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STRESS RADIOGRAPHICAL MEASUREMENT OF THE ANTEROPOSTERIOR, MEDIAL AND LATERAL STABILITY OF THE KNEE JOINT

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A hydraulically operated machine for applying well-defined forces to the knee joint is described. The measurement of anteroposterior as well as lateral and medial stability in the knee joint is based upon roentgenograms exposed while the forces are being exerted on the patient. The advantage of the radiological measuring method over methods using external measurements is the elimination of inaccuracies due to displacements of the soft tissues of the limb. The accuracy was evaluated by test/retest examination of 50 healthy subjects. The radiographs were measured at random after cessation of examinations in the gonylaxomèter. The accuracy is ± 1.2 mm for medial/lateral, ± 2.4 mm for drawer sign. Diagnostically the difference between the two knees must exceed 2.0 mm (collateral instability) or 3.1 mm (drawer) to exceed standard values. The standard values for the different ligament laxities are given. The applied force to be used for evaluation of medial/lateral stability is recommended to be 9 kg, and for anteroposterior stability between 20 and 30 kg.

Key words: gonylaxometry; knee ligament stability; drawer sign; collateral knee ligament laxity; radiological measurement

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A method for the exact measurement of ligament stability in the knee joint would be of clinical importance from the diagnostic point of view as well as from the desire to introduce measurement of stability either pre- and postoperatively, or before and after conservative treatment of ligament ruptures in the knee joints. A measurable criterion of assessment would be of definite value in supplementing the patient's subjective assessment as well as the doctor's clinical (subjective) assessment which have so far characterized all analyses of therapeutic results.

The author has designed a machine and revised the method of measurement on the roentgen films in an endeavour to create a method, as exact and reproducible as possible, for measuring not only medial and anterior, but also lateral and posterior instability in the knee joint.

METHOD

Measuring apparatus

The apparatus is called the "gonylaxometer". It operates in conjunction with a roentgen tube suspended in the ceiling and which may be lowered to 60 cm above floor level. It is built up over a horizontal steel trolley (2 × 1 m) with a central swivel (Figure 1). This frame supports a seat for the patient (posteriorly) a control panel (anteriorly) containing the hydraulic mechanism, measuring and operating apparatus as well as slides and pistons to act upon the patient's lower limbs. The seat, floor, and slides are furnished with fasteners.

The steel frame has four swivelling ball wheels which make the machine movable, even in a small space. Centrally there is a swivel base whose axis is midway between the patient's lower legs and knees, through the middle of the sagittal cassette holder (Figure 2). During the radiography the apparatus may be turned on this axis when changing between views of the two knees from the lateral aspect, obviating any need for moving the roentgen tube. The swivel base may be raised and lowered manually.

Between the control panel and the chair the steel frame is lined with aluminium flooring. Its central part, where the patient's feet rest during radiography, with knee joints flexed to 90°, can be raised and lowered to adapt to the leg length of the patient.

Posteriorly on the frame there is an upholstered seat for the patient with a back that may be shifted in the anteroposterior direction in relation to the seat. The seat is raised and lowered by a pedal-operated hydraulic cylinder (dental chair) to allow adjustment for different leg lengths and the right degree of flexion in the knee. The entire seat can be shifted anteroposteriorly. It may be rotated 90° to both sides on a vertical axis. Anteriorly on the seat the thighs are placed into cup-shaped metal supports.

The control panel holds the hydraulic mechanism, consisting of an oil reservoir and an electrically operated pump, three cylinders, a

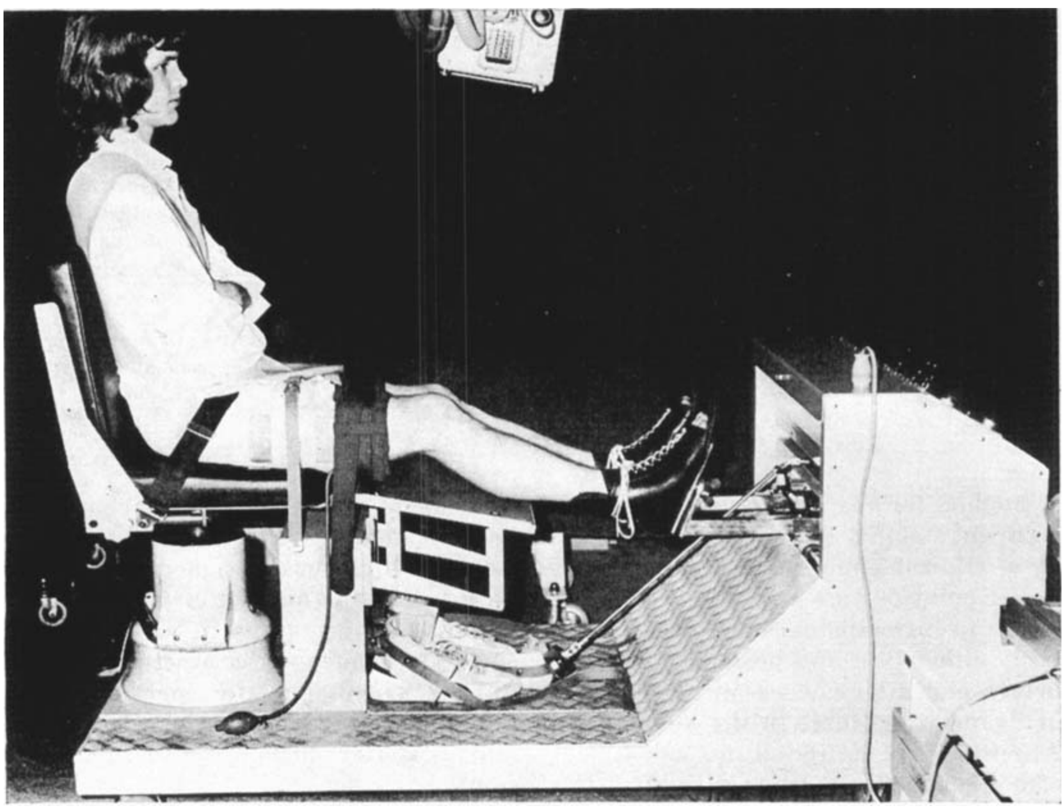

Figure 1. Gonylaxometer, lateral view. Patient in position for measuring medial or lateral instability. Note the cassette holder in position under the patient's knees.

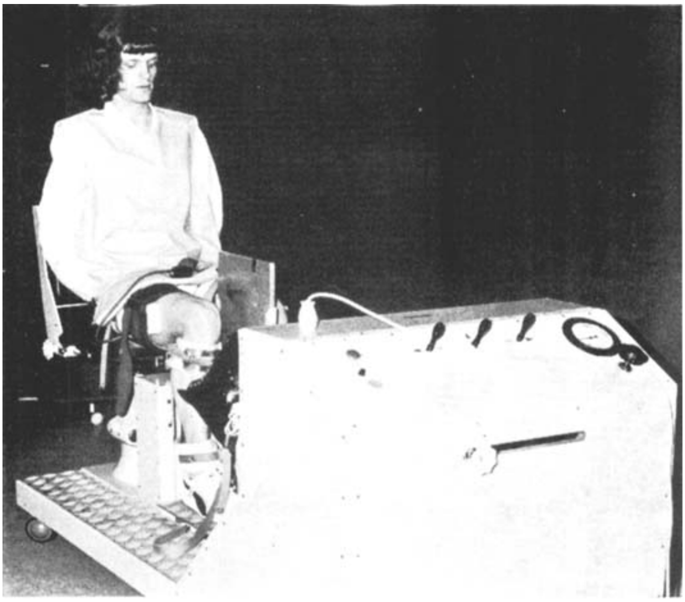

Figure 2. Gonylaxometer. Patient in position for measuring anteroposterior instability. Note sagittal cassette holder between the patient's knees. Floor elevated to adapt to the length of the patient's legs.

reducing valve for rough control and a reducing valve for fine control of the pressure. The valve for rough control of the pressure, which can regulate the pressure between 0 and 200 kg, is sealed after the required force has been fixed, such that it permits pressure variations in a range from 0 to 30 kg. Variations within this range are made by means of the other valve on a manually operated screw connected with a manometer mounted anteriorly on the panel (on the right in Figure 2). The movement of the cylinders is operated by the three handles anteriorly on the panel. The middle handle operates the cylinder which exerts anteroposterior traction and pressure on the head of the tibia in the 90° flexed knee (anterior and posterior drawer sign—Figure 2). The two outermost handles operate the adduction and abduction forces (Figure 1).

The connection to the patient's knees during drawer manoeuvre is via a 65 cm long piston shaft which is fastened to the upper part of the lower leg by a padded canvas cuff. The other two cylinders each operate a slide with ball bearings on steel rails in the panel. Each slide may be shifted medially and laterally and carries fastening gear for the feet, for use in abduction and adduction manoeuvres with a slightly flexed knee joint (160° position). The fastening gear consists of laced boots mounted on a plate on a steel arm which can be shifted by a telescope system to suit varying lower-leg lengths. Padded canvas straps for fastening the proximal part of the thigh, and inflatable cuffs for fastening the more distal part of the thigh are used. The latter two cuff systems are fixed around the metal thigh rests.

To obtain lateral views of the 90° flexed knees, a casette holder (for 24 × 30 cm films) is placed sagittally between the patient's knees (Figure 2). For adduction and abduction exposures a casette holder is placed beneath the knees (for 30 × 40 cm films) (Figure 1).

Procedure

Measurements are made in two positions: (a) In measurements of abduction and adduction laxity (medial and lateral stability, respectively) the legs are flexed 20° at the knee joint. The exposure in the AP projection is made of both knees at the same time. The initial position, in which the knees are unloaded and feel relaxed and the feet are 5° externally rotated in relation to the normal anatomical position, is called "neutral position 160°". (b) In measurements of anteroposterior stability the legs are flexed 90° at the knee joints. The exposure in the lateromedial projection is made of each knee separately. The initial position, with the foot resting on the floor of the machine and with the apex of the patella, the 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 machine, i.e. in the direction of traction.

The first exposure is made in the position

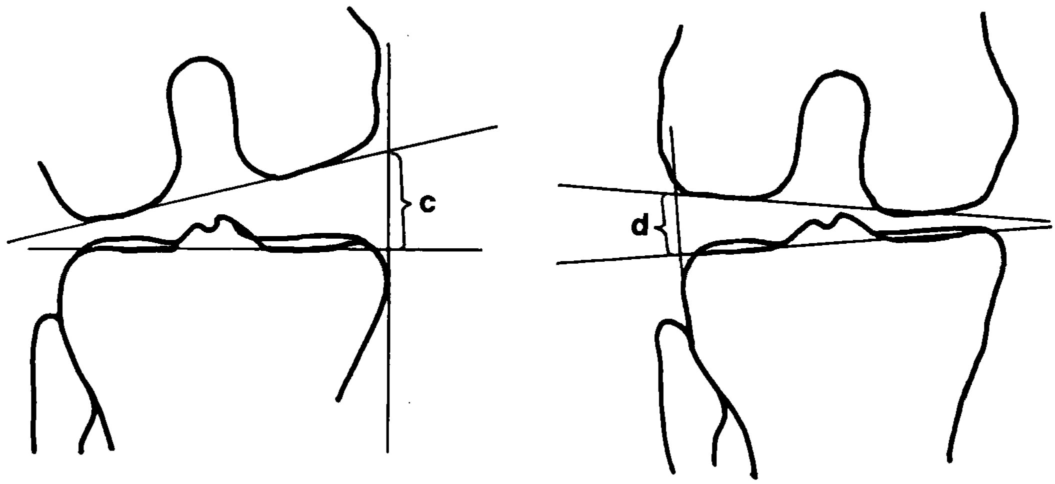

Figure 3. Measurement of medial looseness, distance c, and lateral looseness, d, on the AP radiograph.

160°. With a goniometer a measurement is made from the greater trochanter to the lateral femoral epicondyle (vertex) and lateral malleolus. The large cassette holder, which forms an angle of 10° with the horizontal plane, is mounted. A film is exposed while abducting both lower legs, each being subjected to a force of (normally) 9 kg, followed by a film with simultaneous adduction of both lower legs (force normally 9 kg).

Thereafter the patient is fastened in neutral position 90° and a lateral view is exposed of the unloaded knee joint. The roentgen tube is adjusted to be at right angles to the now sagittally placed film cassette holder midway between the patient's knees. The direction of the beam is lateromedial. The thigh cuffs are inflated, prior to each exposure, to about 300–350 mmHg, but are deflated between each exposure to allow circulation in the lower limbs.

When exposures of the other knee are started, the gonylaxometer is turned 180° on its central swivel foot, so that the roentgen tube need not be moved. All forces upon the joint are kept below the pain limit in healthy subjects (i.e. within the above-mentioned forces) to avoid damage to the ligaments. Control measurements of the hydraulic force (checking the manometer scale) are done for each 10 subjects. The procedure takes 1 hour per subject.

Measuring technique on the film

On the roentgen films the distances between the bony components of the joint are measured. Rupture of a ligament manifests itself on the film as an increased distance between the various bones. Comparison may be made with the patient's uninvolved knee or with standard values (see below).

The measurements on the radiographs are carried out by means of a Vernier scale along certain lines, the radiographs being placed on a horizontal viewing-box; the distances measured are illustrated in Figures 3 to 5. Distance c on Figure 3 represents medial stability (or looseness), distance d lateral stability. Distance e (Figure 4) is measured on a baseline through the highest anterior and posterior points of the medial tibial condyle cut off between the tangents of the anterior point of the lateral femoral condyle and the posterior point of the lateral tibial condyle (exactly where the posterior arch of the lateral tibial intercondylar tubercle joins the posterior contour of this condyle). Distance f is the analogous distance cut off on the same baseline by analogous tangents of the medial femoral and tibial condyles. While c and d represent distances measured when stress is applied to the knee, e and f are measured on the lateral radiograph when the knee is not acted upon by any force. When measured on a radiograph exposed during traction on the upper part of the tibia, the corresponding distances are called g when connected with the lateral condyles and h when connected with the medial ones. When exposed during application of a pushing force, the analogous distances are called i and j (greater than e and f). As is seen from Figure 5, the anterior displacement of the lateral tibial condyle can be expressed as (e–g), and analogously the anterior displacement of the medial tibial condyle can be expressed as (f–h). Posterior displacement of the lateral condyle

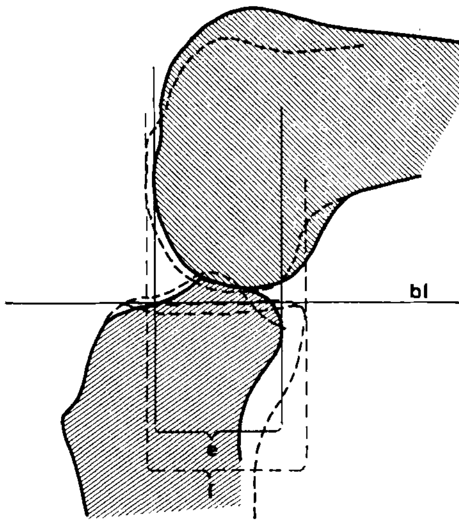

Figure 4. Measurements on the lateral radiograph in neutral, 90° flexed position. No forces applied. Unbroken lines: Lateral condyles. Broken lines: medial condyles. bl: base line. e: distance cut off on bl by "tangents" to anterior point of lateral femoral condyle and posterior point of lateral tibial condyle. f: distance cut off on bl by tangents to the medial condyles. The lateral tibial condyle is identified by the form of the lateral tubercle (two arches, an anterior and a lower posterior).

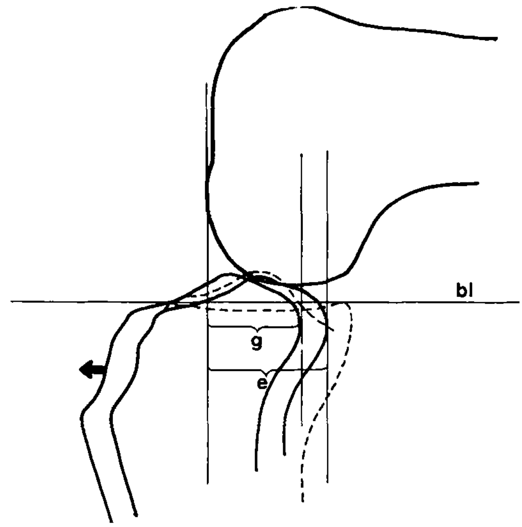

Figure 5. The movement of the lateral tibial condyle during traction (anterior drawer). Because of the anterior movement of the posterior point and its tangent the distance g, measured during traction is smaller than distance e, measured in the neutral position. The anterior movement of the lateral tibial condyle is: e–g.

becomes (i–e), and of the medial condyle (j–f). Total anterior displacement is expressed as the mean of the displacements of the two condyles $\frac{(e-g)+(f-h)}{2}$.

Posterior displacement $= \frac{(i-e)+(j-f)}{2}$.

This measuring procedure takes half an hour.

Material of healthy controls

Fifty normal subjects, 25 females and 25 males, were examined and the results of the measurements were used for assessing the accuracy of the method from one measurement to the other on the same subject. These 50 persons had never had knee injuries, diseases, or complaints, and their knees were found to be normal on clinical examination. Persons with a valgus deformity of the knee joints exceeding 10° were excluded, as Thestrup Andersen (1955), in a material of persons with sound knees, found the variation of the angle between the femur and the tibia in the frontal plane to be between 0 and 10°. The length of the lower extremity was measured from the point of the greater trochanter to the point of the fibular malleolus. Persons having a difference of more than 1½ cm in the lengths of the two legs were excluded. All roentgenograms were normal. The age and sex distribution is shown in Table 1.

A test/retest procedure was used: After the measurement had been completed, the subject was released from the machine and walked

Table 1. Age and sex distribution.

Age	Women			Men		
	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

about in the room while the movable parts of the machine were returned to zero position. Thereafter, the subject underwent another measuring procedure. Each envelope containing one set of roentgenograms of this subject's knees was marked by a 5-digit code number. Thereafter, the subject's name and code numbers were filed in a sealed envelope. Measurement of the above-mentioned parameters on the roentgenograms were performed in randomized sequence and not until all subjects had undergone this test/retest procedure. After the measurements had been performed, the code with the name and 5-digit code numbers was broken, so that the duplicate examinations could be compared. No measurements were excluded from the analysis.

FINDINGS

Thirty-four persons (Group I, Table 1), 17 males and 17 females, were investigated by an abduction and adduction force of 9 kg and a pressure and traction force of 20 kg. A smaller group (Group II, Table 1) of eight females and eight males was investigated using other forces, in particular an abduction force of 18 kg and a traction force of 13 kg.

The accuracy of the measurement was assessed on the basis of the mutual difference between the duplicate determinations (the difference is designated d): SD' = standard deviation of difference $= \frac{1}{2} N \Sigma d^2$ (Therkelsen 1968). In the measurements of lateral and medial laxity, parameters c and d, the $SD'_c = 0.56$ mm, $SD'_d = 0.59$ mm, were calculated on the basis of measurements on 34 persons (force 9 kg). The inaccuracy of each measurement is then $\pm t_{2\alpha} \times SD'$, i.e. less than $\pm$ 1.2 mm. For anterior displacement (parameter e–g lateral tibial condyle and f–h medial tibial condyle) and posterior displacement (i–e lateral tibial condyle and j–f medial tibial condyle) and total anteroposterior displacement (i–g and j–h, respectively) the inaccuracy of measurement (determined with 95 per cent limits of confidence) was less than $\pm$ 2.4 mm.

When measuring a parameter in a person it can then be expected that a subsequent measurement of the same parameter in the same person (without intervening injury or treatment) will be within these limits. Thus, if a reduction of instability after operation or other treatment is to be demonstrated, it must be demanded at follow-up that the demonstrated reduction of the instability exceeds 1.2 mm. As far as the drawer sign is concerned, the reduction must exceed 2.4 mm.

If the abduction force of 18 kg is used in measuring medial stability (investigated in eight females and eight males) which the subjects feel as an uncomfortably strong force, the inaccuracy of the measurement is twice as great ($\pm$ 2.2 mm). In the same subjects the accuracy of the measurement with a traction force of 13 kg in the anterior direction (drawer sign) is $\pm$ 2.4 mm, i.e. of the same magnitude as when using a traction force of 20 kg. In four of the male subjects a force of 30 kg demonstrated the same accuracy.

The standard values, defined as $\bar{x} \pm t_{2\alpha} \times SD$ of the various parameters, calculated on the basis of the measurements on the 34 persons (abduction and adduction force 9 kg and traction and pressure force 20 kg) are shown in Table 2. There is no difference between the standard values for the right and left leg. The table shows that the variation between subjects is very marked. Therefore, the difference between the measurements for the right and left leg on the same person was analysed and the standard values of this difference calculated. As far as abduction and adduction instability is concerned the difference between the two sides was normally less than 2.0 mm. With regard to anterior and posterior instability as well as total anteroposterior instability, this difference was less than 3.1 mm, for both condyles. Thus, lacking a preoperative measurement, the affected and the sound

Table 2. Standard values of knee stability in healthy subjects: $\bar{x}_n \pm t_{2}\alpha \times SD$. 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) $\bar{x} \pm t_{2}\alpha \times SD$	SD	Upper limit (right-left) $\bar{x} + t_{2}\alpha \times SD$	SD
Medial=valgus=abduction	c	men : 5.8–12.1	1.3	men & women:	
		women : 5.2–9.8	1.2	1.4	0.4
Lateral=varus=adduction	d	both sexes: 9.2–16.9	1.9	2.0	0.6
Anterior displacement:					
lateral condyle	e–g	both sexes: 0.2–8.8	2.1	3.1	1.0
medial condyle	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 condyle	i–e	both sexes: 0.2–6.0	1.4	2.9	0.8
medial condyle	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 AP displacement:					
lateral condyle	i–g	both sexes: 3.1–12.0	2.2	3.1	0.9
medial condyle	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

leg may be compared postoperatively. A diagnostic evaluation before treatment can also best be done on the basis of the difference between the various parameters of the right and the left knee. If both knee joints are injured, the standard values of the parameter concerned must be used, but the wide biological variation of this value gives a less reliable diagnosis.

There is a statistically significant difference between women and men only in the case of parameter c ($P = 0.01$). For other parameters there is no significant difference between the sexes (neither for $P = 0.01$ nor for $P = 0.05$). Table 2, therefore, lists the standard values for women as well as for men only for parameter c and not for the other parameters. The values listed in the Table are the distances measured on the roentgenograms and are thus not corrected for the magnification (which is 1.1 or 10 per cent).

In addition, four subjects, two men and two women, characterized by hyperlavity of the joints (knee extension greater than 195°, elbow extension greater than 190°, valgus deformity in the knees greater than 10° as well as hypermobility in the thumb) were examined. All the above mentioned gonylaxometer parameters and differences were within the normal limits (found for the 50 normal subjects).

DISCUSSION

The advantage of the radiological measuring method over those in which an instrument is placed on the outside of the lower limb is that it presents directly a distance between the bones of the joint, as a measure of the magnitude of instability. As the ligaments of the knee joint join bone to bone, the magnitude of this distance depends directly upon the state of the ligaments. The unknown inaccuracy in measurement introduced by soft tissue displacement is avoided. This inaccuracy also applies to Sprague & Asprey's photographic method (1965) in which marks are placed on the skin to indicate the direction of lines used in the measurement on the film. This inaccuracy can be read from the relatively low correlation coefficient which does not show a particularly good conformity between repeated measurements on the same persons ($r = 0.42$ to 0.82).

These displacements in the soft tissues cannot be eliminated by fixation. In the author's machine the patient's hip region is fixed in the seat by a strap, and both thighs are fixed by a canvas strap as well as a broad cuff inflated to a pressure of about 350 mmHg. In measuring, for example, anteroposterior instability with the knee flexed 90°, the sighting point marked on the lateral aspect of the knee shifts, nevertheless, 2–3 cm between the two extreme positions, indicating a displacement of the soft tissues of the thigh. This error is eliminated on the roentgen film.

An instrument designed by Klein (1962), constructed to measure medial and lateral instability in the extended or straight position of the leg, is said to be able to demonstrate isolated ruptures of the collateral ligaments of the knee. This is a technical as well as clinical error. Lateral or medial instability in the extended position is possible only in the case of rupture of a collateral ligament plus the anterolateral cruciate ligament or both cruciate ligaments plus the posterior capsule of the joint—or in cases with loss of substance in the condyles (Hallén & Lindahl 1965, Palmer 1938). Accordingly, Klein's instrument can demonstrate only extensive, combined injuries. For the same reason, abduction and adduction instability is measured in the gonylaxometer with the leg in the 160° position in which instability due to an isolated injury to the collateral ligaments can be demonstrated, as the other structures are relaxed. The 2.3° to 2.6° abduction and adduction instability measured by Klein in extended normal knees may easily have been due solely to displacements of the soft tissues.

The advantage of the hydraulic system acting upon the knee joint is the possibility of reproducing an examination of the same patient using exactly the same force. Moreover, the machine ensures the same radiological projection.

The author disagrees with Kennedy & Fowler (1971) regarding the landmarks they use for identifying the tibial and femoral condyles. In a subsequent paper this will be demonstrated. Confusion regarding the position of the posterior contours of the tibial condyles may explain why the anterior displacement found on traction in Kennedy & Fowler's material of normal knees was different from the present findings. Kennedy & Fowler found anterior displacement to be the same for both tibial condyles, whereas in the present material there was a considerably greater anterior mobility of the lateral tibial condyle in normal knee joints: up to 9 mm as compared with Kennedy & Fowler's 5 mm for both tibial condyles (cf. Table 2). In the present study the anterior displacement of the medial condyle was found to be 5.5 mm.

An abduction and adduction force of 9 kg has proved to be the most suitable, as it is of sufficient strength and is not too uncomfortable for the patients. It, therefore, affords the most accurate measurements, as pain-conditioned contractions of the muscles are avoided. In examinations for the drawer sign a force of 20 to 30 kg is optimal.

The measurement accuracy of the machine (± 1.2 mm for lateral and medial instability, ± 2.4 mm for measuring anteroposterior instability) has proved to be quite adequate for the assessment of results of operations and other treatment, as it cannot be expected, in a biological material, to improve instabilities in the knee joint of a magnitude as slight as 1–2 mm by operation, for example. Moreover, an instability which troubles the patient is empirically of a considerably greater magnitude.

For diagnostic use, in acute injury to the knee as well as in chronic instability following prior, untreated injuries, the upper limits stated for the normal difference between the two knees (rather than the fairly wide standard values) have also proved to be very satisfactory. The difference between the two knee joints has to exceed 2.0 mm to fall outside the standard values for lateral and medial instability and 3.1 mm for the drawer sign. A comprehensive pathological material, measured and operated on, is being analysed at present.

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