Kinematics after tear in the anterior cruciate ligament

Dynamic bilateral radiostereometric studies in 11 patients

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ABSTRACT – We studied the kinematics of both knees using radiostereometry in 11 patients with unilateral injury of the anterior cruciate ligament and normal contralateral knee. Continuous radiostereometric exposures at a speed of 2–4 exposures a second were performed, when the patients ascended an 8 cm high platform.

The tibial center was more dorsally displaced and the tibia more externally rotated on the injured side. This increasing external tibial rotation was associated with increased anterior displacement of the lateral femoral condyle. The latter also displayed less anterior-posterior translations during continuous extension. The anterior-posterior translation of the medial condyle was about the same as on the uninjured side.

Changes in the kinematics of the knee joint due to rupture of the anterior cruciate ligament can result in an abnormal joint load, which may increase the risk of damage to the cartilage and the menisci.

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Changes in the kinematics of the knee after anterior cruciate ligament (ACL) injuries have been discussed as an important factor in the development of secondary arthrosis (Kannus and Järvinen 1989, Roos et al. 1995). Laboratory studies of cadaver knees have frequently been used to evaluate the effect of ACL injuries on knee kinematics (Nielsen and Helmig 1985, Rong and Wang 1987, Noyes et al. 1989, Östgaard et al. 1991, Lane et al. 1994, Torzilli et al. 1994). These methods may not mimic the clinical situation sufficiently well because the combined action of the musculature and gravity is difficult to reproduce. There are also limitations in in-vivo measurements. Soft-tissue movements will increase inaccuracies in electrogoniometric measurements (Granberry et al. 1990). Invasive methods using of intracortical pins (Lafortune et al. 1994, Reinschmidt et al. 1997) overcome this problem, but they can only be applied to limited patient populations. The insertion of skeletal landmarks, as in radiostereometric analysis (RSA), also permits the detailed delineation of small changes in the kinematics of the knee (Kärrholm 1989). This method has been used with increasing frequency to study the kinematics of joint motion in vitro and in vivo (Kärrholm et al. 1988a, b, 1989, Jonsson et al. 1989, Fridén et al. 1992, Jonsson et al. 1993, Jonsson and Kärrholm 1994, Jorn et al. 1997, 1998). However, none of these studies has included measurements of knee kinematics during continuous active extension and simultaneous weight bearing, since no appropriate method of examination has been available.

We studied the kinematics of the ACL-injured knee during continuous extension. Evaluation models permitting studies of the relative tibial or femoral motions were used to compare the injured and intact sides.

Patients and methods

11 patients (median age 24 (17–41) years, 8 men) with a chronic rupture of the ACL were studied at a median 4.5 (1.5–12) months after the injury. All patients complained of instability. None of them had previously been subjected to knee surgery. They had positive Lachman and Pivot shift tests. At arthroscopy of the injured side, 4–5 tantalum markers (Ø = 0.8 mm) were inserted percutaneously into the distal femur and proximal tibia on

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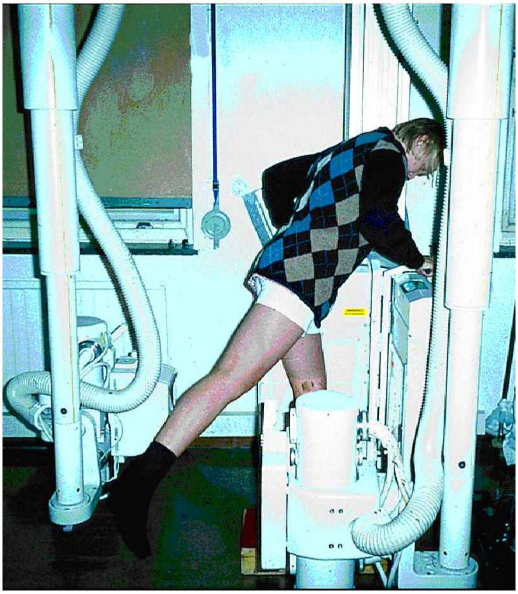

Figure 1. Radiostereometric film-exchanger examination. The patient is performing a step-up.

the injured and contralateral intact sides. Lateral meniscal tears were treated with partial resection in 4 patients.

The patients were examined in a radiographic laboratory specifically designed to perform RSA examinations of joint kinematics during active motion. Two ceiling-mounted radiographic tubes, connected to separate generators, were used to obtain simultaneous exposures. Two film exchangers were mounted on a stand, which allowed adjustment upwards/downwards and in the transverse direction. In addition, the film exchangers could be angled stepwise in relation to each another. In this study, the angle was consistently set at 90° (Figure 1).

Before examination of active motions, the knee was exposed in the straight position (0° of flexion/extension), with the patient supine. All subsequent examinations were related to this straight reference position. The latter position was chosen to facilitate comparisons with previous studies (Kärrholm et al. 1988a,b, 1989, Jonsson et al. 1989, Jonsson and Kärrholm 1994). Furthermore, we found it difficult to standardize the alignment of the knee to the laboratory coordinate system in the weight-bearing position. At this examination and on the lateral view, the longitudinal axis of the tibia and femur should be as parallel to each other as possible and also parallel with the longitudinal axis of the cage. The posterior part of the femoral condyles should project over each other as closely as possible. On the anterior-posterior view, we aimed at parallel alignment of the longitudinal axis of the tibia and the cage, which defined the laboratory coordinate system.

The patients performed a number of trial extensions of the knee, while ascending a platform (height 8 cm) from about 55°–65° of knee flexion to full extension. The height of the platform was chosen to permit use of a standardized examination routine even by older patients with arthrosis or total knee replacements. After 5–7 trials, when the patients had attained a reproducible speed, the knee motions were recorded using simultaneous and sequential exposures (2–4/second) from both tubes. In all, each series consisted of a total of 9 (7–12) exposures corresponding to a period of about 3–5 seconds. Both the injured and intact knees were studied. The radiographs were measured manually on a highly accurate measuring table or transformed to digitized images, using a scanner (Sharp JX-610) for subsequent digital analysis (Börlin and Kärrholm 1997).

The reproducibility of the motions recorded with this method has been determined in patients with total knee replacements (Uvehammer et al. 2000). The standard deviations (SD) of the rotation were 1.6°–2.3° and the SD of the translation ranged from 1.2 to 2.2 mm, between two step-ups (performed at an interval of 15 minutes). These values are at least 10 times higher than the measurement error. Despite a number of preceding trials, the patient therefore could not reproduce the exact path of motion from one examination to the next.

For this study, we evaluated the following parameters: the relative tibial rotations about the longitudinal (internal/external rotation) and anterior-posterior axes (adduction/abduction). The translations were measured as both tibial and femoral translations in separate evaluations. The medial/lateral, proximal/distal and anterior/posterior translations were recorded using the tantalum markers in the distal femur as a fixed reference segment. To obtain a reference point in the tibia, the two tips of the tibial intercondylar eminence were marked on the radiographs of the extended knee. The coordinates

Tibial rotations, translations and femoral condyle translations in the normal and ACL-injured knee

	55° of flexion		0° of flexion		P-value [a]
	Normal knees	ACL-injured knees	Normal knees	ACL-injured knees	
Tibial internal (+) / external (-) rotation	6.4°	2.5°	-1.7°	-2.6°	0.03
range	-1.4–9.2	-0.4–10.4	-5.2–7.6	-7.4–2.7	
Tibial adduction (+) / abduction (-)	-2.2°	1.3°	0.3°	0.4°	0.6
range	-5.4–6.8	-4.5–7.1	-0.18–0.95	-2.12–1.32	
Tibial medial (+) / lateral (-) translation (mm)	1.7	2.1	-0.3	-0.2	0.7
range	-1.5–3.3	-0.9 –4.4	-0.6 –0.4	-1.1–0.8	
Tibial proximal (+) / distal (-) translation (mm)	7.1	6.0	0.5	0.6	0.5
range	3.6 –11.2	3.8 –11.8	0.1–0.7	0.1–1.3	
Tibial anterior (+) / posterior (-) translation (mm)	-14.0	-16.2	1.6	0.06	0.008
range	-16.1– -10.4	-18.6– -13.8	0.1–3.6	-2.6–5.5	
Medial femoral condyle transl. (mm) (ant. (+) / post. (-))	3.5	2.5	-2.5	-2.2	0.9
range	2.0–10.0	-5.6–8.3	-3.1– -1.1	-7.2 –0.3	
Lateral femoral condyle transl. (mm) (ant. (+) / post. (-))	-4.2	-1.7	-0.7	-1.5	0.02
range	-10.7–10.9	-4.7–3.7	-4.6 –3.0	-9.3–5.7	

All values are shown as the median and range.
[a] Significance (injured knee vs reconstructed knees from 10º to 50º)

of these points were calculated for all the subsequent positions, using the known positions of the tibial markers (Jonsson et al. 1989, Jonsson and Kärrholm 1994). We also measured the anterior/posterior translations of the medial and lateral femoral condyles, using the tibial markers as fixed references. To obtain reproducible points to measure translations, two points were plotted at the circular center of the medial and lateral condyles, respectively (Kärrholm et al. 2000). These centers were reconstructed using circular templates. The distance of these points from the joint line was recorded and used to find the corresponding distance on the AP view. The medial/lateral positions of the points were measured by identifying the denser cortical bony edges on the medial and lateral aspects of the femoral condyles, respectively. Transformation of these points to the subsequent examinations was done mathematically in the same way as for the tibial reference points, but with use of the positions of femoral tantalum markers.

All the patients gave their informed consent before they were included in the study. The local ethics committee approved the study.

Statistics

Repeated measure analysis of variance (ANOVA) was used to compare the ACL-injured knees with the normal knees. The statistical comparisons were made using values between 10° and 50° of flexion where observations from 10 or 11 pairs of knees were available. A p-value of < 0.05 was regarded as statistically significant. Data are presented as median and range. All the data in the results are related to the unloaded reference position.

Results (Table)

Tibial rotation

On the injured side, and at 55° of flexion, we found a median internal tibial rotation of 2.5º (Figure 2), which changed to –2.6º (external rotation) at 0° compared to the unloaded reference position. The corresponding rotational positions of the tibia on the intact side were 6.4º and –1.7º. Between 50° and 10°, the tibia maintained a more externally rotated position on the injured side (p = 0.03).

At 55°, we found a median adduction on the injured side of 1.3º, but the intact side showed a small abduction (–2.2°). During active extension, these positions changed by only 1–2°. Between 50° and 10°, there was no significant difference between the 2 sides (p = 0.6).

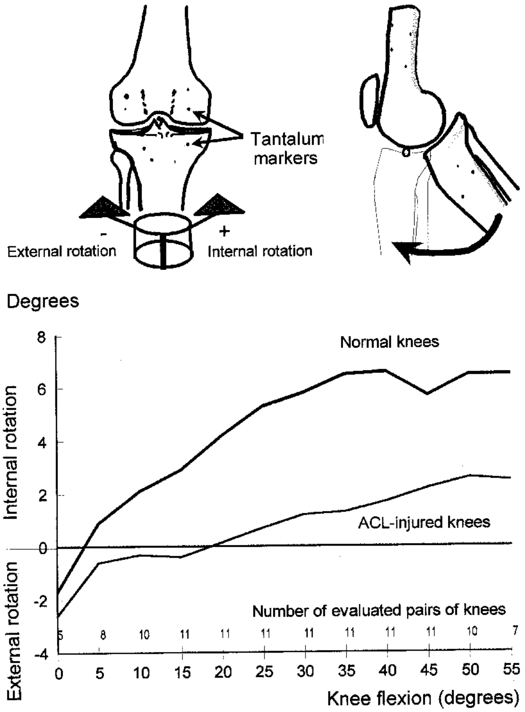

Figure 2. Relative tibial rotations around the longitudinal axis—internal (+) / external (-) rotation. All the motions were related to the positions of the tibia and femur at the unloaded supine reference position, defined as 0 degrees of flexion/extension.

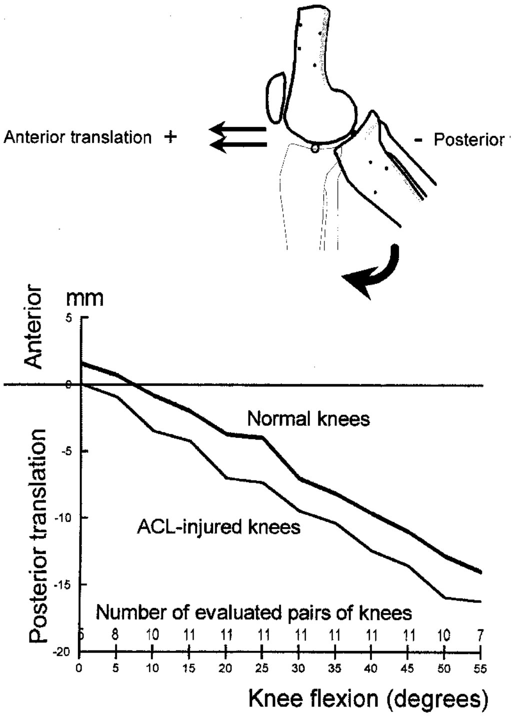

Figure 3. Relative anterior (+) / posterior (-) translations of the tibia, compared with the reference examination.

Tibial translation

The intercondylar eminence displaced laterally from a slightly medial position at 55° (median 2.1 mm) to –0.2 mm at 0°. In the normal knees, the corresponding displacement was from 1.7 mm at 55° to –0.2 mm at 0°. Between 50° and 10°, the tibia maintained almost the same lateral displacement in both the injured and the normal knees ($p = 0.7$).

At 55°, the intercondylar eminence was displaced 6.0 mm proximally, compared to the unloaded reference position, and translated 5.4 mm distally to 0.6 mm at 0°. The corresponding values in the normal knees were from 7.1 mm to 0.5 mm. Between 50° and 10°, the proximal to distal translations were about the same on the injured and normal sides ($p = 0.5$).

The tibial intercondylar eminence displaced anteriorly during extension in the knees when the ACL was torn (Figure 3). This displacement was from a posterior position (–16.2 mm) at 55° to 0.06 mm at full extension. In the normal knees, the tibial eminence was displaced about 2 mm more anteriorly at 55° and 1.6 mm more anteriorly at 0° of flexion. Thus, during extension from 50° to 0°, the tibial intercondylar eminence maintained a more anterior position on the normal side ($p = 0.008$).

Anterior-posterior translation of the femoral condyles

In the knees with ACL injury, the medial femoral condyle displaced posteriorly during extension. Compared to the reference position, the medial condylar center was positioned 2.5 mm anteriorly at 55° and translated to a posterior position (–2.2 mm at extension). In the normal knees, the corresponding displacement was from 3.5 mm to –2.5 mm. Between 50° and 10°, we found no difference between the two sides ($p = 0.9$).

During extension, the lateral condyle displaced about 0.2 mm anteriorly between 55° and 0° on the injured side. On the normal side, the anterior

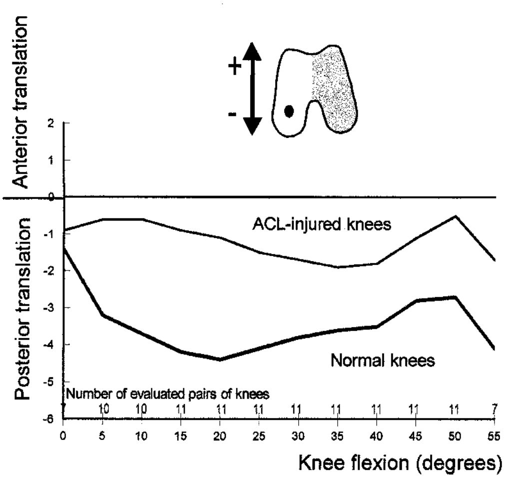

Figure 4. Relative anterior (+) / posterior (-) translations of the lateral femoral condyle center, compared with the reference examination.

displacement was 3.5 mm. Between 50° and 10°, the lateral condyle maintained a significantly more anteriorly displaced position on the normal side (p = 0.02) (Figure 4).

Discussion

All our examinations of knee kinematics were related to a straight reference position of the knee with the patient in a non-weight-bearing position. The abnormal kinematics after rupture of the ACL may be due to changes, which were already present in the supine reference position. In a previous study of cadaver knees, Kärrholm et al. (1988a) found that sectioning of the ACL resulted in minimal external tibial rotation and posterior displacement of the intercondylar eminence at 20°–30° of flexion. If these findings are also present in the living knee at 0° of extension, it seems unlikely that differences in the relative femoral-tibial position at the reference position could explain our findings of increased external rotation. However, we examined only the knee during low-velocity activity. It is probable that the kinematics could be different during high-velocity activity.

In a study in vivo, Kärrholm et al. (1988b) found that associated meniscal injuries increased the anterior-posterior laxity. In our study, 4 patients had lateral meniscal tears. These tears were small and too few to permit a reliable evaluation.

When interpreting data on the kinematics of the knee joint, the experimental method and the use of specimens or living subjects must be considered. Marans et al. (1989) measured the kinematics of the knee with an electrogoniometer. They showed an increase in anterior-posterior translations after tearing the ACL, but found no other differences compared to normal knees. In a cadaver study, Grood et al. (1984) reported an increase in anterior tibial displacement in the range of 30° to 0° after sectioning the ACL. This finding was expected since this ligament, when the knee is close to full extension, normally counteracts anterior tibial translation.

Jonsson and Kärrholm (1994) studied the kinematics of the knee during active and loaded extension. At that time, they were unable to perform dynamic measurements. Thus, the patient could actively stabilize the knee during different degrees of extension, while being radiographed. Furthermore, their patients climbed a higher platform than that used in the present study (40 vs 8 cm). Compared to this static study, we found less tibial rotation and smaller medial-lateral translations of the tibial intercondylar eminence in the normal knees. The corresponding findings in terms of the proximal-distal and anterior-posterior translations did not differ from the study of Jonsson and Kärrholm. In contrast to our measurements, they found no difference in tibial rotation between the injured and intact sides.

As has previously been observed during active flexion, but without weight bearing, Kärrholm et al. (1988b) found increased posterior tibial translation after rupture of the ACL. The reason for the difference in pattern of tibial rotation during dynamic and static extension is not clear. It could be that hamstring activity increased during motion compared to the static position. To avoid anterior subluxation, especially of the lateral tibial condyle, increased tension in the biceps tendon would be beneficial (Kålund et al. 1990). Another explanation could be that absence of the ACL for mechanical reasons changes the restraints of the knee which, as a result of muscular activity, attains a position in which the relative axial rotations are changed.

Some studies have shown that patients can voluntarily change the kinematics of the normal knee

(Kärrholm et al. 2000). This certainly also occurs after an ACL rupture. Jonsson et al. (1989) examined active extension without weight-bearing in the knee and found an initial internal tibial rotation from 30° of flexion, followed by external rotation closer to full extension. The early phase of this motion corresponded to the activation of the musculature in a relaxed knee and differed from observations during load-bearing. This observation further supports the hypothesis that the kinematics of the knee vary within certain limits, depending on the type of activity. The extent to which these limits change after rupture of the ACL is not known. However, our study and previous ones have shown that this injury changes the pattern of motion of the knee, even when motions occur at low velocity. This might make the cartilage and menisci more susceptible to damage, because of changes in contact points and loading pattern.

Rudolph et al. (1998) studied knee-motion using external markers and cameras. The patients with rupture of the ACL, who returned to their preinjury activity level without limitations (coopers), had similar kinematics in the injured and normal knees. However, all the patients had an abnormal gait. Those who had symptoms of instability during activities of daily living (non-coopers) had reduced flexion and used a stabilization strategy to reduce knee joint laxity. The findings in the latter group are to some extent in line with our observation of reduced anterior-posterior motions of the lateral femoral condyle. The patients may have increased the joint compression forces on the injured side to obtain better stability. This may be another reason for the increased risk of degenerative changes. It seems probable that the amount of accumulated damage from abnormal pathways of motion during all types of activity and any subluxations of the joint correlate to the risk of developing clinically manifest arthrosis. The individual anatomy of the joint and the quality of the cartilage and the subchondral bone before injury may also be important.

In conclusion, active continuous extension of the ACL-injured knee from 55° to 0° was associated with a more externally rotated and dorsally displaced tibia than in the normal knee. The lateral femoral condyle was more anteriorly placed at 50° of flexion and moved less during extension than did the normal knee. This abnormal kinematics could increase the joint pressure and may be one of the reasons for degenerative changes seen after ACL injuries.

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Börlin N, Kärrholm J. Radiostereometry based on digitised radiographs. Trans Orthop Res Soc, San Francisco 1997: 626.

Fridén T, Sommerlath K, Egund N, Gillquist J, Ryd L, Lindstrand A. Instability after anterior cruciate ligament rupture. Measurements of sagittal laxity compared in 11 cases. Acta Orthop Scand 1992; 63 (6): 593-8.

Granberry W M, Noble P C, Woods G W. Evaluation of an electrogoniometric instrument for measurement of laxity of the knee. J Bone Joint Surg (Am) 1990; 72 (9): 1316-22.

Grood E S, Suntay W J, Noyes F R, Butler D L. Biomechanics of the knee-extension exercise. Effect of cutting the anterior cruciate ligament. J Bone Joint Surg (Am) 1984; 66 (5): 725-34.

Jonsson H, Kärrholm J. Three-dimensional knee joint movements during a step-up: evaluation after anterior cruciate ligament rupture. J Orthop Res 1994; 12 (6): 769-79.

Jonsson H, Kärrholm J, Elmqvist L G. Kinematics of active knee extension after tear of the anterior cruciate ligament. Am J Sports Med 1989; 17 (6): 796-802.

Jonsson H, Kärrholm J, Elmqvist L G. Laxity after cruciate ligament injury in 94 knees. The KT-1000 arthrometer versus roentgen stereophotogrammetry. Acta Orthop Scand 1993; 64 (5): 567-70.

Jorn L P, Fridén T, Ryd L, Lindstrand A. Persistent stability 3 years after reconstruction of the anterior cruciate ligament. A radiostereometric analysis (RSA) of 20 patients. Acta Orthop Scand 1997; 68 (5): 427-9.

Jorn L P, Fridén T, Ryd L, Lindstrand A. Simultaneous measurements of sagittal knee laxity with an external device and radiostereometric analysis. J Bone Joint Surg (Br) 1998; 80 (1): 169-72.

Kannus P, Järvinen M. Posttraumatic anterior cruciate ligament insufficiency as a cause of osteoarthritis in a knee joint. Clin Rheumatol 1989; 8 (2): 251-60.

Kålund S, Sinkjær T, Arendt-Nielsen L, Simonsen O. Altered timing of hamstring muscle action in anterior cruciate ligament-deficient patients. Am J Sports Med 1990; 18 (3): 245-8.

Kärrholm J. Roentgen stereophotogrammetry. Review of orthopedic applications. Acta Orthop Scand 1989; 60 (4): 491-503.

Kärrholm J, Selvik G, Elmqvist L G, Hansson L I. Active knee motion after cruciate ligament rupture. Stereoradiography. Acta Orthop Scand 1988a; 59 (2): 158-64.

Kärrholm J, Selvik G, Elmqvist L G, Hansson L I, Jonsson H. Three-dimensional instability of the anterior cruciate-deficient knee. J Bone Joint Surg (Br) 1988b; 70 (5): 777-83.

Kärrholm J, Elmqvist L G, Selvik G, Hansson L I. Chronic anterolateral instability of the knee. A roentgen stereophotogrammetric evaluation. Am J Sports Med 1989; 17 (4): 555-63.

Kärrholm J, Brandsson S, Freeman M A R. Changes of axial tibial rotation caused by forced rotation at the weight-bearing knee studied by RSA. J Bone Joint Surg (Br) 2000; 82 (8): 1201-3.

Lafortune M A, Cavanagh P R, Sommer H J, Kalenak A. Foot inversion-eversion and knee kinematics during walking. J Orthop Res 1994; 12 (3): 412-20.

Lane J G, Irby S E, Kaufman K, Rangger C, Daniel D M. The anterior cruciate ligament in controlling axial rotation. An evaluation of its effect. Am J Sports Med 1994; 22 (2): 289-93.

Marans H J, Jackson R W, Glossop N D, Young C. Anterior cruciate ligament insufficiency: A dynamic three-dimensional motion analysis. Am J Sports Med 1989; 17 (3): 325-32.

Nielsen S, Helmig P. Instability of knees with ligament lesions. Cadaver studies of the anterior cruciate ligament. Acta Orthop Scand 1985; 56 (5): 426-9.

Noyes F R, Grood E S, Suntay W J. Three-dimensional motion analysis of clinical stress tests for anterior knee subluxations. Acta Orthop Scand 1989; 60 (3): 308-18.

Reinschmidt C, van den Bogert A J, Nigg B M, Lundberg A, Murphy N. Effect of skin movement on the analysis of skeletal knee joint motion during running. J Biomech 1997; 30 (7): 729-32.

Rong G W, Wang Y C. The role of cruciate ligaments in maintaining knee joint stability. Clin Orthop 1987; (215): 65-71.

Roos H, Adalberth T, Dahlberg L, Lohmander L S. Osteoarthritis of the knee after injury to the anterior cruciate ligament or meniscus: the influence of time and age. Osteoarthritis Cartilage 1995; 3 (4): 261-7.

Rudolph K S, Eastlack M E, Axe M J, Snyder-Mackler L. Movement patterns after anterior cruciate ligament injury: a comparison of patients who compensate well for the injury and those who require operative stabilization. J Electromyogr Kinesiol 1998; 8 (6): 349-62.

Torzilli P A, Deng X, Warren R F. The effect of joint-compressive load and quadriceps muscle force on knee motion in the intact and anterior cruciate ligament-sectioned knee. Am J Sports Med 1994; 22 (1): 105-12.

Uvehammer J, Kärrholm J, Brandsson S. In vivo kinematics of total knee arthroplasty: concave vs. posterior-stabilised tibial joint surface. J Bone Joint Surg (Br) 2000; 82 (4): 499-505.

Östgaard S E, Helmig P, Nielsen S, Hvid I. Anterolateral instability in the anterior cruciate ligament-deficient knee. A cadaver study. Acta Orthop Scand 1991; 62 (1): 4-8.