat. condyle: 1.9 mm
Ant. displ. med. condyle: 3.0 mm
Post. displ. lat. condyle: 0.5 mm
Post. displ. med. condyle: 3.0 mm
Ant. drawer: (2.5 = neg.)
Post. drawer: (1.8 = neg.)
Total ant.post. displ. lat. condyle 2.4 mm
Total ant.post. displ. med. condyle: 6.0 mm

In other words, it is the displacement of the medial condyle which predominates and at the same time causes the high E_n value. This case was depicted as Fig. 4 in (6). Considering the high critical levels fixed for rotation in Addenda I and II, the critical levels have not been exceeded in this case.

Case 126

is the only one of group 3 which exhibited any significant lateral instability (using the rounded-off critical levels defined in the thesis). At operation the LCL was found to be lax, but intact, and it was not possible to locate the site of the previous rupture. Both cruciate ligaments were intact. No rotatory instability was demonstrated.

Case 127,

in which rotatory instability had not been recognized previously, exhibited with the new methods of calculation a marked external rotatory instability on traction in the neutral position: $F_n = -4.8$ mm. Operation disclosed that the MM had been torn in its entire circumference, being attached only at the anterior and posterior horns. The entire meniscus was 180° turned and dislocated into the intercondylar fossa, curled up. Evidently, it had been lying like that for a long time, as it preserved its curled-up shape after removal. The ACL appeared somewhat thinner than normal, but otherwise there were no ligament abnormalities. In this case, then, the method demonstrated simple external rotatory instability due to the meniscus being torn from its anchoring and adjacent medial structures (the DMCL, the OMCL, and the posteromedial capsule). Owing to the long interval from the trauma, however, it is not possible to tell whether some of these structures have been ruptured and have healed with elongation, but lateral/medial instability was not demonstrated.

Anterior instability was demonstrated in 22 of 23 cases in the form of TP anterior drawer signs from Cases 128 - 151. In one FN case, No. 135, anterior displacement during traction was prevented by locking of the lateral condyles in the injured knee caused by an injury to the LM. The meniscus had been torn loose at the posterior horn and had curled in anterior to the femoral condyle. A drawer sign could also not be demonstrated on examination under general anaesthesia. The MM and PCL were normal, but the ACL was absent. There was a small, fresh tear in the SMCL.

Furthermore, gonylaxometry showed one FP drawer sign within this group, viz.:

Case 143:

This patient exhibited an anterior drawer sign of 5.0 mm, measured as the difference from the uninjured knee. However, when measured in relation to the upper critical level, defined as the 97½% upper confidence limit for normal knees separately, the excess is only 0.2 mm. Using this, less accurate critical level, and measuring in whole mm, would not have assigned this case to an abnormal group. However, it had a clinically definite anterior drawer sign, determined by two different examiners, and this sign also proved positive at examination under general anaesthesia. It is beyond doubt, therefore, that the measurement, and the findings of the other examination, must be considered FP, as operation did not show injury to either cruciate ligament.

History: Two years previously, the patient had sustained an abduction trauma. While he was digging a ditch his leg got squeezed by the fore part of a tractor. The present author did an operation upon the patient at that time, suturing the medial collateral ligament. There were no injuries to the cruciate ligaments or menisci. There exists a thorough record, of the same type as in the present examination, but the first operation is not included in the present analysis, as the stress radiological measurements had not been started then. In other words, this patient is not represented as a "duplicate case". He was re-admitted 2 years later for evaluation, since after transient improvement and short-lasting resumption of work he had developed increasing pain in the knee, felt it was unstable, and was unable to work. There had been no intermediate trauma. At re-admission there was no medial or lateral instability, but a difference in quadriceps circumference between the injured and uninjured leg of 2 cm and a 3 cm atrophy of the injured leg (and 1 cm on the uninjured leg) as compared with the measurement at the former admission to hospital. On the injured limb there was also oedema of the lower leg, and radiologically visible, marked decalcification of the bones as compared with the contralateral leg - as seen in reflex dystrophy in the upper limbs. In spite of this appearance, we did not rest content with this diagnosis and performed an exploratory arthrotomy which showed completely normal-looking, thick, strong cruciate ligaments which, however, appeared to be too lax, and so did the joint capsule appear to be (had been distended by repeated episodes of hydrarthrosis). The menisci and articular cartilage were also normal.

Apart from these two remarkable cases (one FN and one FP), 9 showed drawer signs between 3.2 and 5 mm. Two of them were less than 3.5 mm, but in one of these cases there was only a partial rupture of the anterior cruciate ligament. Another case of partial rupture of the anterior cruciate ligament had an anterior displacement of 4.7 mm.

The greatest value of an anterior drawer sign, calculated without subtracting the value for the uninjured knee, is 21.0 mm (range 6.3 - 21.0 mm). A total a-p instability of 23.8 mm was found in Case 148. The corresponding mean values in this group of patients with injury to the ACL were 11.1 and 14.8 mm. The posterior drawer sign (without substraction of the value for the uninjured knee) was most marked in Case 152: 12.6 mm (total antero-posterior instability = 19.3 mm). These calculations were performed in order to enable comparison with the materials published by others.

Thus, the findings concerning the magnitude of the anterior drawer sign are considerably more varied than reported by previous authors. With reference to the discussion in the present survey, however, it must be mentioned that several workers have found a free interval between a normal knee and a knee with a drawer sign, so that a definite distinction could be made between normal and abnormal findings. This is in conflict with the above-mentioned findings in the present study which showed the even transition between normal and abnormal values which are generally found in biological materials. Conflicting findings by others must be due to a pronounced selection of their materials.

There were two cases of rupture of the posterior cruciate ligament, both total (Cases 152 and 153). The drawer signs were demonstrated by all three diagnostic procedures.

Rotatory Findings in Group 3:
In addition to the cases already mentioned, viz. 121, 124, 125, and 127, the group contains yet another case of simple rotatory instability, Case 120 which showed mild medial instability and external rotation on traction.

Complex anteromedial rotatory instability was found in ten cases: 129, 130, 133, 137, 139, 140, 141, 148, 150, and 151.

Case 129
exhibited an anterior drawer sign and external rotation on traction in the neutral position ($F_n = -3.9$).

Case 130:
The same findings, cf. Table 12. In this case there was also a fresh injury to the medial meniscus.

Case 133
had a marked anterior drawer sign and external rotation of the tibia on traction. No medial instability. The medial meniscus of this knee had previously been removed.

Case 137

also exhibited, on stress radiography, both an anterior drawer sign and external rotation on traction. It was, moreover, close to the critical level for internal rotation on pressure. All these findings indicate anteromedial instability. In this case there was no meniscal injury.

Cases 139 and 141

also showed anteromedial complex rotatory instability with injury to the medial meniscus.

Case 140

was found to have an anterior drawer sign in all stress radiographic positions Rotatory instability manifested itself first as external rotation in the position in which the foot is maintained in 15° external rotation during pressure: $G_{15^{\circ}\text{ ext.}}$ = 5.4 mm (critical level 3.4 mm).

Case 148:

In addition to pronounced anterior drawer sign in various positions an internal rotation was found, the foot being rotated 30° internally, without traction or pressure: $H_{n30^{\circ}\text{ int.}}$ = 4. 6 mm (positive in internal rotation), critical level about 3.0 mm (Addendum I, Table 32, bottom). This ought to predispose to a positive external rotation on traction in this position of the foot, but $F_{30^{\circ}\text{ int.}}$ = -2.7 mm did not exceed the critical value, although a tendency to external rotation (negative sign) was present. The explanation may be that the ACL was ubsent, which tends to internal rotation (the reverse situation to that on Fig. 31). Medial meniscectomy had previously been performed on this knee.

Case 150

showed anterior drawer sign in three positions as well as abnormal external rotation in the injured knee on 30° external rotation of the foot: $H_{n30^{\circ}\text{ ext.}}$ = -5.3 mm. This rotation was abolished on forward traction in the same position of the foot: $F_{30^{\circ}\text{ ext.}}$ = 5.9 mm. It will be seen that both values are of approximately the same size, but with opposite signs.

Case 151

exhibited an anterior drawer sign, internal rotation on traction (F_n), and external rotation on pressure (G_n), explicable by an almost total rupture of the LM (plus total rupture of the ACL and previous excision of the MM). The LM was torn off posteriorly and along its circumference, attaching only anteriorly and folded into the intercondylar fossa.

Case 152:

Out of the total anteroposterior displacement, E_n, the posterior drawer sign, D_n, made up by far the greater part. It is reasonable to assume, therefore, that the total value of E_n is due to a posterior drawer sign, also because:

$$e_{inj.} - e_{uninj.} = 1.4$$

$$f_{inj.} - f_{uninj.} = 3.4 \text{ mm}$$

so that the tibial condyles of the injured knee had, already before the measurement, become 2.4 mm depressed as compared with those of the uninjured knee. Operation also could not demonstrate a fresh or a previous injury to the ACL. Let it be added, however, that at the time of operation 9 months had elapsed since the trauma. The PCL was totally ruptured.

Case 153,

in which there is no doubt that the entire anteroposterior displacement was due to a posterior drawer sign, is mentioned merely because the patient had previously sustained a trauma to the other knee. Therefore, the medial and lateral instability was compared with the critical level for total excursions in one knee - and these levels were exceeded for both - but not by particularly high values. Rotatory instability could not be demonstrated.

Rotatory Instability in the Total Series

Simple Medial Rotatory Instability

was found in a total of 23 cases: 1, 2, 16, 22, 28, 35, 38, 39, 43, 45, 49, 52, 54, 95, 96, 101, 105, 106, 107, 108, 114, 120, and 127.

Simple Lateral Rotatory Instability:

Two cases, 121 and 124.

Complex Anteromedial Instability:

Twenty cases, 71, 75, 78, 80, 82, 83, 84, 85, 115, 116, 129, 130, 133, 137, 139, 140, 141, 148, 150, and 151.

Complex Anterolateral Instability:

Case 70.

Complex Posteromedial Instability:

Cases 76 and 89 (87).

Complex Posterolateral Instability:
Case 86 (70).

Rotation on Rotation of the Foot:
A total of six patients (Cases 43, 49, 52, 95, 148, and 150) exhibited abnormal rotation on rotation of the foot alone, without traction or pressure. In one case the rotation increased on traction (Case 43), while in the others the new critical levels were not exceeded or else the knee joint rotated back to its normal position when a force was applied. The small change as compared with (6) is due to the slightly altered critical levels.

Non-classified Rotations:
Cases 61 and 88 (external rotation on pressure), cf. Summary for Cases 60 - 90.

SUMMARY

A total of 51 (or 53) cases of rotatory instability. This accords with (6), but a few cases have been omitted because of the new, higher critical levels, while a few new ones have been added by means of the algebraic formulae which have now been introduced.

Relation of Trauma Mechanism to the Instability Findings

It was previously established (5) that the forms of instability observed, in particular medial/lateral instability and anteroposterior instability, were in conformity with the injuries found. The rotatory findings too have been largely consistent with what could be expected in association with the injuries. Particular attention should be devoted to the role of the meniscus in rotatory stability (cf. Case 127 and others). If the mechanism of the trauma can be elucidated, it ought to be possible to record conformity between its direction and the form of resulting instability.

As apparent from the tables, this was attempted by questioning the patients regarding the mechanism of the trauma, and the most useful information was obtained from patients with fresh injuries and with sports injuries. For skiing and football they are quite characteristic, and largely of the same type. Abduction and external rotation as well as a degree of flexion up to a fully extended knee constituted the most common mechanism of trauma. Therefore, stress radiography revealed most cases with a component of abnormal external rotation. This was demonstrated in the course of the examination by externally rotating the foot only, by exerting traction only, or by traction in the externally rotated position in 32 cases (1, 2, 28, 39, 43, 49, 52, 70, 71, 75, 78, 80, 83, 84, 85, 86, 87, 95, 101, 105, 106, 107, 115, 116, 120, 129, 130, 133, 137, 139, 141, 150). Internal rotation on pressure was demonstrated in 9 cases (16, 22, 35, 38, 45, 54, 76, 96, 114). On reviewing the findings, however, it would appear that the abduction component was more pronounced in these last-mentioned traumas than was the external rotation (Cases 35, 38, 54, 114). Case 76 had so severe an injury that many instability patterns were naturally found at the measurement. Case 96 cannot be distinguished from the 32 cases mentioned above as far as the mechanism of the trauma was concerned.

The study does not appear to show any regularity as to when the medial ligaments alone rupture in the abduction-external rotation traumas and when the ACL also ruptures. When considering the most reliable reports, in Cases

1 - 90, the type of trauma has usually been the same, but with a varying degree of flexion in the knee. The resulting injury presumably depends upon when the trauma stops, meaning when the muscular defence reaction sets in or the inertia of the trauma has been absorbed. In extremely violent traumas the PCL also ruptures, as seen in group 1 of this series. The injuries in Case 90 (rupture of the posterior capsule and PCL) were presumably produced by a pure hyperextension trauma, as indicated by the simultaneous bone injuries. This mechanism is in agreement with the cadaver experiments of Kennedy et al. (1974). In Case 90 the energy at the trauma had been absorbed before the ACL also ruptured, and before a tendency to dislocation of the knee set in. The force has been absorbed through compression fractures in the subchondral cancellous bone of the medial condyles. The axial force in the longitudinal direction of the thigh, cf. Palmer (1938, pp. 42-44) has been quite strong.

Kennedy et al. (1974) report that especially in internal rotation traumas of the tibia in relation to the femur, they have seen 7 cases of isolated rupture of the ACL. This could not be confirmed in the present material in which there were only four cases in which an internal rotation component was included in the mechanism of trauma. In these cases the injuries were: LM injury in Case 10, partial rupture of the LCL in Case 59, and injury to both these structures in Cases 121 and 126. In the first-mentioned case there was also an extension factor, in the remaining three a flexion factor. Other combinations of forces and degrees of flexion have evidently been present in the material of Kennedy et al.

Operated, but Not Stress Radiographically Examined Patients During the Study Period

During the study period four patients with major injuries were not subjected to gonylaxometry and are therefore not included in the material:

P.M., 18 12 52, a 21-year-old man, because of associated fractures of the thigh and lower leg. Operation on the knee revealed total rupture of the PCL.

B.L.B., 08 01 44, a 30-year-old man, because of anterior dislocation of the knee joint which required immediate operation. Operative diagnoses: Total ruptures of the ACL and LCL, iliotibial tract, tendon of the biceps muscle, and posterior capsule of the left knee.

E.E.B.J., 14 01 29, a 45-year-old woman, because of a fracture of the intercondylar eminence which was interpreted as a contra-indication to gonylaxometry, as further displacement of the fracture was feared. Operative diagnoses: Total rupture of the ACL as well as the DMCL and SMCL.

A.L.H., 15 04 55, a 19-year-old man with radiological evidence of avulsion of bone from the internal aspect of the lateral femoral condyle. Stress radiographic examination was felt to be contra-indicated for fear of further displacement of the fragment or destruction of possible remaining parts of the ligament, as the diagnosis could be made already on the basis of the conventional radiography. Operative findings: Total tear of the ACL with a fragment of bone from the origin at the femoral condyle.

From this is apparent what were considered <u>contra-indications to the examination:</u>

1. Conditions requiring hyperacute treatment and thereafter rest. These are conditions in which the popliteal artery is threatened, and perhaps injured (e.g. dislocation of the knee).
2. Complicating major fractures of the thigh, lower leg, pelvis, or other sites.
3. Intraarticular fractures of the knee which are feared to be aggravated by the examination.
4. Conditions in which a diagnosis of ligament rupture has been established by conventional radiography, e.g. chips of bone avulsed from the sites of origin or insertion of the cruciate ligaments, as in that case aggravation of the injury may be feared during the examination.
5. Life-threatening conditions which must have preference over orthopaedic treatment.

We did not feel the examination was contra-indicated in the only case in which there was a question of a peroneal nerve palsy (neuropraxia) (Case 70), but it is a matter of discussion whether it ought in future be included among the contra-indications.

Basis for Selection of Calculation Programmes and Choice of Standard Procedure

The evaluation which is the aim now is not an evaluation of the stress radiographic method as a whole. En route we have already done several evaluations of the method, e.g. of the force action upon the knee joint, X-ray projections, magnification on the X-ray films, inaccuracy of the measurement, interpretation of rotatory findings, and the diagnostic ability of the method clinically, in the form of PV_{pos} and PV_{neg}.

Here it will be endeavoured to evaluate which of the many modes of calculation of the various forms of instability are most advantageous.

Such a selection of calculation programmes is practicable only on the basis of the presuppositions made: How many exposures are felt to be suitable, how great an accuracy is wanted in order to cover all possibilities of instability finding. It must be mentioned that all the calculation methods have separately contributed positive findings which would otherwise have escaped detection. These are in particular various forms of rotatory instability which have been divulged by means of the formulae introduced in this Addendum.

On the other hand, the large register of formulae - and as presuppositions for them a number of different positions of the foot during the lateral exposure - requires quite a large number of X-ray exposures of each person if all calculations are to be included in a standard set of formulae. For research purposes the projections and sets of formulae which seem most suitable have to be selected.

In selecting a standard method there can be no doubt that formula sets A and B as well as C_n, D_n, and E_n, F_n, and G_n (Table 1) ought to be used. They are the ordinary exposures for medial/lateral instability, of anteroposterior displacement in the neutral position of the foot, a total of 8 exposures. The last two sets of formulae, F_n and G_n, concern rotation.

By this, most simple solution (8 X-ray exposures) 35 of the 53 cases of rotatory instability (66%) were detected, viz. Cases 1, 2, 22, 28, 35, 38, 45, 49, 54, 61, 70, (70), 71, 75, 76, 84, 85, 86, 88, 89, 95, 96, 108, 11 120, 121, 124, 127, 129, 130, 133, 137, 139, 141, 151.

If 2 additional exposures are made of each knee, i.e. a total of 12 exposures, adding an exposure with 15° externally rotated foot both without applying force and with 30 kp traction, F_{15}, C_{15}, H_{n15}, and F_{n15} can also be calculated. By calculating F_{15} it was possible to detect 5 additional cases of rotation, viz. Cases 39, 80, 83, 107, and 115. Furthermore, C_{15} $= \frac{(e_{15} - g_{15}) + (f_{15} - h_{15})}{2} = (\text{inj.} - \text{uninj.})$ can be calculated.

This test is used as a stress radiographic counterpart of Slocum and Larson's clinical test (1968) and indicates instability of the structures on the medial aspect of the knee and a resulting external rotatory instability, unless both condyles move extremely much. In that case it must be interpreted as a sign of complex anteromedial instability. An increase in an already positive C_n ($F_{15} > C_n$) under these conditions invariably means the presence of medial rotatory instability - in other words complex anteromedial rotatory instability.

The highest C_{15} value found without associated rupture of the cruciate ligaments and due exclusively to injury affecting the medial structures, was C_{15} = 5.6 mm (Case 101). Another 6 of the rotatory instabilities were based upon calculation of the C_{15} - Cases 78, 82, 87, 101, 105, 106.

H_{n15}, i.e. rotation without any force applied, can also be calculated on the basis of the 12 stress radiographic exposures. This meant another three positive rotation findings (Cases 43, 52, and 116). Thus, by means of this number of exposures and the appurtenant calculations, it was possible to ascertain 49 of the 53 rotation findings. This is 92% (95% confidence limits 82 - 98%) of the rotation findings.

As exposures during pressure in a 15° externally rotated position afforded only one additional positive result (Case 140), and since it requires 2 further exposures, this extension of the examination can be omitted. A complete examination in 30° externally rotated position of the foot afforded one additional positive rotation finding (Case 150), but requires 6 further exposures. In my opinion, therefore, this extension of the method can also be omitted. Examination in 30° internally rotated foot requires 6 additional exposures, and in this study it gave only two findings (Cases 16 and 148) which could not be disclosed by simpler means. This extension too should, therefore, presumably be omitted. However, in connection with this evaluation it must be mentioned that these major examinations could not be performed very often in the present material. If they had, they might possibly have disclosed more cases of rotation.

Accordingly, the comparison of simple and more complex methods should be regarded merely as an applicable, practical guidance - and of course methodological and statistical objections can be raised against it. Nevertheless, it represents the number of examinations and comparisons which were possible and practicable, and I am convinced that it is good guidance.

According to requirement, 8 or 12 exposures will presumably be used, and the appurtenant possibilities of calculation.

The values for these rotation terms have often been fairly close above the critical level, but when reaching somewhat higher values they have been numerically from about 5.0 mm to 9.5 mm (the latter being the $F_{n15^{\circ}\,ext.}$ in Case 107).

Predictive Values

PV_{pos} and PV_{neg} have been defined in the survey and in (5). In the latter (5, p. 306) it was stated how PV_{pos} and PV_{neg} altered further in favour of gonylaxometry in relation to the clinical examination, if an attempt is made to distinguish between anterior and posterior drawer signs. Such a calculation was carried out for group 1 (shown in Table 14). The figures reported in paper (5) still apply.

A matter of very great importance is what happens to the PV_{pos} and PV_{neg} on rounding the results of measurements and calculations to whole figures. These probabilities reflect whether changes in the distribution of TP, TN, FP, and FN measuring results will occur on such a change in the critical levels, as the rounding is strictly speaking a slight alteration of these critical levels. It must be endeavoured, therefore, to carry out this alteration of the critical levels in a way which makes for the least possible change in the predictive values of the test.

Basis for Deciding to Round Off the Calculation Results to Whole Millimetres (mm)

As it has been demonstrated previously that the inaccuracy of the measurement for all parameters exceeds 1 mm (3), it seems reasonable to round off the test results to whole mm. Thereby, the critical levels will also be subjected to a rounding.

When rounding the critical level for medial instability to 2 mm, this figure will be considered normal, whereas values rounded to 3 mm will be abnormal. This presupposes a numerical calculation as follows: /parameter value of injured knee less that of the uninjured knee/. With one decimal, the new limit will be 2.4 mm. At this value and below it the result is normal (rounded to 2 mm), but if it is 2.5 mm or over it is abnormal (as in that case the figure will be elevated to 3 mm).

This will transfer the results for medial/lateral instability in Cases 18 (A = 2.3 mm), 113, 120, 135, and 150 to the group of FN. In the total result, it will mean a further 5 FN values and 5 TP values less:

total number N = 152, TP = 82, TN = 60, FP = 0, FN = 10,

$$PV_{pos} = \frac{TP}{TP + FP} = \frac{82}{82 + 0} = 100\% \ (96 - 100\%)$$

$$PV_{neg} = \frac{TN}{TN + FN} = \frac{60}{60 + 10} = 86\% \ (75 - 93\%)$$

with the 95% confidence limits in brackets.

Expressed in words: The PV_{pos} remains unchanged, while the PV_{neg} has been reduced from previously 92% to 86% (cf. (5) p. 308). However, the injuries which escape detection (new FN) are very mild, and it must be included in the reflections that such mild instabilities do not usually indicate operation. Therefore, the reduced PV_{neg} under these conditions is of no importance (Wulff 1973 b). This speaks for using, when rounding off, the following limits:

for medial stability: values $\leq$ 2 mm
instability: values $\geq$ 3 mm.

Measurement of Lateral Stability

With the same rounding, i.e. the same alteration of the level as for medial instability, Case 61 ($B = 2.1$ mm) will have to be re-evaluated from FP to TN. Case 142 ($B = 2.3$) becomes negative. As this was an old injury, in which both menisci of the knee had previously been removed, it is difficult to classify this finding as a true or false negative - and it is of no importance as this negligible instability hardly requires any treatment. Case 153 will not be altered, as the value is 0.6 mm above the normal limit. The few major lateral injuries (Cases 70, 76), in which operation is indicated int. al. because of lateral instability in the frontal plane, showed stress radiographic measurements of lateral instability far above the level at which the small roundings exert any influence, and they are accordingly not affected thereby.

It is then permissible to use the same critical levels as those mentioned for medial instability.

Anteroposterior Displacement

In a concrete and well-defined concept unit, such as traumatic injuries to the knee with rupture of ligaments, it must be reasonable to use the 97½% centile for measurements in normals as the critical level for injuries. A lower value would hardly be expedient. After rounding, this critical 97½% level gives 3 mm for anterior, posterior, or total anteroposterior displacement of each of the tibial condyles separately or the mean thereof (drawer sign). Therefore, it must be attempted to set up the following critical levels for anteroposterior displacement:

values $\leq$ 3 mm: normal
values $\geq$ 4 mm: abnormal.

This transfers Cases 75 and 144 from TP to FN, and this causes a small, but acceptable change in the final result.

$TP = 45$, $FP = 1$, $TN = 98$, $FN = 6$, $N = 150$,

$$PV_{pos} = \frac{TP}{TP + FP} = \frac{45}{46} = 98\% \ (88 - 100\%) \text{ unchanged,}$$

$$PV_{neg} = \frac{TN}{TN + FN} = \frac{98}{98 + 6} = \frac{98}{104} = 94\% \ (87 - 97\%) \text{ (previous-}$$

ly 96%).

Levels for Rotatory Instability

As apparent from Addendum I, rounding off the critical levels selected there for rotation (cf. Also Addendum II, Calculation Rules) gives 3 mm, so that values of 4 mm or over must be considered abnormal. This applies to neutral position of the foot, 15° externally rotated foot, and 30° internally rotated foot.

As mentioned in the conclusion of Addendum I, measurement at 30° external rotation gave in one normal person up to 4 mm in one rotation measurement - still as the difference between the person's two knees. However, as this position is not among those recommended for standard measurements, it will be disregarded here. The suggestion concerning critical levels applies to foot positions neutral and 15° externally rotated. If the same values for these positions are used as in anteroposterior displacements,

values $\leqq$ 3 mm: normal,
values $\geqq$ 4 mm: abnormal,

the rotation will be overlooked in Cases 43, 115, 120, 121, 133, and 141. That is, six out of 51 rotation cases (12%). This seems a reasonable price for the simplification of the critical levels.

Table 2. (foot rotation ext. = externally, int. = internally)

	Patient Nr. 1	2	3	4	5	6	7	8	9	10	11
A	1.8	0.0	1.8	0.2	0.1	0.3	0.4	1.8	1.0	0.1	1.1
B		0.3	0.4			0.1	0.3	0.6	0.9	0.4	0.5
C_n	0.9	-0.6	-0.7	-1.6	1.7	-0.6	0.3	0.0	2.0	-0.6	1.9
C_{15^0} ext.		0.5	1.0					1.5		-1.1	1.3
C_{30^0} int.										0.8	
D_n	0.0	0.5	-0.6	0.4	-0.3	-0.6	0.7	0.1	-1.4	0.3	-0.3
E_n	0.9	-0.1			1.5			0.2	0.6		1.6
F_n	-4.6	-7.1	1.6	1.9	2.2	-0.6	-3.2	1.0	-0.2	-1.4	-1.6
$F_{15°}$ ext.		-7.2	(-3.6)					0.2		-2.3	-0.1
F_{30^0} int										1.5	
G_n	1.7	0.4	-1.4	-3.1<3.4	-1.1	-0.7	1.7	-1.8	-1.2	3.4	0.3
$H_{n\ 15°}$ ext			$(k-1)_{norm.}-8.1$ $(k-1)_s-3.1$					0.5		1.1	0.7
$H_{n\ 30°}$ int										inj. 0.6 uninj 4.3	

Table 3.

Trauma, operative findings, and evaluation of instability, at clinical examination, under general anaesthesia, and at stress radiography. Cases 1 - 11.

Case No.	Sex	Age	Type of Trauma	Findings at operation	Assessment of Instability					
					Clinically		Under gen. anaesthesia		At gonylaxometry	
					medial	drawer	medial	drawer	medial	drawer
1	M	29	Skiing. Flex., e.-rot.	SMCL, part.	FP	FP	FP	TN	TN	TN
2	M	29	Football, abd., ext.	SMCL, part.	FP	TN	TN	TN	TN	TN
3	M	25	Football, abd.,e.-rot.	SMCL, part.	FP	TN	TN	TN	TN	TN
4	M	34	Fell on floor, e.-rot. + direct trauma on front of knee	Contusion of infrapatellar fat pad + haemarthrosis	FP	TN	TN	TN	TN	TN
5	F	31	Handball, abd., flex.,e.-rot.	Dislocation of patella	FP	TN	TN	TN	TN	TN
6	M	21	Running downhill, e.-rot.	Dislocation of patella	FP	TN	TN	TN	TN	TN
7	M	28	Football, abd., e.-rot.	Dislocation of patella	FP	TN	TN	TN	TN	TN
8	M	18	Judo, e.-rot.	Dislocation of patella	TN	FP	TN	TN	TN	TN
9	F	24	Skiing, abd., flex., e.-rot.	DMCL, part.	FP	TN	TN	TN	TN	TN
10	M	31	Football, i.-rot., ext.	LM	TN	TN	TN	TN	TN	TN
11	M	32	Slid on floor at work, e.-rot., abd., flex.	Dislocation of patella	FP	TN	TN	TN	TN	TN

Special abbreviations used in table 3 and the following tables having odd numbers :
abd.: abduction, add.: adduction, caps.: fibrous capsule of knee, ext.: extension, flex.: knee flexion
m.flex.: middle(45°)flex., e.-rot.: external rotation, i.-rot.: internal rot., part./tot.:partial/total rupture.

Table 4.	Patient nr.12	13	14	15	16	17	18	19	20	21	22	23	24
A	2.8	3.4	3.6	2.6	4.6	2.6	2.3	3.6	3.2	3.2	3.7	5.5	4.2
B	0.2	0.2	-0.8	0.4	0.1	0.1	0.4	1.1	0.6	0.1	0.2	0.3	0.8
C_n	-0.3	1.5	-0.6	Gonylaxometry not carried through with flexed knee because of pain reaction.	-1.5	0.4	0.5	-1.1	-0.1	-1.6	-2.7	Gonylaxometry not carried through with flexed knee because of pain reaction.	0.5
C_{15° ext					2.1	2.2			0.9	0.6	-0.5		0.0
C_{30° int					-1.0	0.7					-3.3		
D_n	-1.4	0.1	-1.4		0.6	1.0	-4.4	-1.9	0.9	-1.1	-2.7		-2.3
E_n	-2.8	1.6	-2.0		-0.9	1.4			1.0	-2.3	-5.4		-1.9
F_n	0.8	-1.2	-1.3		-0.7	0.8	1.1	-2.7	-0.7	-2.8	-2.1		-0.9
F_{15° ext					0.8	-0.9			0.6	0.3	-2.5		-0.9
F_{30° int					-3.6	-1.3					-0.7		
G_n	3.0<3.4	-3.2	2.0		-3.1	0.1		0.1	2.2	-0.1	-4.4		-0.7
H_n 15° ext									-0.3	0.5	3.2		-0.2
H_{30° int											-1.4		

Table 5.

Trauma, operative findings and evaluation of instability in Cases 12 - 24.

Case No.	Sex	Age	Type of Trauma	Findings at operation	Assessment of Instability					
					Clinically		Under gen. anaesthesia		At gonylaxometry	
					medial	drawer	medial	drawer	medial	drawer
12	F	26	Skiing, flex., abd., (rot. ?)	DMCL tot.	TP	TN	TP	TN	TP	TN
13	M	28	Skiing, flex., abd., e.-rot.	DMCL tot.	TP	TN	TP	TN	TP	TN
14	M	28	Judo, trauma to lateral side of knee	DMCL tot.	TP	TN	TP	TN	TP	TN
15	M	37	Football, abd., e.-rot.,flex.	SMCL part., DMCL part.	TP	TN	TP	TN	TP	*
16	M	28	Football, e.-rot. when turning	SMCL part.	TP	TN	TP	TN	TP	TN
17	M	28	Stumbled, abd., e.-rot.,m.-flex.	SMCL part.	TP	TN	TP	TN	TP	TN
18	M	21	Football, abd.,e.rot.,m.flex.	SMCL part.	TP	TN	TP	TN	TP	TN
19	M	48	Football, abd.,e.rot.,m.flex.	SMCL part., DMCL part.	TP	TN	TP	TN	TP	TN
20	M	22	Football, abd.,e.rot.,m.flex.	SMCL part.	TP	TN	TP	TN	TP	TN
21	M	32	Football, abd., m.flex.	SMCL part.	TP	TN	TP	TN	TP	TN
22	M	28	Football, abd.,e.rot.,m.flex.	SMCL part.	TP	TN	TP	TN	TP	TN
23	F	24	Skiing, abd., e.rot., flex.	DMCL and DMCL tot.	TP	TN	TP	TN	TP	*
24	M	30	Football, abd.,e.rot.,m.flex.	SMCL part., DMCL tot.	TP	TN	TP	TN	TP	TN

*Gonylaxometry done in the frontal plane (abd./add.), but not in the sagittal plane (drawer) because of pain.

Table 6.	25	26	27	28	29	30	31	32	33	34	35	36	37
A	6.0	5.0	5.5	5.7	7.3	6.1	5.3	6.9	5.3	8.0	7.8	5.1	5.1
B	0.9	1.4	-1.5	0.4	-0.2		0.4	2.8	-0.7		-0.3	-1.6	
C_n	1.0	0.3	-0.7	1.9	0.8	1.2	-0.2	0.9	-4.9	-0.7	2.2	-0.6	-1.9
C_{15°ext							-1.5	-0.9					
D_n	0.7	0.5	1.4	0.5	-1.5	0.3	1.7	-0.1	-0.6	-2.0	-1.5	1.3	0.6
E_n	1.7	0.8	0.7	2.4	-0.7	1.5	1.5	0.8	-5.5	-2.7	0.7	0.7	-1.3
F_n	-0.2	-1.2	-2.5	-3.5	-1.1	-0.9	-1.8	0.6	1.6	-1.8	1.6	2.3	0.7
F_{15°ext							-1.2	-2.0					
G_n	-0.6	-0.4	-0.9	0.5	0.9	0.0	1.7	-2.2	2.0	-2.0	-4.8	1.3	-0.1
$H_{n\ 15^\circ}$ext							-1.9						

Table 6, continued	38	39	40	41	42	43	44	45	46	47	48	49	50
A	8.5	4.6	6.8	4.6	5.2	7.9	4.3	6.8	6.4	6.3	5.0	8.3	5.7
B	0.2	0.4	0.2	-1.9	0.1	1.3	1.1	0.4	0.0	1.2		0.1	0.9
C_n	-1.1	-0.7	-2.5	-3.0	-1.0	0.0	0.9	1.3	-2.0	-1.5	-0.5	2.4	0.8
$C_{15^\circ\text{ ext}}$		-2.1	-1.9	-5.1	1.1	-1.6						0.6	1.9
$C_{30^\circ\text{int}}$		-2.5	-2.8	-1.9	-1.2								-2.1
D_n	2.9	0.7	0.6	-0.2	0.7	0.2	0.3	0.0	0.7	0.0	-0.4	-0.7	0.2
E_n	1.6	0.0	1.9	-3.2	-0.3	0.2	1.2	1.3	-2.7	-1.5	-0.9	1.7	1.0
F_n	1.6	-1.6	-1.1	0.0	-0.8	-0.6	-2.8	1.2	-0.4		-0.7	-3.4	-2.5
$F_{15^\circ\text{ext}}$		-3.5	-1.2	-3.5	-1.3	0.2				-2.3		0.3	-2.1
$F_{30^\circ\text{int}}$		-2.8	-1.8	-1.5	0.7								1.0
G_n	-2.7<3.4	0.4	2.6	-4.8	-0.2	0.9	-0.5	-3.7	-1.1	-0.6	-1.0	1.6	-0.4
H_n 15°ext			-0.2	1.0	0.2	-3.1						-4.0	-0.6
H_n 30°int					0.0								-0.7

Injuries of LCL

Table 6. continued	51	52	53	54	55	56	57	58	59
A	4.7	3.9	5.6	6.6	5.9	6.2	6.5		1.3
B	0.2	2.4	0.7	-0.5	-1.7	1.1	-0.3	0.6	1.6
C_n	-0.3	2.1	0.8	0.0	0.5	0.0	-0.2	-1.0	1.6
$C_{15°ext}$	-0.2	3.0	2.6	0.5	1.4	1.1			
D_n	1.0	-0.6	0.8	-0.8	-1.0	-0.6	-1.0	-0.6	0.5
F_n	0.3	0.8	1.1	0.1	0.7	-1.3	-0.5	-0.9	-2.4
$F_{15°ext}$	0.5	3.0	1.9	-1.0	0.9	-1.1			
$F_{n\ 15°ext}$	0.7	-0.6	0.2	-1.4	-1.2	-3.2			
G_n	-1.2	0.5	0.6	-4.3	-0.3	-2.7	-0.3	-1.7	2.9
$H_{n\ 15°ext}$	0.2	-3.6	-1.7	-0.4	-2.1	-2.1			

Table 7. Trauma, operative findings and evaluation of instability in Cases 25 - 59.

Case No.	Sex	Age	Type of Trauma	Findings at operation	Assessment of instability: Clinically medial	Clinically drawer	Under gen. anaesthesia medial	Under gen. anaesthesia drawer	At gonylaxometry medial	At gonylaxometry drawer
25	M	25	Football,opponent against lat. side of knee,abd. and 5°flex.	SMCL tot., DMCL tot.	TP	TN	TP	TN	TP	TN
26	M	19	Football,abd.,e-rot.,m-flex.	SMCL,DMCL,OMCL tot. and caps.	TP	TN	TP	TN	TP	TN
27	M	35	Skiing, abd., e-rot., m-flex.	SMCL,DMCL,OMCL tot.	TP	FP	TP	TN	TP	TN
28	M	19	Football,kicked med.,abd,m-flex	SMCL and OMCL tot.	TP	FP	TP	TN	TP	TN
29	M	13	Traffic, fell off bicycle, unconscious	SMCL and DMCL tot.	TP	TN	TP	TN	TP	TN
30	M	32	Football,abd., e-rot.,m-flex.	SMCL and DMCL tot.	TP	TN	TP	TN	TP	TN
31	M	17	Fight, abd., e-rot.	SMCL and DMCL tot., and anteromedial caps. comb. with disloc. of patella	TP	TN	TP	TN	TP	TN
32	M	43	Work with heavy burden, e-rot. m-flex.	SMCL and OMCL tot.,DMCL part.	TP	TN	TP	TN	TP	TN
33	F	59	Traffic, abd., flex.	SMCL tot., OMCL part.	TP	TN	TP	TN	TP	TN
34	M	29	Football,abd.,e-rot., m-flex.	SMCL,DMCL,OMCL tot.	TP	TN	TP	TN	TP	TN
35	F	68	Traff.,fell off bicycle, abd.	SMCL,DMCL,OMCL tot.	TP	TN	TP	TN	TP	TN
36	F	27	Skiing, abd., flex., (rot. ?)	SMCL,DMCL,OMCL tot.	TP	TN	TP	TN	TP	TN

Table 7 contd.

Case No.	Sex	Age	Type of trauma	Findings at operation	Clinically med.	Clinically drawer	Under gen.an. med.	Under gen.an. drawer	Gonylaxomet. med.	Gonylaxomet. drawer
37	M	23	Football,knee locked by opponent	SMCL,DMCL,OMCL tot.,ACL part. (Fig. 28)	TP	FN* TN	TP	FN* TN	TP	FN* TN
38	M	21	Football,abd., kick on tibia medially	SMCL tot.	TP	FP	TP	TN	TP	TN
39	M	18	Football,abd.,e-rot.,20^0 flex.	SMCL part., DMCL and OMCL tot.	TP	TN	TP	TN	TP	TN
40	M	19	Football,abd.,e-rot., ext.	SMCL part., DMCL and OMCL tot.	TP	TN	TP	TN	TP	TN
41	M	20	Football,slid,abd.,e-rot.,90^0flx.	SMCL, DMCL, OMCL tot.	TP	FP	TP	TN	TP	TN
42	M	20	Football, abd., e-rot., ext.	SMCL: fibres coiled-up in fresh granul. tissue beneath intact peritendineum.Lig. elongated.	TP	TN	TP	TN	TP	TN
43	M	28	Football, abd., e-rot., m-flex.	SMCL, DMCL, OMCL tot.	TP	TN	TP	TN	TP	TN
44	M	30	Work accident,heavy burden against lower leg laterally,abd., slightly flexed knee.	SMCL: almost tot., hindmost fibres intact.	TP	TN	TP	TN	TP	TN
45	M	22	Football, abd.,e-rot., flex.	SMCL tot.	TP	TN	TP	TN	TP	TN
46	M	24	Football, abd.,e-rot., m-flex.	SMCL tot.	TP	TN	TP	TN	TP	TN
47	M	32	Football,trauma to tibia from front.	SMCL tot.	TP	TN	TP	TN	TP	TN
48	F	26	Fell in forest,abd,e-rot.,flex.	SMCL tot.	TP	TN	TP	TN	TP	TN

For meaning of asterisk and double evaluation of drawer sign in Case 37, cf. text.

Table 7 contd.

Case No.	Sex	Age	Type of trauma	Findings at operation	Clinically		Under gen. an		Conylaxomet.	
					med.	drawer	med.	drawer	med.	drawer
49	F	42	Handball, opponent fell against lat. side of ext. knee.	SMCL, DMCL, OMCL tot.	TP	TN	TP	TN	TP	TN
50	M	19	Football, abd., e-rot., flex.	SMCL, DMCL, OMCL tot.	TP	TN	TP	TN	TP	TN
51	F	38	Skiing, fell forward (unable to tell position of leg)	SMCL, DMCL, OMCL tot.	TP	TN	TP	TN	TP	TN
52	M	31	Football, abd., e-rot., m-flex.	SMCL tot.	TP	TN	TP	FP	TP	TN
53	M	23	Football, abd., e-rot., ext.	SMCL, DMCL, OMCL tot.	TP	TN	TP	FP	TP	TN
54	M	20	Football, abd., e-rot., ext.	SMCL and OMCL tot.	TP	TN	TP	TN	TP	TN
55	M	27	Football, collision, abd.,flex. e-rot.	SMCL tot.	TP	FP	TP	TN	TP	TN
56	M	26	Football, abd., e-rot., m-flex.	SMCL and DMCL tot.	TP	TN	TP	TN	TP	TN
57	M	19	Football, abd., e-rot., 10^oflex	SMCL,DMCL,OMCL tot. and caps.	TP	TN	TP	TN	TP	TN
58	M	25	Football, collision,add.(varus)	LCL part.	TN	TN	TN	TN		TN
59	M	25	Handball, add., i-rot., flex.	LCL part.	TN	TN	TN	TN	TN	TN

Table 8. Parameter - values in Case 60 - 90.

Case No.	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76
A	0.0	0.2	1.7	8.4	0.4	-0.5	0.3	1.7	1.6	9.3	-0.3	9.3	7.9	5.9	6.4	-0.7	17.5
B	-0.5	2.1	0.3	-0.6	0.1	-0.6	0.5	-1.5	0.6		20.8	-0.4	0.0	0.1	-0.6	0.4	1.9
C_n	2.5	-3.3	-1.1	7.3	3.2	-0.4	1.2	3.9		9.2	6.7	16.1	-0.6	4.8		2.5	7.7
C_{15° ext.	4.1	-0.2					3.8	1.4	see						refused further examination		
C_{30° int.	0.0						1.4		text								
D_n	-1.1	2.4	-0.8	-0.5	1.9	0.7	0.0	-0.5	-	0.2	4.7	-1.5	-0.8	-0.8		0.8	18.5
E_n	1.4	-0.9	-1.9	6.8	5.1	0.3	1.2	3.4	-	9.4	11.4	14.6	-1.4	4.0		3.3	26.1
F_n	-1.2	-0.4	0.4	-2.7	-0.8	1.7	-1.8	-0.6	-	-0.4	2.8	-5.3	-0.9	1.4		-4.2	-0.5
F_{15° ext.	1.6	-0.5							-								
F_{n15° ext.	-0.3						-0.6	0.6	-								
F_{30° int.	-1.0								-								
G_n	2.4	4.8	-2.1	1.3	-4.1	-5.1	0.0	-0.9	-	1.0	1.6	0.2	-3.1	-0.7		1.3	-2.1
H_{n15° ext.	-1.9	-1.3							-								
H_{n30° int.	-2.7								-								

Table 8 contd.

Case No.	77	78	79	80	81	82	83	84	85	86	87	88	89	90
A	4.5	5.7	1.5	12.7	0.0	7.2	16.3	4.8	9.1	0.1	7.4	3.6	8.6	1.0
B	0.0	0.2	0.3	1.8	0.8	1.6	-0.5	-0.2	1.2	$\underline{4.1}$	0.4	-0.8	-0.5	-1.6
C_n	6.7	6.7	0.2	7.7	-0.2	2.1	$\underline{12.5}$	3.0	$\underline{12.1}$		2.8	$\underline{5.8}$	-0.2	1.5
C_{15° ext.	5.0	$\underline{11.6}$	1.1	$\underline{15.2}$		$\underline{7.6}$	$\underline{13.4}$	$\underline{4.4}$			$\underline{4.2}$			
C_{30° int.			0.9											
D_n	-0.9	0.1	1.9	0.7	2.5	-0.1	1.1	0.8	-0.4	$\underline{4.7}$	$\underline{14.0}$	$\underline{6.2}$	$\underline{6.2}$	$\underline{13.8}$
E_n	$\underline{5.8}$	$\underline{6.8}$	2.1	$\underline{8.4}$	2.3	2.0	$\underline{13.6}$	$\underline{3.8}$	$\underline{11.7}$		$\underline{16.8}$	$\underline{12.0}$	$\underline{6.0}$	$\underline{15.3}$
F_n	-1.7	-0.4	-0.8	-0.2	1.1	-0.9	0.2	$\underline{-3.8}$	$\underline{-3.7}$		-1.7	1.2	1.1	2.5
F_{15° ext.	-1.6	2.1	0.5	$\underline{-3.5}$		-0.5	$\underline{4.1}$	-3.1			-2.2			
F_n 15° ext.		1.6	-0.3	-0.4		-0.7	3.3	$\underline{-4.1}$			-2.5			
F_{30° int.			0.3											
G_n	1.1	-1.4	3.0	-2.5	0.4	1.2	0.2	0.6	0.6	$\underline{5.7}$	0.6	$\underline{5.9}$	$\underline{-4.6}$	-0.6
H_n 15° ext.	-0.1	-0.5	-0.8	5.7		-0.2	-0.9	-1.0			-0.3			
H_n 30° int.			2.5											

Table 9. Trauma, operative findings and evaluation of instability in Cases 60 - 90.

Case No.	Sex	Age	Type of trauma	Findings at operation	Instability					
					Clinically		Under gen. anaesthesia		At gonylaxometry	
					med.	drawer	med.	drawer	med.	drawer
60	M	30	Football, abd.,e-rot,15°flex.	ACL part.,DMCL tot.,MM part.	TP	TP	FN	FN TN*	FN	FN TN*
61	M	19	Football, fell after heading ball, abd., e-rot., ext.?	ACL, DMCL and OMCL tot.	FN	FN	FN	FN	FN	FN
62	M	48	Skiing, abd., e-rot., flex.	ACL part. subsynovial and SMCL, DMCL, OMCL tot.	TP	FN	TP	TP	FN	FN TN*
63	M	41	Skiing, abd., e-rot., flex.	ACL,SMCL,DMCL,DMCL tot.	TP	TP	TP	TP	TP	TP
64	M	16	Traffic, fell off moped, dir. trauma(unable to state details	ACL tot., part. avulsion of iliotibial tract from Gerdy's tubercle.	TN	FN	TN	FN	TN	TP
65	M	13	Traffic, fell off bicycle, (unable to state details)	ACL part. (with fracture of intercondylar eminence)	TN	FN	TN	FN TN*	TN	FN TN*
66	M	25	Football, tackling,abd,20°flx.	ACL part.(postero-lat. fibres)	TN	TP	TN	FN TN*	TN	FN TN*
67	M	16	Football, tackling,abd,(rot.?)	ACL part.(posterolat. fibres)	TN	TP	TN	FN	TN	TP
68	M	24	Football, abd., e-rot., m-flex.	ACL,DMCL,OMCL tot. and caps.	TP	FN	TP	TP	FN	TP
69	M	25	Fell down staircase (unable to state details of rotation)	ACL tot. + old tot. rupture of SMCL and DMCL	TP	TP	TP	TP	TP	TP

Table 9 contd.

70	M	18	Football,kicked on knee med.	ACL, PCL and all lateral structures tot., see text	TN	TP	TN	TP	TN	TP
71	F	21	Long jump,abd,e-rot,max.flex.	ACL, SMCL, DMCL tot.	TP	TP	TP	TP	TP	TP
72	F	22	Volleyball, complic. trauma, cf. text	ACL tot., PCL part., SMCL and DMCL tot., caps. (cf. text)	TP	FN	TP	FN	TP	FN
73	M	20	Football,tackling,abd.,m-flex.	ACL part.,SMCL and DMCL tot.	TP	FN	TP	TP	TP	TP
74	F	17	Traffic, moped,abd.,max. flex.	ACL and PCL tot., SMCL, DMCL, OMCL tot., LM, caps. medially and posteromedially, disloc. of patella.	TP	TP	TP	TP	TP	
75	F	17	Dancing, abd., m-flex.	ACL tot., SMCL part.(small)	FP	FN	TN	TP	TN	TP
76	M	17	Water -skiing,abd.,e-rot., max. flex.	cf. text.	TP	TP	TP	TP	TP	TP
77	M	35	Handball, abd.,e-rot.,m-flex.	ACL tot.,SMCL part.,DMCL tot.	TP	TP	TP	TP	TP	TP
78	F	41	Badminton,abd.,e-rot., flex.	ACL,SMCL,DMCL tot., LM	TP	FN	TP	TP	TP	TP
79	F	25	Handball, abd.,e-rot.,m-flex.	ACL part., SMCL part., DMCL tot., LM	FN	FN	FN	FN	FN TN$^+$	FN TN$^+$
80	M	46	Traffic, fell off moped, abd., e-rot., flex.	ACL, SMCL, DMCL, OMCL tot.	TP	TP	TP	TP	TP	TP
81	M	17	Football, e-rot., slight flex.	ACL part.(2/3),post.-lat.fibr	FP	FN TN$^+$	TN	TP	TN	FN TN$^+$

Table 9 contd.

82	F	48	Skiing, abd., e-rot., m-flex.	cf. text	TP	FN TN^+	TP	FN TN^+	TP	FN TN^+
83	M	27	Basketball, stopped abruptly on rubber shoes, abd., e-rot., m-flex.	ACL,SMCL, DMCL,OMCL tot.,caps. anteromed. and posteromed. and disloc. of patella	TP	FN	TP	TP	TP	TP
84	M	43	Skiing, abd., e-rot., m-flex.	ACL tot.(subsynovial), SMCL part., DMCL and OMCL tot.	TP	TP	TP	FN	TP	TP
85	F	48	Skiing, abd., e-rot., m-flex.	ACL,SMCL,DMCL tot., MM part.	TP	TP	TP	TP	TP	TP
86	M	22	Traffic, pedestrian, direct frontal trauma to tibia	PCL and LCL tot.	TN	TP	TN	TP	TN	TP
87	M	20	Traffic, fell off moped(unable to state direct. of trauma)	PCL,SMCL,DMCL,OMCL tot.	TP	TP	TP	TP	TP	TP
88	F	52	Fell on staircase on top of left leg, abd.,e-rot., flex.	PCL, DMCL, OMCL tot.+ caps.	TP	TP	TP	TP	TP	TP
89	M	67	Traffic, fell off bicycle,abd. e-rot., m-flex.	PCL,SMCL,DMCL, OMCL tot.+caps.	TP	FN	TP	TP	TP	TP
90	M	15	Fell at a building site while drunk, cannot remember anything (hyperext.?).	PCL tot. and post. caps. tot.	FP	TP	FP	TP	TN	TP

Table 10. (foot rotation ext. = externally, int.=internally)

nr.	91	92	93	94	95	96	97	98	99	100	101	102	103	104
A	0.8	-1.4	-1.3	-0.1	-0.8	0.7	-1.4	3.4	5.2	4.0	7.3	4.2	2.8	0.9
B	0.5	-0.2	1.5	1.5	-0.3	0.6		0.8	-1.0	-0.1		-0.4		-0.7
C_n	0.7	0.0	1.4	-1.8	3.0	1.8	-0.8	0.3	0.1	0.8	1.0	2.7	-1.3	2.2
C_{15° ext.	-1.1				2.7				0.3		5.6			2,5
C_{30° int.	0.7			[C_{30° ext: 0.2										
D_n	0.5	0.1	0.6	0.7	-0.8	-0.3	-1.3	-2.8	0.0	0.8	0.2	1.8	-0.3	-0.6
E_n	1.0	0.1	1.9	-1.1	2.2	1.5	-2.1	-2.5	0.1	1.6	1.2	4.3	-1.6	1.6
F_n	1.3	-2.0	1.5	-1.9	1.8	-1.7	-1.4	-1.5	-0.9	-0.2	-1.4	1.3	1.6	-2.1
F_{15° ext.	-0.8				-1.1				-0.8		0.7			-2.9
F_n 15° ext.	0.0				1.6				-2,1		-1.8			-1.4
F 30° int.	1.2			[F_{30° ext-0.9										
G_n	1.4	0.5	0.3	0.5	-4.5	-4.2	-1.6	-1.6	1.0		-0.7	3.2	-3.0	0.3
H_n 15° ext.	0.6				-7.3				-1.3	-1.6	-2.5			1.5
H_n 30° int.	-2.5			[H_n 30° ext-3.3										

Table 10 continued. (cl.= critical level)

nr.	105	106	107	108	109	110	111	112	113	114	115	116
A	4.5	1.4	2.7	4.4	3.7	1.6	0.5	-0.4	2.2	-0.2	-0.5	5.9
B	1.6	0.7	-0.3	0.1	0.8	0.1	-0.2	1.2	0.2	-0.7	0.7	0.2
C_n	0.9	2.8	3.2	1.6	1.8	0.8	1.9	1.2	3.5	-1.5	2.3	7.4
C_{15° ext.	3.7	4.4	-1.5	1.0	-1.4	-1.2		0.8		-1.1	4.7	6.4
C_{30° ext.	6.6			-0.4 30° int				0.9 30° int				3.1 30° int
D_n	0.6	-1.8	-0.2	1.1	0.9	0.7	-0.5	-0.6	-1.3	-2.6	0.4	0.8
E_n	1.5	1.0	3.0	2.7	2.7	1.5	1.4	0.6	2.2	-4.1	2.6	8.2
F_n	-1.7	-0.1	0.1	3.9	-0.6	-0.5	-1.4	-3.1	-1.9	0.5	-2.7	-2.1
F_{15° ext.	-1.5	1.5	-9.5	1.8	-2.0	0.4		-1.3		0.3	-3.1	-3.0
F_n 15° ext.	-0.4	0.0	-2.5	3.1<cl.	-1.5	-0.3		-2.0		1.0	-1.7	-1.2
F 30° ext.	0.5			-0.1 30° int				-1.6 30° int				-1.3 30° int
G_n	-2.1	-3.4	-0.6	-0.4	1.5	-2.1	0.0	-3.0	-1.8	-4.6	-2.1	2.2
H_n 15° ext.	1.1	-1.7	-1.8	1.3	0.5	-0.7		-0.7		-0.7	1.4	1.8
H_n 30° ext.	0.6											
H_n 30° int.				2.3				-2.4				0.6

Table 11. Trauma, operative findings and evaluation of instability in Cases 91 - 116 (patient-group II).

Case No.	Sex	Age	Type of trauma	Findings at operation	Instability Clinically med.	drawer	Under gen. anaesthesia med.	drawer	Gonylaxometry med.	drawer
91	M	39	Football, add.,(direct. of rot. unknown)	Loose body, chondromalacia, history of lat. meniscectomy.	FP	TN	TN	TN	TN	TN
92	M	22	Football,abd,e-rot,slight flx.	MM (buckett - handle)	FP	FP	TN	TN	TN	TN
93	M	23	Football,abd.,e-rot.,m-flex.	MM (post. horn)	FP	TN	TN	TN	TN	TN
94	M	40	Football, rotation(direct. unknown)	MM (post. horn)	TN	TN	TN	TN	TN	TN
95	M	23	Ice hockey,abd,e-rot,m-flex.	Expl. arthrotomy:normal find.	FP	FP	TN	TN	TN	TN
96	M	21	Ice hockey,abd.,e-rot., flex.	SMCL,DMCL part. (scar tissue)	FP	FP	FP	TN	TN	TN
97	M	34	Badminton, abd., e-rot., flex.	SMCL,DMCL part. (scar tissue)	FP	TN	TN	TN	TN	TN
98	M	28	Football, kick on knee laterally, abd., flex.	SMCL, DMCL tot. (scar tissue)	TP	TN	TP	TN	TP	TN
99	F	21	Football,abd.,e-rot., m-flex.	SMCL tot. (scar tissue)	TP	TN	TP	TN	TP	TN
100	M	27	Football,abd.,e-rot., m-flex.	SMCL (scar tissue)	TP	TN	TP	TN	TP	TN
101	M	19	Fast running(did not notice rot.)	SMCL (scar tissue)	TP	TN	TP	TN	TP	TN
102	M	30	Judo, abd., m-flex.	SMCL,DMCL part. (scar tissue)	TP	TN	TP	TN	TP	TN

Table 11 contd.

103	F	34	Skiing, abd., e-rot., flex.	SMCL, DMCL tot. (scar tissue)	TP	TN	TP	TN	TP	TN
104	M	26	Football, abd., m-flex.	Firm scar tissue at site of MCLs, tiny but taut ACL	FP	TN	FP	FP	TN	TN
105	M	22	Football, opponent fell against patients knee.	SMCL, DMCL tot. (scar tissue) ACL taut with firm scar tissue	P	P	P	P	TP	TN
106	M	15	Ping-pong,abd,e-rot., m-flex.	Firm scar tissue at origin of SMCL and DMCL,disloc.of patella	P	N	P	N	TN	TN
107	M	25	Handball, opponents weight against knee lat.,abd.,e-rot.	DMCL tot.,SMCL part. (thin scar tissue)	P	N	P	N	TP	TN
108	F	20	Skiing, abd., e-rot., m-flex.	SMCL and DMCL with scar tissue	P	N	P	N	TP	TN
109	F	40	Skiing, abd., e-rot., m-flex.	DMCL and DMCL (scar tissue)	P	N	P	N	TP	TN
110	M	22	Handball, e-rot., ext.	ACL part.(post.-lat. fibres intrasynovial)	P	P	N	N	TN	TN
111	M	20	Football,kick on knee lat., abd., e-rot., m-flex.	ACL part. (post.-lat. fibres)	N	P	N	N	TN	TN
112	M	33	Football, kick on knee lat.	ACL part. (post.-lat. fibres)	N	N	N	N	TN	TN
113	M	18	Football, abd, e-rot.,m-flex.	ACL tot. + firm scar tissue in MCLs.	N	P	N	P	TP	TP
114	F	21	Handball, abd., e-rot.	ACL part. (post.-lat. fibres)	N	N	N	N	TN	TN
115	M	32	Football,abd.(unable to state details).	ACL tot., MM and LM removed previously.	N	N	N	P	TN	FN
116	M	28	Football,abd,e-rot,m-flex. to full ext.	ACL,SMCL,DMCL tot.(loose scar tissue)	P	P	P	P	TP	TP

Table 12 Patientgroup 3: nr. 117 - 153.

nr.	117	118	119	120	121	122	123	124	125	126	127	128	129	130 *
A	0.6	3.7	3.1	2.3	0.5	3.3	4.4	0.5	4.6	-0.1	0.6	-0.3	-1.1	pos
B		0.1	0.2	0.3	1.9	-1.o		6.o 0.1	0.3	3.1	%0.7	1.o	%3.1	0.2
C_n	2.1	-1.5	-0.2	-0.2	3.1	0.8	0.5	5.6	2.5	-1.6	2.6	8.6	5.3	6.5
C_{15°ext						-0.2		4.3	0.9	-2.3				
C_{30°int								1.9	2.1	-0.7				
D_n	-0.8	1.2	-0.3	-0.8	1.6	0.5	-0.3	-0.3	1.8	-0.7	-0.7	-1.4	-0.7	1.9
E_n	1.3	-0.3	-0.5	-1.o	4.7	1.3	0.2	5.3	4.3	-2.3	1.9	7.2	4.6	8.3
F_n	-0.5	-1.o	0.9	-3.1	3.1	2.5	0.6	6.o	-1.2	2.8	-4.8	-2.7	-3.9	-4.1
F_{15°ext						1.9		2.3	-1.6	-1.6				
F_n 15°ext						2.7		5.2	0.o	-1.4				
F_{30° ext								-0.1	-0.9	-0.9				
G_n	0.3	1.7	-0.4	-1.1	0.8	-1.o	-1.8	-4.5	-2.5	-2.4	2.5	-1.2	-1.8	-2.5
H_n 15°ext						0.8		2.9	1.6	0.2				

* In case 130 there has earlier been a MCL - injury in the opposite knee; therefore the upper limit of normal knee laxity must be used to evaluate the recently injured knee (instead of the difference between the two knees). The limit is exeeded by 0.6 mm.

Table 12 continued

nr.	131	132	133	134	135	136	137	138	139	140	141	142	143	144
A	0.9	1.8	1.9	1.7	2.4	1.0	0.2	0.8	0.0	1.5	0.6	3.6	-1.0	0.7
B		1.7	0.3		1.1	0.4	0.8			1.0		2.3	1.9	0.7
C_n	5.3	4.9	10.4	5.9	2.1	3.3	3.8	5.6	6.0	9.6	7.2	6.7	5.0	3.3
C_{15°ext				5.8		4.6	3.2			8.9				
C_{30°int										3.1				
D_n	0.0	0.2	2.0	0.6	0.4	-0.9	-1.3	3.3	1.7	-0.7	4.3	0.7	1.4	1.4
E_n	5.3	5.1	12.4	6.5	2.5	2.5	2.5	8.9	7.7	8.9	11.5	6.0	6.4	4.7
F_n	-0.2	-2.2	-3.4	-2.1	-1.0	-1.6	-5.4	-2.2	-4.9	0.7	-3.2	-1.5	0.9	0.5
F_{15°ext						-2.3	-2.4			-0.6				
$F_{n\ 15^\circ}$ext				-1.6		-1.6	-2.7			1.1				
F_{30°int										-1.1				
G_n	-1.5	-1.5	2.9	1.6	0.4	-0.5	-3.4	2.9	-2.2	0.6	0.3	-1.4	0.3	-2.0
$H_{n\ 15^\circ}$ext						0.7	-0.3			2.7				
D_{15°ext										1.5				
G_{15°ext										5.4				

Table 12 continued

nr.	145	146	147	148	149	150	151	152	153	critical level
A	1.6	0.2	-0.3	3.0	1.1	2.1	1.9	0.5	12.2	> 11.6
B	-0.9	-3.1	1.2	1.1	1.6	1.2	1.8	-0.2	17.5	> 16.9
C_n	7.4	3.8	4.7	15.1	5.9	3.7	4.4	3.4	0.2	
C_{15° ext	6.7		3.3	13.5	6.7	7.5				
C_{30° int				7.4		3.0 30° ext				
D_n	-0.2	0.8	-0.1	-0.6	2.2	0.2	-0.3	9.4	6.7	
E_n	7.2	4.6	4.6	14.5	8.1	3.8	4.1	12.8	6.9	
F_n	-0.2	-1.4	1.6	1.3	0.4	-2.1	4.6	0.7	2.3	
F_{15° ext			-0.9	1.1	2.4	-2.9				
$F_{n\ 15^\circ}$ ext	-0.7		2.1	0.9	1.8	2.2				
F_{30° int				-2.7		5.9 30° ext				
G_n	-0.4	2.9	-0.1	-1.2	0.8	-1.3	3.5	0.3	1.7	
$H_{n\ 15^\circ}$ ext			3.0 < 3.4	-0.2	-0.6	0.7				
$H_{n\ 30^\circ}$ int				4.6		-5.3 30° ext				
$G_{n\ 30^\circ}$ int				-3.0						

Table 13. Trauma, operative findings and evaluation of instability in Cases 117 - 153 (patient-group III).

Case					Instability					
					Clinically		Under gen. anaesthesia		Gonylaxometry	
No.	Sex	Age	Type of trauma	Findings at operation	med.	drawer	med.	drawer	med.	drawer
117	M	26	In childhood knee trauma resulting in severe atrophy of thigh At age 22 jump in basket ball, flex.	Chondromalacia of patella	N	P	N	N	TN	TN
118	M	51	Work. acc., load of flagpole on knee, abd., max. flex.	LM (buckett - handle)	N	N	N	N	TP	TN
119	M	22	Football, abd., e-rot., m-flex.	Firm scar tissue at SMCL, DMCL	P	N	N	N	TP	TN
120	M	20	Football, kick on tibia medially, abd., e-rot., ext.	Firm scar tissue at SMCL, DMCL and OMCL, caps. thin post.-med.	P	N	P	N	TP	TN
121	M	31	Football, add., i-rot., m-flex.	History of lat. meniscectomy shortly after trauma, LCL: loose connective tissue at epicond.	N	N	N	N	TN	TN
122	M	28	Handball, many inj., no details of mechanism.	SMCL loose, no fresh injuries.	P	N	P	N	TP	TN
123	M	17	Football, opponent fell against his knee laterally, abd., m-flex.	SMCL lax, fresh disloc. of patella.	P	N	P	N	TP	TN
124	F	44	13 years previously fracture of the head of tibia. On a scooter collision w. car. Osteosynthesis	Depressio of lat. tib. condyle, no inj. to ligg. or menisci.	N	N	N	N	TN	TN

Table 13 contd.

125	M	37	Skiing, abd., e-rot., ext.	SMCL,DMCL,DMCL tot. and caps.	P	P	P	P	TP	TN
126	M	49	Trauma when skating 30 years previously, abd.,i-rot.,flex.	LCL lax, LM	N	N	N	N	TN	TN
127	M	25	Fell on his knee	MM	P	P	N	P	TN	TN
128	M	36	Football,tackling,abd,e-rot,flx	ACL tot.,MM removed 1 year earl.	P	P	P	P	TN	TP
129	M	31	Football, fell from high heading, abd., e-rot., ext.	ACL tot., MM and LM	N	P	N	P	TN	TP
130	M	20	Football, abd.,e-rot.,m-flex.	ACL tot.(lacking),scar tissue at site of MCL's + part. fresh rupt.,fresh inj. to MM	P	P	P	P	TP	TP
131	M	33	Football, fell from high heading, abd., (unable to state further details)	ACL tot., MM removed earlier	P	N	N	P	TN	TP
132	M	26	Football, abd.,e-rot.,m-flex.	ACL tot.	P	P	N	P	TN	TP
133	F	42	Handball,abd.,e-rot.,max.flex.	ACL tot.,MM removed previously	P	P	P	P	TN	TP
134	F	16	Work acc., fell w. heavy burden, abd., flex.	ACL tot.	N	N	N	P	TN	TP
135	M	22	Long jump, tibia arrested in mid-flexion while thigh continued !	ACL tot., LM (block!),SMCL part. (fresh).	P	N	P	N	TP	FN

Table 13 contd.

136	M	16	Traffic, collided w. car on moped + history of bicycle traumas 7 years and 3 months previously	ACL tot.(+ small shearing fracture post. on medial tibial condyle, subluxation)	N	P	N	P	TN	TP
137	M	20	Football, while jumping up kicked by opponents boot postero-laterally on tibia(hyperextention?)	ACL tot.	N	P	N	P	TN	TP
138	M	20	Football,e-rot, slight flex.	ACL part.	N	P	N	P	TN	TP
139	M	18	Playing w. ball 4 years previously.	ACL tot., MM	N	P	N	P	TN	TP
140	M	36	6 years previously football trauma directly from front (goalkeeper)	History of MM- and LM-ectomy 6 years ago,ACL tot., SMCL, DMCL and OMCL: scar tissue.Destruction of cond. cartilage.	N	P	N	P	TN	TP
141	M	25	Handball, abd., flex.	ACL tot., MM	N	P	N	P	TN	TP
142	F	23	Football 2 years previously (unable to describe mechanism)	ACL tot., MM + LM removed previously, MCL's showing loose scar tissue at origin from epicondyle superiorly.	N	P	P	P	TP	TP

Table 13 contd.

143	M	35	Work acc., tractor fell on extrem. (opration primarily only on medial structures)	All ligaments loose after severe quadriceps atrophy + hydrarthrosis cf. text.	N	P	N	P	TN	FP
144	M	27	Football, abd., e-rot., m-flex.	ACL part.(elongated and loose),LM (ant. *horn),MM removed previously.*	N	P	N	P	TN	TP
145	M	20	Football, hyperext.	ACL tot., scar tissue in MCL's	P	P	P	P	TN	TP
146	M	22	Handball, abd., e-rot., flex.	ACL tot. + fresh shearing fracture from medial tubercle	P	N	N	N	TN	TP
147	M	23	Traffic acc. when pillion rider 3 years previously	ACL part., ipsilat. femoral fract. healed with shortening	N	P	N	P	TN	TP
148	M	30	Football, abd., e-rot., 15° flex.	ACL tot., MM removed previously	P	P	P	P	TP	TP
149	M	28	High jumping,(unable to state details of trauma)	ACL tot.	P	P	N	P	TN	TP
150	M	20	Football, twisting trauma w. no contact w. opponent,e-rot,slight flexion.	ACL tot., loose scar tissue at medial epicondyle	P	P	P	P	TP	TP
151	M	24	Judo, pt's foot getting stuck to the floor as he was thrown, abd., e-rot., ext.	ACL tot., LM (buckett handle), MM removed previously	P	P	P	P	TN	TP
152	M	21	Football, *kick on lower leg medially*, abd., flex.	PCL tot.	N	P	N	P	TN	TP
153	M	31	Traffic, car accident, brain concussion (not able to state any details of trauma)	PCL tot., LM	P	P	N	P	TP	TP

Table 14

PV_{pos} and PV_{neg} at knee injuries ≤14 days for anterior drawer and posterior drawer separately.
95% confidence limits in brackets.

anterior drawer	gonylaxometry	clinical test	test in general anaesthesia
PV_{pos}	94% (71 - 100%)	59% (36 - 79%)	83% (59 - 96%)
PV_{neg}	86% (75 - 93%)	79% (68 - 88%)	83% (73 - 91%)
posterior drawer			
PV_{pos}	100% (59 - 100%)	86% (42 - 100%)	100% (63- 100%)
PV_{neg}	99% (93 - 100%)	96% (90 - 99%)	99% (93- 100%)

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SUBJECT INDEX

LIST OF ABBREVIATIONS

Anatomical names:

ACL: anterior cruciate ligament.
PCL: posterior cruciate ligament.
SMCL: superficial medial collateral ligament.
DMCL: deep medial collateral ligament.
OMCL: oblique medial collateral ligament.
LCL: lateral collateral ligament.
MM: medial meniscus.
LM: lateral meniscus

Radiographic, physical, and statistical terms:

a-p radiographs: anteroposterior radiographs, i.e. anteroposterior direction of the beam.

a-p displacement: displacement of the tibia in the anterior or posterior direction relative to the femur.

kp: kilopond, 1 kp = 9.807 N.

kN: kilo-Newton, 1 N: 1 Newton (in the text)

N: number (in tables and formulae).

PV_{pos}: predictive value of a positive test.

PV_{neg}: predictive value of a negative test.

SD: standard deviation.

TN: true negative.

TP: true positive

FN: false negative

FP: false positive

$\bar{x}$: mean.