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Active knee motion after cruciate ligament rupture

Stereoradiography

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In 10 patients with an old injury of the anterior cruciate ligament, the three-dimensional movements of the knee joint were studied when the patients flexed their knees. Tibial motions were recorded using roentgen stereophotogrammetric analysis. Internal rotation and adduction of the tibia were reduced in the injured knees when compared with the intact knees; during flexion of the knee joint, the tibial intercondylar eminence occupied a more lateral and posterior position on the injured side. Our results may indicate that the knee joint is continuously exposed to abnormal stresses when the anterior cruciate ligament is torn.

Biomechanical tests (Jacobsen 1981, Markolf et al. 1984) have been developed to demonstrate the effects of anterior cruciate insufficiency on knee joint stability. Optoelectronic systems (Andriacchi et al. 1985), high speed photography (Tibone et al. 1986), or electrogoniometers (Marans et al. 1986) have been used to record tibiofemoral motions during gait, but these methods do not permit a detailed three-dimensional analysis.

We used a modification of roentgen stereophotogrammetric analysis (RSA) designed to study joint motions performed by the patient himself (Selvik 1974), measuring tibiofemoral movements during active flexion of the knee in patients with an old injury of the anterior cruciate ligament.

Patients and methods

Patients. Ten patients (9 men, 1 woman) with a mean age of 27 years were examined (Table I). All of them had on an average 2 years previously sustained an injury to the knee and had residual symptoms of instability. Arthroscopy verified the diagnosis. All the patients had a torn anterior cruciate ligament.

Roentgen stereophotogrammetric examinations. Three-to-five 0.8-mm tantalum balls were implanted in the distal femur and the proximal tibia. Three to 6 weeks later, the roentgen stereophotogrammetric examination was performed.

Two film exchangers designed for 24 × 30-cm films were used. Before examination of the patient, a calibration cage (Kärrholm et al. 1982) was radiographed together with two reference plates. These plates contained tantalum balls and were attached to the grids in front of each film exchanger. The cage was removed and the knee was examined in a standardized relaxed position. In this position the knee was extended to 0° with the tibia and femur parallel to the longitudinal axis of the laboratory coordinate system, the posterior cortex of the femoral condyles parallel to the transverse axis and perpendicular to the longitudinal axis, and the sagittal axis perpendicular to both the transverse and longitudinal axes.

At the examination of the tibiofemoral motions during knee flexion (serial radiographs), the patients were lying prone with a load of 15 N attached to the ankle (Figure 1). The trunk and the gonads were shielded with a lead apron. The patient was instructed to flex the knee at a constant speed, and performed 5 to 10 trials of knee flexion before the serial radiographs were

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Table 1. Clinical summary of 10 patients with an old injury to the anterior cruciate ligament.

Sex	Age	Associated injuries[1]	Previous treatment[2]	Giving-way episodes	Clinical instability		
					Lachman[3]	Anterior[3]	Pivot-shift
M	31	ML, MM	Suture MM	+	+++	+++	+
M	22	MM	PMME	+	++	++	+
M	25	LM	–	+	++	+++	+
M	27	MM	PMME	+	++	+++	+
M	21	MM, LM	PMME	+	+++	+++	+
M	32	MM, LM	PMME, PLME	+	++	+++	+
M	26	LM	–	+	+++	+++	+
M	40	–	–	+	++	++	+
M	22	MM	–	+	++	+++	(+)
F	20	–	–	+	++	++	+

[1] ML Medial collateral ligament.
MM Medial meniscus.
LM Lateral meniscus.
[2] PMME Partial medial meniscectomy.
PLME Partial lateral meniscectomy.
[3] + 0–5 mm.
++ 5–10 mm.
+++ > 10 mm.

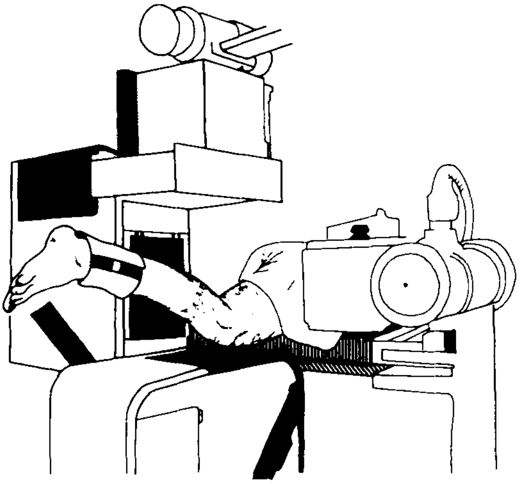

Figure 1. The radiographic set-up at the examination. Two x-ray tubes were used for simultaneous exposure. One film exchanger was placed below and one on the medial or lateral side of the knee. One reference plate supplied with tantalum balls was fastened to the grid of each film exchanger. The weight (15 N) was placed at the level of the ankle of the patient.

exposed. Depending on the most comfortable speed of flexion chosen by the patient, the frame rate was set to 2 or 4 per second.

An average of 10 pairs of radiographs were obtained for each series including the reference position. The absorbed dose by the skin was calculated to be 0.2–0.3 mGy for each AP and lateral projection.

Evaluation of radiographs. The initial exposure of the calibration cage was used to calculate the position of the two roentgen foci in relation to the laboratory coordinate system and the projections of the tantalum markers in the reference plates. At the subsequent exposures of the patient, the film coordinates of the markers of the patient were transformed to the cage system using the images of the tantalum balls in the reference plates.

The two tips of the tibial intercondylar eminence were marked on the radiographs of the reference position (extended relaxed knee) and the three-dimensional coordinates of these two points were calculated. By using the three-dimensional location of the tantalum markers in the proximal tibia at the subsequent positions during knee flexion, the coordinates of the two tips of the tibial intercondylar eminence were calculated at all positions of the knee using point transfer in KINEMA (Tjörnstrand et al. 1981).

At the calculations of tibial rotations and translations, the tantalum balls in the distal femur were used as the reference segment. The average translations of both tips of the tibial intercondylar eminence, corresponding to the tibial insertion of the anterior cruciate ligament, represented the tibial translations.

Reproducibility. The precision of the data measured was evaluated by repeated examinations of three knees. The standard deviations of rotations were 0.8 and 0.2° (rotations about longitudinal and sagittal axes) and of translations 0.2, 0.1, and 0.5 mm (translations along transverse, longitudinal, and sagittal axes) when measured at 10° intervals of knee flexion.

Rotations about the transverse axis. The maximum observed knee flexion was 65° and the most pronounced knee extension −5°. Further flexion of the knee could not be performed due to limited space between the film exchangers and the x-ray tubes.

Inaccurate timing between the film exchangers and the movements of the knees resulted in a slight loss of data at the beginning or the end of the series of roentgenograms. Average values based on at least three observations are presented in Figures 2–6.

Evaluation of the results. In each patient an average of nine measurements were obtained from each series of radiographs. Because the speed of knee flexion varied between the patients, and because the measurements could not be started at a standardized amount of active extension, data were not collected at exactly the same amount of knee flexion. To obtain measurements corresponding to fixed intervals of knee flexion, the rotations about the longitudinal and sagittal axes and the translations were plotted and interpolated at intervals of 5° of knee flexion.

At the statistical analysis the differences between the injured and intact knees were calculated using only those intervals of knee flexion that were in common for all patients (15–40° of flexion). The Student's *t*-test was used to evaluate if the calculated values differed from zero.

Results

Rotations about the longitudinal axis (Figure 2). In all the patients, flexion of the knee was associated with simultaneous rotations about the longitudinal axis. Eight of 10 intact knees displayed an internal rotation that became greater with increasing knee flexion. Five injured knees showed a similar pattern, whereas five showed more or less pronounced external rotation.

In 9 patients the injured knee was more externally rotated from 10° of flexion to the maximum flexion observed. On an average, the intact knees displayed an increased internal rotation between 15 and 40° of flexion of 2.6° ($P < 0.05$).

Rotations about the sagittal axis (Figure 3). Most knees (nine intact, seven injured) manifested an adduction of the tibia when the knee was flexed. When comparing intact and injured knees, this movement into varus was about equal near to the extended position; but as the flexion proceeded, the intact knees displayed a more pronounced adduction. The average difference was 1–2° ($P < 0.05$).

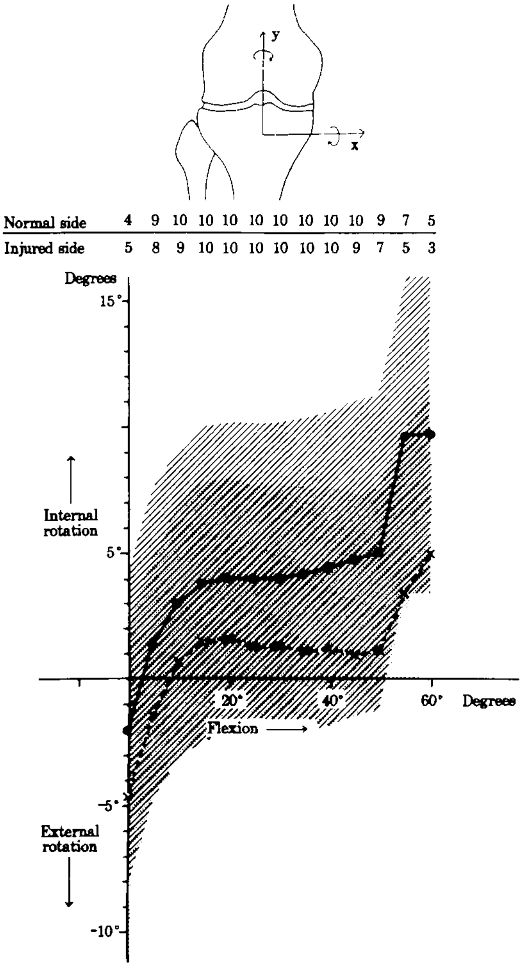

Figure 2. Tibial rotations about the longitudinal axis (internal-external rotation) occurring when the patients flexed their knees. Solid line represents average values of intact knees. Dotted line represents average values of contralateral anterior cruciate ligament-deficient knees. Lined and shaded areas represent ±1 pooled SD on the intact and injured side, respectively. Numbers of observations at each 5° interval of flexion at the top.

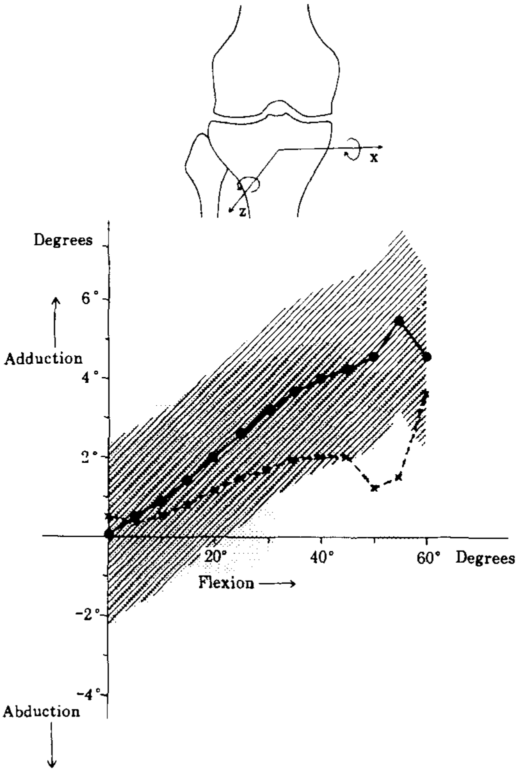

Figure 3. Tibial rotations about the sagittal axis (adduction-abduction) during active flexion of the knee. Number of observations and symbols according to Figure 2.

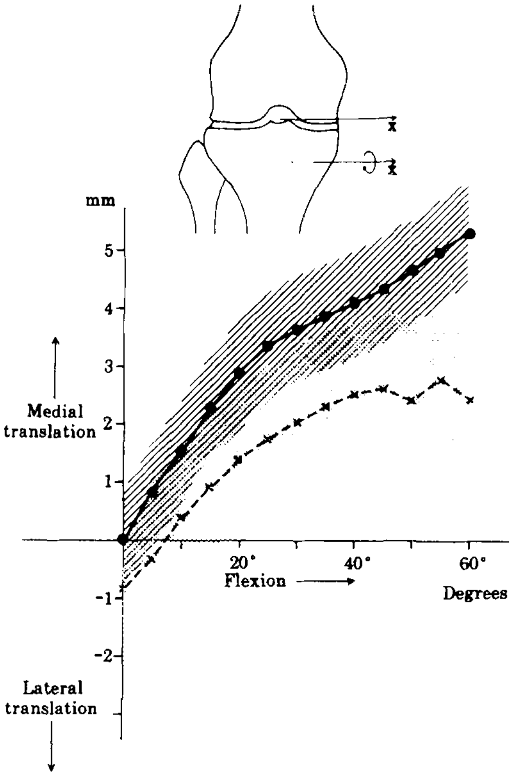

Figure 4. Translations of the tibial intercondylar eminence along the transverse axis (medially-laterally) at active flexion of the knee. Number of observations and symbols according to Figure 2.

Translations of the tibial intercondylar eminence along the transverse axis (Figure 4). During flexion the tibial insertion of the anterior cruciate ligament displaced medially in all but one injured knee. In all the patients, insufficiency of the ligament implied a more lateral position of the tibial intercondylar eminence at flexion of the knee (mean difference 1.6 mm, $P < 0.001$).

Translations of the tibial intercondylar eminence along the longitudinal axis (Figure 5). Flexion of the knee resulted in an increasing average proximal displacement of the tibial intercondylar eminence. At 45° of flexion the points of measurement had, on an average, moved slightly more than 4 mm upwards. No difference between the intact and injured sides was found.

Translations of the tibial intercondylar eminence along the sagittal axis (Figure 6). The tibial intercondylar eminence displaced posteriorly during flexion of the knee. At 55° of flexion the intact knees reached a value of about 16 mm and the injured ones 19 mm. The average difference was 1.7 mm (15 to 40° of flexion, $P < 0.05$).

Discussion

Smillie (1978) believed that the screw-home movement of the knee joint was the key to injury of the anterior cruciate ligament. Frankel et al. (1971) found that intraarticular injuries to the knee might interfere with this mechanism, whereas Hallén and Lindahl (1966) could not confirm the presence of a normal passive screw-home mechanism and questioned its significance. In our study, all the patients with available observations from the zero position or slight hyperextension manifested an initial internal rotation when the knee was flexed, indicating the presence of a screw-home phenomenon also in the

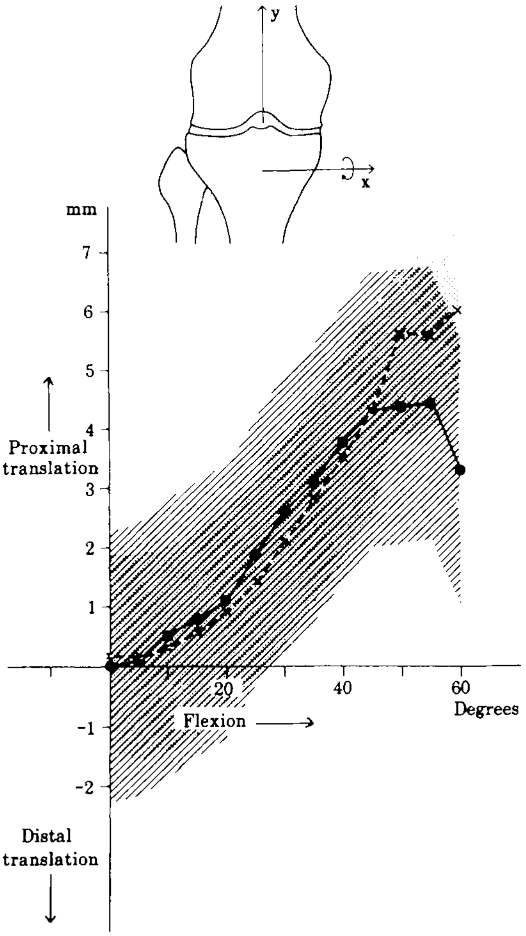

Figure 5. Translations of the tibial intercondylar eminence along the longitudinal axis (proximally-distally) during active flexion of the knee. Number of observations and symbols according to Figure 2.

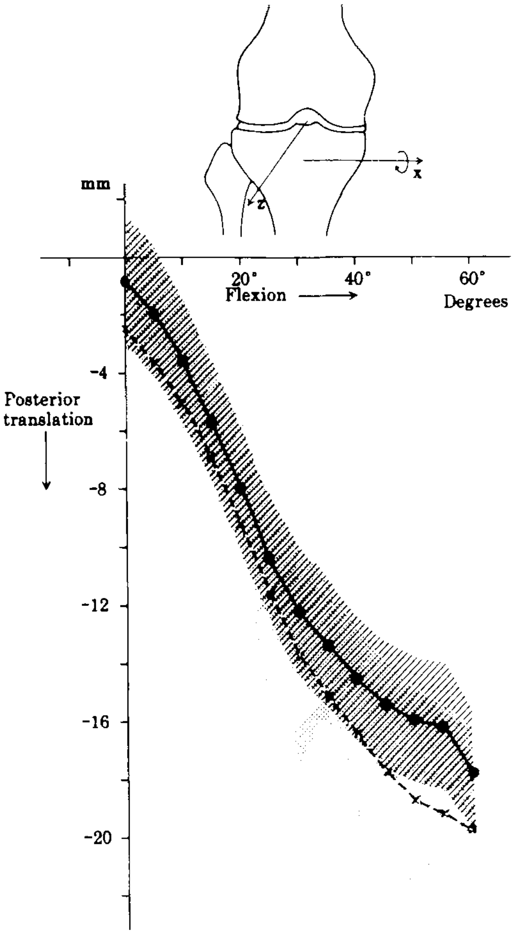

Figure 6. Translations of the tibial intercondylar eminence along the sagittal axis (anteriorly-posteriorly) during active flexion of the knee. Number of observations and symbols according to Figure 2.

injured knees, but in a more externally rotated position.

The slope of the graphs representing the mean values of internal rotation was rather equal during the initial 20° of flexion (Figure 2). At further flexion above 20°, the injured knees seemed to lose further internal rotation in relation to the intact knees. Increased external rotation at passive knee flexion at about 30° has previously been documented in the injured knee with the patient in the supine position (Kärrholm et al. 1987), indicating that this phenomenon is not only an effect of altered muscular balance, but rather an effect of an absence of tension in the anterior cruciate ligament. The abnormal rotations about the longitudinal and the sagittal axes indicate a more multiplanar instability than was previously known.

Measurement of tibial translations at the level of the tibial intercondylar eminence has been recommended (Grood and Suntay 1983), but has not previously been performed during active knee flexion. This position is close to the screw axis of the associated longitudinal rotations; and if a more eccentric position had been chosen, the influence of simultaneous rotations would be larger and more unpredictable. Marans et al. (1986) used electrogoniometers fixed to the skin for measurements of tibial rotations and translations in the normal and ligament-deficient knee during gait. No differences of tibial rotations were found, whereas injury increased the anterior-posterior mobility of the knee. We recorded abnormal tibial translations in the injured knees, more pronounced when measured along the transverse than along the sagittal axis. Increased posterior displacement of the center of the tibial plateau may be an effect of increased external rotation and a medial shift of the center of axial rotation (Lipke et al. 1981) or increased tension of the flexor musculature to stabilize the knee. The instability along the sagittal axis would probably be directed anteriorly if measured during knee extension.

Ligamentous injuries of the knee may cause secondary arthrosis especially if a meniscectomy has been performed (Balkfors 1982, McDaniel and Dameron 1983). According to Fetto and Marshall (1979), there is an increasing risk of degenerative changes arising depending on the severity of the instability. Alteration of tibiofemoral motions during movements of the knee may imply that the joint area, more or less constantly, will be exposed to increased or abnormal compression and shear forces (Frankel and Nordin 1980), which may be of etiologic importance in the development of secondary arthrosis.

Restoration of normal knee joint kinematics is one goal of knee ligament surgery (James 1983). Some extraarticular procedures (Ellison 1979) may induce a further external rotation of the tibia by increasing the tension of the iliotibial band. In addition, insufficiency of the anterior ligament causes a complex pattern of instabilities when the knee is stressed by translatory or rotatory forces (Noyes et al. 1983, Markolf et al. 1984, Kärrholm et al. 1987). If a recontructive procedure has to be performed, it seems more appropriate to use an intraarticular repair (Marshall et al. 1979), enabling a more anatomic position of the graft (Odensten and Gillquist 1985) and more normal knee-joint kinematics.

In conclusion, insufficiency of the anterior cruciate ligament does not only entail altered laxity and stiffness of the knee joint, as measured in instrumented tests (Noyes at al. 1983, Markolf et al. 1984), but changes also the tibiofemoral pattern of mobility when the knee joint is flexed.

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