KNEE JOINT LAXITY AND KINEMATICS AFTER ANTERIOR CRUCIATE LIGAMENT RUPTURE

Roentgen stereophotogrammetric and clinical evaluation before and after treatment

Håkan Jonsson

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Abstract

Rupture of the anterior cruciate ligament (ACL) increases anterior–posterior (AP) laxity. The treatment aims to reduce or teach the patient to control this instability. Altered kinematics due to absent ligament function may result in knee arthrosis. This study evaluated the clinical and functional results of reconstructive surgery. Roentgen stereophotogrammetry (RSA) was used to analyse the stabilising effect of knee braces, reconstructive surgery and the kinematics of the knee with and without weight-bearing.

The stability of the knees were assessed in 86 patients with ACL injuries before and/or after reconstructive surgery with the RSA technique and with the KT-1000 arthrometer. The KT-1000 (89 N) recorded smaller side to side differences than the RSA set-up without any correlation between the methods.

The effect of three different braces on the AP and rotatory laxity was studied on patients with ACL injuries. The ECKO and the modified Lenox Hill reduced the instability with about one third. The SKB had no significant effect. None of the braces decreased the internal rotatory laxity but the Lenox Hill reduced the external rotatory laxity.

Thirty-two patients with old ACL tears were treated with surgical reconstruction using the over the top technique (OTT) with or without augmentation. A small reduction in AP laxity was observed at the 6 month follow-up. The AP laxity was almost the same two years after as before surgery. No correlation was observed between the stability and knee function.

Fifty-four patients with old unilateral anterior cruciate ligament injuries were randomised either to the over the top (OTT) or the isometric femoral tunnel position (ISO) at ACL reconstructive surgery. Seven of 24 (ISO) and 9 of 25 (OTT) had "normal" laxity two years after surgery. The patients operated with the ISO technique did not have better subjective knee function, muscle strength, functional performance or knee stability than patients operated with the OTT technique.

The knee kinematics in patients with chronic unilateral ACL ruptures were examined during active extension in the supine position (13 patients) and during extension and weight-bearing (13 patients). The tibia displaced at an average 1.9 mm more anteriorly and 0.8 mm distally in the injured than in the intact knees during active extension. During extension and weight-bearing the tibia was about 2 mm more posteriorly positioned than in the intact knee. The ACL rupture did not affect tibial rotations.

Conclusions: The RSA recorded larger side to side differences in ACL injured and reconstructed patients than the KT-1000 arthrometer. Some knee braces are able to reduce AP laxity in ACL injured knees. No correlation was observed after surgery between knee laxity and functional scoring or tests. ACL reconstructions with isometric graft position on the femoral side did not offer any advantages compared to the over the top placement. Altered knee kinematics in the ACL injured knees were observed during knee extension with and without weight-bearing. 

Key words: Anterior cruciate ligament, Kinematics, Anterior–posterior laxity, Surgery, Roentgen stereophotogrammetric analysis, Muscle strength, Functional tests
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Till Marie, Henrik, Hanna och Johan
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This thesis is based upon the following papers, referred in the text by their Roman numerals:


Some complementary data not accounted for in I–VI are included in the results and discussion.
DEFINITIONS AND ABBREVIATIONS


ACL: The anterior cruciate ligament

AP laxity: The play in the knee between the anterior and posterior endpoints achieved by separate anterior and posterior traction.

Functional stability: Knee stability during activities accomplished by passive restraints (see static stability) and active restraints (muscle activity and joint load).

Condition number. Mathematical formula used in RSA to objectively express the scattering of bone markers within a rigid body.

Coordinate system: A Cartesian coordinate system with the three axes in right angles to each other.

Give way: Episodes of knee instability described by the patients.

Helical axis (screw axis): Axis used to describe three-dimensional movements in terms of rotations. Movements are defined by the position and direction of this axis and the size of the rotations. Translations may occur along axis.

Mean error of rigid body fitting. Mathematical formula used to evaluate the stability of bone markers between two RSA examination.

N: Newton

NA: Non augmented. ACL surgery without synthetic augmentation.

Nm: Newton meter

n.s. Not significant

OTT: Over the top. ACL surgery with the graft placed over the top on the femoral side.
**ISO:** Isometric. ACL reconstruction using the Stryker drill guide to position the ACL graft.

**Rigid body:** A body with three-dimensional extension not deforming during motion. A rigid body can be defined by a number of landmarks, e.g., tantalum markers. These landmarks have a constant distance to each other during the motion.

**RSA:** Roentgen stereophotogrammetric analysis

**SD:** Standard deviation. In the text proceeded by ± and in tables within brackets.

**Side to side difference:** Difference of the anterior–posterior knee joint laxity between the injured and the normal knees in one patient.

**Static stability:** The stability in the knee provided by passive restraints such as ligaments, capsules and other soft tissues.
INTRODUCTION

Injuries to the anterior cruciate ligament were first recognised in the middle of the 19th century (Stark 1850). Braces remained the treatment of choice for many decades (Hey Groves 1917). In 1919 Harding suggested a supervised increase in activity after knee sprains. Physiotherapy is still one of the corner stones in the care of ACL injured patients (Tegner et al. 1986). Surgical procedures were introduced early this century (Robson 1903, Hey Groves 1917, Smith 1918). Later, Palmer (1938) held that early repair of the ligament was the treatment of choice. O'Donoghue (1950) set the goal of full recovery and believed it could be fulfilled with surgery. During the following decades reconstructive ACL surgery expanded resulting in the use of many methods (Burnett and Fowler 1985).

The aim of the therapy is to eliminate or teach the patient to control instability. The increasing number surgical procedures and treatment modalities have called for objective evaluation of the results. Clinical examination of knee stability has been regarded inaccurate (Sylvin 1975, Hooper 1986, Feagin and Blake 1983, Markolf and Amstutz 1987, Daniel 1991), focusing on the need for objective measurements of knee stability.

Absence of functioning anterior cruciate ligament leads to changed knee kinematics (Marans et al. 1989, Berchuk et al. 1990) and has been postulated to be responsible for abnormal joint wear (Palmer 1938, Noyes 1980, Fetto and Marshall 1980). In the long term it may lead to osteoarthritis of the knee (Balkfors 1982, Kannus and Järvinen 1987, Sherman et al. 1988, McDaniel and Dameron 1983). One of the major goals with ACL surgery is to restore kinematics (Noyes et al. 1980, Gillquist 1993) and thereby avoid this deterioration.

Physiotherapy after surgical reconstruction of the ACL is a prerequisite for successful results (Howe et al. 1991). The postoperative rehabilitation includes contradictory ambitions. It has to protect the graft and at the same time avoid secondary adverse effects of immobilisation, obtain preinjury strength, aerobic fitness, coordination and patient confidence (Curl et al. 1982). Knowledge about the in vivo kinematics is necessary to be able to understand the long term effects of an ACL rupture and to create postoperative rehabilitation programs (Shelbourne et al. 1990, Curl et al. 1982).

The roentgen stereophotogrammetric technique used in this thesis enables detailed three-dimensional determination of skeletal motions in vivo. The method
has a potential to increase our knowledge about the effects of anterior cruciate ligament rupture and its treatment. This thesis was initiated to evaluate kinematics in the ACL injured knees and the effects of surgical reconstruction and brace therapy. A comparison was made with the most frequently used knee arthrometer.

Measurement of knee laxity

Loss of function of the anterior cruciate ligament implies mainly increased anterior – posterior (AP) instability of the knee. Different methods have been developed to measure the femoro-tibial play in the sagittal plane. Factors related to the examination technique such as the degree of knee flexion, size and application of loads, choice of reference position, measurement techniques, choice of coordinate systems will all influence the results. Variability is also caused by factors related to the patient.

Degree of knee flexion. The classic way to assess the integrity of the ACL is to perform an anterior drawer test with the knee in 90 degrees of flexion. Examination of the knee close to full extension was described early this century (Jones 1906, Paessler and Michel 1992), but has not been in general use until Torg et al. (1976) reintroduced this technique as the Lachman test. Cadaver studies have later confirmed that the optimum position to reveal sagittal instability due to ACL tear is at 20–30° of knee flexion (Markolf et al. 1976, Nielsen and Helmig 1985, Fukubayashi et al. 1982, Sullivan et al. 1984).

Size of forces applied. The ligaments of the knee are elastic indicating that there is a non-linear relationship between the forces applied and the recorded displacements. The stiffness of the knee ligaments increases at larger loads (Markolf et al. 1976, Edixhoven et al. 1989). Recordings at high loads are preferable to obtain reproducible data. On the other hand the forces applied should not be uncomfortable to the patient or harm any reconstructed graft. In the early postoperative phase the fixation site of the graft provides the least resistance. Some graft fixations fail with loads of 100 N or less (Robertson et al. 1986, Kurosaka et al. 1987). In clinical settings external forces between 67 (Daniel et al. 1985A) and 300 N (Jacobsen et al. 1976) have been used.

The way to apply external loads also has to be considered. Anterior laxity recordings will change when the same loads are applied at different distances from
the knee joint because of changes of the lever arm (Andersson et al. 1990). The loading time may also have an influence due to time dependent deformation of the soft tissues.

**Choice of reference position.** A reference position or landmark is required to measure the effects of externally applied forces. Before the anterior traction is applied, this position can be obtained by repeated posterior pushing until a reproducible relaxed position is achieved (Daniel et al. 1985A, Sherman et al. 1987). Shino et al. (1987) and Jonsson et al. (1990) repeated the anterior tractions until the same displacements were recorded. To eliminate uncertainty in the determination of an unloaded reference position anterior and posterior forces can be applied and the play between the endpoints measured (Boniface et al. 1989, Wroble et al. 1990).

The flexed and unloaded position of the knee has been used as the reference in several radiographic techniques (Kennedy et al. 1971, Jacobsen et al. 1976, Torzilli et al. 1981, Hooper 1986). One or several distances between anatomic landmarks on the femur and the tibia are measured on radiographs exposed with the knee in the unloaded reference position and after the application of anterior forces. The knee play is then calculated as the increase in distance(s) between these landmarks. Levén (1977) and McPhee and Frazer (1980) applied anterior and posterior forces and measured the displacement between the endpoints. Franklin et al 1990, Moyen et al. 1990 and Stäubli et al 1992 exposed only one radiograph during anterior traction of the knee. They measured the distance between the posterior margin of the tibia and the femur on the lateral radiographs.

**Technique to record the displacement.** The measuring techniques in clinical use have either been based on externally applied devices or on radiographic techniques. The external devices have pads, velcro straps or plates applied to the patella or distal femur and to the tibia. Changes in distance between the appliances at the patella/femur and the tibia are recorded when installing displacing forces (Sylvin L E. 1975, Markolf et al. 1978, Johnson et al. 1984, Daniel et al. 1985A, Shino 1987, Jonsson et al. 1990, Boniface et al. 1989, Edixhoven et al. 1989). Externally applied computer based systems with four (Riederman et al. 1991) or six degree of freedom electrogoniometric linkages (Oliver and Coughlin 1987) measure multiplanar displacements. Radiographic technique using the lateral projection has been used in numerous studies (Kennedy et al. 1971, Jacobsen et al. 1976, Levén 1977, Torzilli

**Choice of coordinate system and points of measurement.** When performing an anterior or posterior drawer test multiplanar tibial displacements occur. Complete description of these motions requires measurements with six degrees of freedom (Grood and Suntay 1983, Kärrholm et al. 1988B). These six components are rotations about and translation along the three axes of a coordinate system. A cartesian coordinate system fixed to the tibia is commonly used (Daniel and Biden 1987). Because of the simultaneous rotations around all axes, points in the tibia display different patterns of motion. Thus, a specific point on the tibia has to be defined to describe translations in a standardised way.

Externally applied arthrometers such as the KT-1000, the Stryker and devices described by Sylvin, Shino and Edixhoven record one dimensional displacements of the tibia. They measure along an axis fixed to the device. The firmness of the device fixation to the tibia determines the possibilities for tibial rotations relative to the device during the test. These rotations determine how accurate the measurements will correspond to anterior–posterior translations according to a tibial coordinate system. The position of the tibial measuring pad determines the tibial measuring point.

Conventional radiographic techniques measure displacement on the lateral projection and the film plane defines the axis of measurements. In most methods, the lateral and medial femoral and tibial compartments are identified and the displacements of each compartment are calculated. This procedure gives some information about tibial external/internal rotation. Levén (1977) reconstructed a central femoral point based on the contours of the condyles and used the intercondylar eminence as the tibial reference point.

RSA enables three-dimensional motion analysis in a laboratory coordinate system. Translations and rotations are related to tibial axes. Accurate alignment of the tibia in relation to the laboratory coordinate system (Kärrholm et al. 1988, Fridén et al. 1992) during one of the examinations is important if the true anterior–posterior translations are to be measured. The midpoint between the two tips of the
tibial intercondylar eminence has been chosen to represent tibial translations (Kärrholm et al. 1988, Fridén et al. 1992).

**Patient related factors.** The weight of the lower leg, the degree of relaxation, the soft tissue mass and elasticity affect the recordings. The importance of muscle relaxation was demonstrated by Dahlstedt and Dalén (1989), who found larger displacements under anaesthesia in both ACL injured and intact knees.

**Knee stability and function**

The static stability is provided by passive restraints such as ligaments, capsule and other soft tissues and can be measured by arthrometric techniques. Functional stability, i.e., during standing or physical activity (Noyes et al. 1980) is also influenced by active restraints such as muscle activity (Tegner et al. 1986A), proprioception (Barrett 1991) and joint load (Hsieh and Walker 1976). Arthrometric tests cannot be expected to fully predict functional stability (Noyes et al. 1980). A more comprehensive evaluation can be accomplished by rating the knee disability with subjective scores (Lysholm and Gillquist 1982). Subjective knee function depends on the activity level and has to be considered when evaluating the outcome based on different scores (Noyes et al. 1984). In 1985 Tegner and Lysholm modified their original score by excluding objective parameters and described a complimentary scale, the Tegner activity scale. Other systems evaluate the subjective function and activity level in the same score (Noyes et al. 1984). Recent described scoring systems also include the results of the clinical examination of the knee (Orthopaedische Arbeitsgruppe Knie form; Müller et al. 1988, International Knee Documentation Committee, IKDC form; Kipnis et al. 1993, Engström 1993).

**Treatment of the anterior cruciate ligament injured knee**

**Braces.** Braces can be used according to three principles, prophylactic, rehabilitative and functional bracing (Millet and Drez 1987). Prophylactic braces are used in high risk activities to protect the uninjured knee, but its efficacy has been questioned (Teitz et al. 1987). The rehabilitative braces aim to keep the knee within a safe range of motion after surgery. Functional braces are designed to counteract the instability and enable increased level of activity. Numerous studies
have evaluated the effect of braces on knee laxity (Cawley et al. 1991). Externally applied arthrometers have been used in vivo (Beck et al. 1986, Colville et al. 1986, Mishra et al. 1987, Cook et al. 1989) to measure AP laxity, whereas the rotatory stability has been difficult to assess. These examinations have been done manually (Bassett et al. 1983, Colville et al. 1986) making the results dependent on the examiner (Noyes et al. 1991).

**Surgery.** The surgical options for ACL reconstruction are influenced by the time between injury and treatment. In the acute situation repair, repair and augmentation or intraarticular reconstruction can be done. Old ACL ruptures have been operated with extraarticular compensating or intraarticular reconstructive procedures.

Patients with ACL injuries often suffer from knee instability or a feeling of "giving way". These problems occur mostly in activities where sudden changes of the direction of motion is common as in sports, but may also play a role in activities of daily living. Anterior subluxation of the tibia and especially the lateral tibial plateau at extension is probably the pathomechanism for the giving way episodes. This instability can be demonstrated by the pivot shift examination (Galway and MacIntosh, 1980). Extraarticular surgery of the lateral ligaments of the knee aim to counteract this subluxation. Most procedures described consist of iliotibial band transfers or tenodesis (Carson Jr 1987). Slocum and Larson (1968) used a pes anserine transfer on the medial side to correct antero-medial instability. The extraarticular techniques have been used singly, as combined medial and lateral procedures (Dahlstedt et al. 1988) or in combination with intraarticular surgery (Clancy et al. 1982, Bertoia et al. 1985, Zarins and Rowe 1986, Noyes et al. 1991). The extraarticular procedures may not offer the patient sufficient stability (Dahlstedt et al. 1988) or any additional benefits when combined with intraarticular surgery (Roth et al. 1987, O’Brien et al. 1991).

Subjective good or excellent results have been reported in more than 80% of the patients after intraarticular reconstructive surgery (Clancy et al. 1982, Bertoia et al. 1985, Dahlstedt et al. 1990, Elmqvist et al. 1988, Howe et al. 1991, Squaglione et al. 1992). The same frequency of normal or close to normal AP laxity has been recorded in several studies (Yasuda et al. 1992, Shelbourne et al. 1990, Howe et al. 1991). Less satisfactory results on knee stability have also been reported with failure rates exceeding 20% (O’Brien et al. 1991, Squaglione et al. 1992, Aglietti et
Squaglione et al. (1992) obtained better results according to subjective ratings than objective stability tests.

**Graft material.** The objective with the intraarticular surgery is to replace the ACL with a graft. Autografts, tendons and ligaments close to the injured knee are common substitutes. Allografts, xenografts and synthetic ACL prostheses have also been utilised.

The autografts do not have any vascular supply when inserted, and they undergo necrosis, revascularisation and remodelling. During this time they are weak and at risk for elongation or rupture (Alm et al. 1974, Kennedy et al. 1980, Arnoczky et al. 1982, McPherson et al. 1985.) In 1980 Kennedy et al. summarised the experience with autografts as disappointing due to insufficient strength. He introduced a synthetic braid (Kennedy LAD) to be used as an augmentation (Kennedy et al. 1980). The rationale for this polypropylene braid was to stress-shield the autograft during the period of reduced strength. Initially the LAD was used with a patellar tendon–quadriceps tendon graft and placed over the top on the femur (Marshall et al. 1979, Kennedy et al. 1980, Roth et al. 1985). It was wrapped into and covered by the biological graft. Later on the Kennedy LAD device has been combined with the semitendinosus tendon (Squaglione et al. 1992), bone–patellar tendon–bone autografts (Field and Barrett 1993) or allografts (Noyes et al. 1992). It has also been used to reinforce acute ACL repairs (Engebretsen et al. 1990).

**Intraarticular graft positioning.** Correct placement of the graft attachments was considered important for the outcome of surgery by Palmer (1944) and later surgeons (Lam 1968, Hewson 1982) have tried to achieve isometric attachment sites for the graft. Isometry denotes two points, one femoral and one tibial, being positioned at the same distance from each other throughout the range of motion. The rationale for isometric positioning is to obtain constant graft tension during motion.

There are two basic ways to position the graft in the femur, through a tunnel (Hey Groves 1917) or a route over the proximal/posterior aspect of the lateral femoral condyle – over the top (OTT, MacIntosh 1974). On the tibial side Jones (1963) placed the graft over the tibial edge, but this technique has been abandoned in favour of a tunnel position.
To obtain the same tension in the graft throughout the range of motion Clancy et al. (1982) recommended the femoral drill hole to be placed posterio-superiorly and the tibial one anterio-medially to the original ACL insertions. The margins of the holes should coincide with the centres of the ACL insertions. In 1982 Hewson claimed that the femoral insertion of the graft was the single most important factor influencing the success of surgery. In a cadaver study Hoogland and Hillen (1984) found the optimum femoral attachment to be situated in the superior/posterior aspect of the original insertion and that the placement of the tibial insertion was less critical. They as well as Penner et al. 1988 and Good (1993) favoured a slightly anteriorly positioned tibial tunnel. Odensten and Gillquist (1985) observed that the centres of the original ACL insertions were isometric and that any divergence from the tibial insertion site had a significant influence on the isometry. Raunest (1991) and Schutzer et al. (1989) confirmed the importance of an anatomic placement of the attachment sites. Several groups (Hefzy et al. 1989, Saepa et al. 1990, Schutzer et al. 1989,) failed to identify any absolute isometric positions. Arbitrarily Hefzy et al. (1989) accepted deviations of 2 mm from isometry and found that a narrow area on the medial side of the lateral condyle was the optimum. The tibial position was less important than the femoral one. Saepa et al. (1990) observed that the anterio-medial bundle was the most isometric part of the intact ACL and accepted deviations from isometry up to 3 mm at surgery. Thus, most of these in vitro studies support either an anatomical placement or a slightly anterior/medial and superior/posterior placement of the tibial and femur tunnels, respectively.

Although the femoral OTT placement is not isometric and has been disapproved for anterior cruciate ligament surgery (Hoogland and Hillen 1984, Odensten and Gillquist 1985, Raunest 1991, Schutzer et al. 1989) there are some arguments for its use. The OTT placement is more forgiving than the isometric one by avoiding the risk for a disastrous anterior tunnel position (Grood et al. 1986). It offers a smoother force transmission between graft and bone at the femoral insertion reducing the risk for graft abrasion (Montgomery et al. 1988). Fleming et al. (1992) observed less variability of the AP laxity after surgery using the OTT than the isometric tunnel technique. By making a groove over the top with a depth of 3–11 mm the isometric position can be approached (Penner et al. 1988, O’Meara et al. 1992).

As indicated above many authors have recommended a tibial position anterior to the original insertion site. Recent studies have stressed the risk for notch

Knee kinematics

Most information on knee kinematics has been accomplished by *in vitro* studies (Blacharski et al. 1975, van Dijk 1983, Grood et al. 1984, Nielsen et al. 1984, Kurosawa et al. 1985, Nielsen and Helmig 1985, Reubens et al. 1989, More et al. 1993) or two-dimensional *in vivo* studies (Frankel et al. 1971). Some authors have examined three-dimensional kinematics with electrogoniometers applied on the skin (Shiavi et al. 1987, Marans et al. 1989). These devices are subject to errors due to soft tissues motions (Granberry et al. 1991). Direct skeletal motions during gait have been studied by inserting pins into the skeleton but to my knowledge not in ACL injured subjects (Levens et al. 1948, Lafortune and Cannavagh 1984).

To study the knee kinematics the concept of instant center of zero velocity has been used. It is the intersection of a flexion axis, describing the motion between two observations, with a parasagittal plane (O’Connor et al. 1990). The instant center can be calculated according to Reulaux (1875, Van Dijk, 1983). Frankel et al. (1971) observed changes in the pattern of the instant centre during knee motion due to meniscus pathology. The hypothesised influence of the cruciate ligaments on knee motion has been explained with a mechanical model, "the four bar linkage" (Strasser 1917, Kapandji 1970, Huson 1974, Menschik 1974, O’Connor et al. 1990). In this model the instant centre of zero velocity has been located at the crossing of the cruciate ligaments. During flexion/extension with fixed femur the intersection of the axis with a central sagittal plane moves along a path called the femoral centrode. With the knee flexed the axis starts at the femoral insertion of the anterior cruciate ligament and moves distally, anteriorly and finally proximally during the extension ending at the insertion of the posterior cruciate ligament at full extension (Menschik 1974, O’Connor et al. 1990). The disadvantage with the instant center technique and the four bar linkage model is that they simplify the kinematics of the knee to motions in one plane. Blacharski et al. (1975) applied the method of Reulaux *in vitro* to study the influence of the cruciates on knee motion. To overcome the restrictions of planar motion the instant center was calculated on both the medial and lateral side of the knee. They concluded that joint geometry
was the major factor determining knee kinematics and the cruciates were of minor importance.

In another *in vitro* study Reuben et al. (1989) examined motions of a Steinman pin drilled through the centre of the two femoral condyles during extension performed by traction in the quadriceps muscle. Sectioning the ACL resulted in an anterior displacement of the tibia. Using a six degree of freedom goniometer Marans et al. (1989) and Shiavi et al. (1987) observed changes in kinematics during gait and pivoting. In the first study the results were analysed according to a cartesian coordinate system. In the later one the helical axes were calculated. Both authors concluded that the absence of the ACL changed the knee kinematics.

**Kinematics and physiotherapy after surgery.** During the remodelling phase the biological grafts has to be protected. Immobilisation leads to decreased ligamentous strength (Noyes et al. 1973), periarticular and intraarticular changes with arthofibrosis and degeneration of the cartilage (Akeson et al. 1973, Evans et al. 1960, Finsterbush and Friedman 1975).

*In vitro* and *in vivo* studies have shown increased strains in the ACL during knee extension, isometric quadriceps contractions and squatting (Arms et al. 1984, Renström et al. 1986, Beynnon et al. 1992, 1993). *In vitro* measurements (More et al. 1993) and indirect calculations of shear forces suggest that squatting and simultaneous isometric quadriceps and hamstring contractions may be safe (Yasuda and Sasaki 1987A, Ohkoshi et al. 1991). Even maximum isometric quadriceps contraction might cause less anterior tibial displacement than the Lachman test (Howell 1990). Despite that the issue of safe rehabilitation is not solved there is a development towards more aggressive training programs. These protocols emphasise immediate passive full extension, walking without weight-bearing restrictions, squatting and stair climbing (Shelbourne and Nitz 1990, Willis et al. 1992).
AIMS OF THE STUDY

Measurement of knee laxity

• To compare the RSA set-up with the KT-1000 arthrometer. (I)
• To establish a cut off value for the RSA set-up discriminating injured from normal patients. (I)
• To investigate the reproducibility for the KT-1000. (I)

Knee stability and function

• To compare achieved knee stability after surgery with subjective and objective knee function (III, IV)

Treatment of the anterior cruciate ligament injured knee

• To delineate the influence of three different brace designs on AP and rotatory laxity in ACL injured patients. (II)
• To evaluate changes in AP laxity after over the top ACL surgery during the first two years after surgery (III)
• To compare over the top and drill guide aided isometric positioning of the femoral attachment at reconstructive surgery. (IV)

Knee kinematics

• To assess the three-dimensional kinematics of the knee during active extension in the supine position. (V)
• To assess the three-dimensional kinematics of the knee during extension and weight-bearing. (VI)
• To reconstruct the helical axes during extension and weight-bearing in the normal and ACL injured knees using anatomical landmarks including the femoral insertion point of the ACL (VI)
PATIENTS AND METHODS

Patients

142 patients (44 women/98 men) with a mean age of 26 years (15–46) were studied. One hundred twenty seven patients were examined with roentgen stereophotogrammetry. All had their injuries verified at arthroscopy. Ninety-four patients in the material were operated between 1984 and 1990 with an anterior cruciate ligament reconstruction and 86 of them were followed during the two postoperative years (III, VI). Further 16 patients (9 men, 7 women, mean age 22.5 years) with arthroscopically verified unilateral anterior cruciate ligament tears were included in the reproducibility tests of the KT-1000 arthrometer.

Table 1 The 127 patients in the RSA studies. Most of the patients participated in more than one study. Ia denotes the patients examined with KT-1000 and RSA. Ib denotes 100 unilateral ACL injured patients examined with RSA. Study III/IV denotes patients in whom the AP laxity also was examined the day after surgery. The number of patients, sex (M= male, F= female) and the mean age are reported. For additional information see the appendix.

<table>
<thead>
<tr>
<th>Study</th>
<th>Patients n</th>
<th>Sex M/F</th>
<th>Age years</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ia</td>
<td>86</td>
<td>57/29</td>
<td>26</td>
</tr>
<tr>
<td>Ib</td>
<td>100</td>
<td>68/32</td>
<td>26</td>
</tr>
<tr>
<td>II</td>
<td>20</td>
<td>15/5</td>
<td>26</td>
</tr>
<tr>
<td>III</td>
<td>32</td>
<td>29/3</td>
<td>26</td>
</tr>
<tr>
<td>IV</td>
<td>54</td>
<td>35/19</td>
<td>25</td>
</tr>
<tr>
<td>III/IV</td>
<td>8</td>
<td>7/1</td>
<td>23</td>
</tr>
<tr>
<td>V</td>
<td>13</td>
<td>11/2</td>
<td>24</td>
</tr>
<tr>
<td>VI</td>
<td>13</td>
<td>10/3</td>
<td>25</td>
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</table>

Specimens

A cadaver study was performed to enable a reconstruction of the femoral insertion of the anterior cruciate ligament on the stereoradiographs. Ten specimens (7 men
and 3 women) with a mean age of 76 (54–88) years and without degenerative joint
disease were examined.

**Surgical technique (I,III,IV)**

Ninety-one patients were reconstructed with a graft made of the central strip of
the quadriceps and patellar tendons connected by the prepatellar tissue according to
In 20 no augmentation was used (I, III); in 46 a Kennedy LAD braid (Kennedy et
al. 1980, Roth et al. 1985) was inserted (I, III, IV). Twenty-five patients had the
augmented graft placed "isometrically" in bone tunnels (I, IV). Eight operated
patients did not enter study III or IV (see appendix). One did not want to
participate, three did not fulfil the inclusion criterias in study IV, and one was
operated by a surgeon not included in the study at that time. Three patients had
their anterior cruciate ligament reconstructed with a Goretex ® graft (I).

**Incision.** Surgery was performed with open technique through a lateral or central
skin incision. A notchplasty was made routinely. In the over the top procedure the
tractus iliotibialis was incised proximal to the knee joint. The septum
intramuscularis was detached from the bone to gain access to the posterior joint
capsule.

**Graft preparation.** A graft with a length of about 17 cm from the tibial insertion
was prepared. The outer half of the central third of the quadriceps tendon with a
width of 1 cm was harvested. The graft was widened over the patella and ended
with the middle third of the patellar tendon. The insertion at the tibial tuberosity
was left intact.

The patients operated without the LAD augmentation (III) had their grafts
reinforced with two none absorbable (either Ethibond® or Goretex ®) Bunell
sutures. The Kennedy LAD braid used as augmentation was 8 mm wide and 14–16
cm long. The braid was sutured to and wrapped into the biologic graft.

**Placement of fixation points.** The tibial tunnel was free hand drilled when the
OTT technique (I, III, IV) was used, aiming at the old anterior cruciate ligament
insertion. A groove was prepared for the graft in the superior part of the lateral
femoral condyle (over the top).
To obtain an isometric position of the two tunnels in the ISO group (IV) a drill guide was used (Figure 1, Stryker, Kalamazoo, MI, USA, Odensten and Gillquist 1986). The guide was introduced with the knee at 90° of flexion. With the aid of fluoroscopy the tip of the guide was placed at the proximal end of Blumensaats line. A 2.5 mm guide pin was drilled through the tibia and femur giving the graft a straight line at 90° of flexion and an intraarticular graft length of about 31 mm at an angle of 28° in relation to the femoral longitudinal axis (Odensten and Gillquist 1986). The guide pin was overdrilled with a cannulated 8 mm drill. A test ligament was inserted and changes in distance between the chosen graft fixation points in both the OTT and ISO group was roughly tested without any isometer. Changes in distance estimated to be more than 2 mm resulted in redrilling (ISO) or deepening of the femoral groove (OTT). The bony tunnels were bevelled.

The graft was inserted and manually tensioned. A number of flexion/extensions were performed before the graft was fixed to the femur at about 30° of flexion. One or two barbed staples were used for the femoral fixation in the OTT operated patients. Thirty-eight of them had their graft fixated using staples in belt buckle fashion. Fifteen of the ISO patients had their graft fastened with a screw and washer. Two barbed staples (belt buckle fashion) were used in nine patients.

Figure 1 The drill guide with the drill inserted
Postoperative rehabilitation

The patients operated with the Marshall technique with and without Kennedy – LAD in study III had different protocols according to Table 1. All patients in study IV passed the same postoperative protocol according to table 2.

Table 2 Rehabilitation programs used in study III. Restrictions in range of motion within brackets.

<table>
<thead>
<tr>
<th>Time (Postop)</th>
<th>None Augmented</th>
<th>Augmented</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Plaster</td>
<td>Brace</td>
</tr>
<tr>
<td>Week &gt;6</td>
<td>Removable splint (30°–full flexion)</td>
<td>(30°–full flexion)</td>
</tr>
<tr>
<td>Week &gt;9</td>
<td>Brace (30°–full flexion)</td>
<td>(30°–full flexion)</td>
</tr>
<tr>
<td>Week &gt;13</td>
<td>Full weight bearing (15°–full flexion)</td>
<td>(15°–full flexion)</td>
</tr>
<tr>
<td>Week &gt;26</td>
<td>Full range of motion.</td>
<td>Full range of motion</td>
</tr>
<tr>
<td>Week &gt;33</td>
<td>Full activity allowed</td>
<td>Full activity allowed</td>
</tr>
<tr>
<td>Week &gt; 52</td>
<td>Full activity allowed</td>
<td></td>
</tr>
</tbody>
</table>
Table 3 Postoperative rehabilitation protocol used in study IV

<table>
<thead>
<tr>
<th>Time</th>
<th>Immobilisation</th>
<th>Muscle training</th>
</tr>
</thead>
<tbody>
<tr>
<td>Day: 0–2</td>
<td>Brace fixed at 30° of flexion</td>
<td>Isometric quadriceps (quad) and hamstring (ham)</td>
</tr>
<tr>
<td>Day: 3–7</td>
<td>Brace 30°–full flexion No weight-bearing</td>
<td></td>
</tr>
<tr>
<td>Week: 4</td>
<td>Brake: 15°–Full flexion Start weight-bearing</td>
<td>Dynamic quad and ham</td>
</tr>
<tr>
<td>Week: 8–9</td>
<td>Brace: Full Range of motion</td>
<td>Isokinetic quad/ham Eccentric hams water training</td>
</tr>
<tr>
<td>Week: 10</td>
<td></td>
<td>biking</td>
</tr>
<tr>
<td>Week: 12</td>
<td></td>
<td>Eccentric quad, jumping</td>
</tr>
<tr>
<td>Week: 14</td>
<td></td>
<td>Increased functional training</td>
</tr>
<tr>
<td>Week: 22</td>
<td></td>
<td>Full activity allowed</td>
</tr>
</tbody>
</table>

Braces

Two custom made (SKB, a modified Lenox Hill) and one ready made brace (ECKO) were investigated (II) (Figure 2). The SKB was designed for prophylactic use. The ECKO represents rehabilitative and the modified Lenox Hill functional bracing.

The SKB brace (LIC, Sweden) is built up by metal frames, hinged laterally and medially, and elastic straps proximally. Immobile moulded pads are attached medially at the knee joint, laterally on the thigh, and anteriorly and laterally on the calf. Elastic straps around the waist prevent the brace to slip down.

The ECKO (Extension Control Knee Orthosis) brace (Orthomedics USA), is available in three different sizes, and consists of a thermoplastic hinged frame with two transverse anterior bars over the thigh and calf. The brace is stabilised to the knee with proximal and distal straps and popliteal bands.
The Lenox Hill brace (Lenox Hill brace shop Inc. USA, Nicholas 1983) has metal frames hinged medially and laterally, fixed lateral supports proximally and distally and a mobile medial support. Above and below patella there are adjustable pads. Strips and an oblique elastic strap provide further stability. The modified Lenox Hill brace reaches more proximally on the thigh, more distally on the calf and the contact surfaces against the extremity are larger compared with the original version (Karlsson and Eghamn 1981).

![Figure 2 The braces in the study. From the left the SKB, ECKO and modified Lenox Hill](image)

**Roentgen stereophotogrammetric analysis (RSA)**

Roentgen stereophotogrammetry is the science of obtaining reliable three-dimensional measurements from radiographs. The system that was developed by Selvik is called roentgen stereophotogrammetric analysis and includes evaluation of rigid body kinematics (Selvik 1974, 1989). The method has been used especially to record skeletal movements (Van Dijk 1983, Ryd 1986, Snorrason 1990,

The RSA technique includes 4 steps:

**1: Implantation of the tantalum markers**

The patients included in this thesis had symptoms of knee instability and uni- or bilateral chronic anterior cruciate ligament injuries. Surgical reconstructions were planned in all of them. Before this operation a diagnostic arthroscopy was made and 4 to 5 tantalum markers (diameter: 0.8 mm) were implanted in the distal femur and proximal tibia in both knees. The markers were inserted in a cannula made of stainless steel. The cannulas were drilled percutaneously and by hand into the bone. The markers were pushed out of the cannula into the bone by a troacar. Marker positions were controlled with fluoroscopy. The markers were spread out as much as possible to facilitate identification and optimise accuracy.

**2: Radiographic examinations**

AP laxity (I,II,III,IV). The stereoradiographic examination was done three weeks or later after the insertion of the markers. The knee was placed in a Plexiglas cage (Figure 3, page 29) attached to a frame supplied with cassette holders. Two x-ray tubes, perpendicular to each other and positioned 1 meter from the film plane, were used to get simultaneous exposures.

The AP laxity test consisted of four exposures; extended reference position, flexed reference position at 30° of flexion, anterior and posterior traction.

Extended reference position. All recorded motions were directly or indirectly related to the extended position of the knee (0° of flexion, supine). To achieve a standardised orientation of the patient coordinate system the knees were placed according to the axes defined by the cage. The y – axis of the cage was aligned with the longitudinal axis of the tibia. On the simultaneously exposed lateral view the posterior cortex of the tibial condyles projected over each other close to the central x-ray beam corresponding to parallellity with the x-axis of the cage. The z-axis being perpendicular to the x and y – axes ran in the anterior–posterior
direction. At the following examinations standardised positioning was not a must, because absolute motions between the double exposures were corrected at the subsequent evaluation.

*Flexed reference position.* A tourniquet was applied around the thigh. The knee was flexed to about 30°. The thigh with the tourniquet was then fixed to a frame. To minimise the femoral motions the tourniquet was insufflated to 80 mm Hg at this and the subsequent three exposures. This position defined the starting position for the anterior and posterior displacement.

*Anterior and posterior traction.* A sling was placed 7–8 cm distal to the knee joint and a load of 150 N was used for the anterior traction. This sling was removed and a second sling, with two cords hanging down on both sides of the radiographic table, was put around the proximal calf. A weight of 80 N was fastened to each of the cords, resulting in a posterior force of 80 N (Kärrholm et al 1988B).

Eight patients (III, IV) were examined the day after surgery. Surgery was performed under epidural anaesthesia. The epidural catheter was left in place for postoperative pain relief. Half an hour before the examination local anaestheticum was injected in the catheter. The postoperative brace was removed at the examination.

*Rotatory laxity (II).* All motions were related to the extended relaxed position of the knee (0°).

*Internal–external rotation with and without traction.* The knee was flexed to about 20°. The foot was placed in a shoe mounted to an adjustable circular disc with a central groove at the circumference of the disc. The disc was fastened to a platform. Two thin cords were fastened to the edge of the disc enabling internal or external rotation. The foot could be rotated internally or externally by applying tractions to the cords. The generated torque was calculated at 8 Nm. This examination was also performed with anterior traction of 150 N.

*Active knee extension in the supine position.* (Figure 5, page 29) Two film exchangers were used providing an AP and a lateral view. A reference plate with tantalum markers was attached to each film exchanger. Prior to the patient examination the reference plates were radiographed with the reference cage. The cage was removed and the same position of the film exchangers and roentgen tubes were maintained throughout the examination. At the subsequent mathematical
evaluation data from this examination enabled calculation of the position of the x-ray foci and transformation of the cage coordinate system to the patient examinations. The knee movements were calculated in relation to the extended reference position (see above).

The patients were examined in the supine position. Before the serial radiographs were exposed they performed trial extensions. Depending on the most comfortable speed of extension chosen by the patients the film exchanger rate was set at either 2 or 4 frames/second. The patients flexed the knee examined as much as the space between the examination table and the film exchanger allowed and they were asked to relax. A pair of radiographs were exposed to document this position. Then the active extension started. Both knees were studied.

*Knee extension in the standing position*. The patients ascended a platform about 40 cm high which was fastened to a metal frame (Figure 6). Two cassette holders moveable in the proximal-distal direction and perpendicular to each other were attached to the frame. The center of the cassette holders were adjusted to the level of the joint line. Reference plates were fastened to the holders. The film-focus distance was about one meter. Before the patient examination the calibration cage was radiographed together with the reference plates.

The patients placed the foot on the platform at about 100 degrees of knee flexion and were asked to push the foot against the platform corresponding to the first simultaneous exposures of the two x-ray tubes. At the subsequent exposures the patients were examined at increasing amount of extension weight-bearing only on the leg examined. The patients stopped the motion at each exposure. The examinations ended at maximum active extension. Five to six pairs of films were exposed for the injured and the intact knees.
Figure 3 (left) The examination set-up for measurements of AP laxity.
Figure 4 (right) The examination set-up for measurements of rotatory instability.

Figure 5 The examination set-up to study active extension in the supine position (left)
Figure 6 The examination set-up to study extension during weight-bearing (right)
3: Measurements of stereoradiographs

The images of the patient, reference cage or plate markers were numbered in a standardised way. On the reference examination the two tips of the tibial intercondylar eminence were plotted on the two views. These fictive points and the images of the tantalum markers were digitised on a measuring table originally designed for aerial photography (Wild Autograph A7 Z, Heerbrugg, Switzerland). The two-dimensional coordinates were stored in a microcomputer.

4: Mathematical calculations

Between 1984 and 1990 the software was adopted for microcomputers. This software has been improved by optimising the mathematical calculations and by adding more functions. In 1990 a comprehensive software package (UMRSA, UNIKUM, University of Umeå) was completed that has been subjected to further updatings. In this thesis the following programs in UMRSA were used.

**Xray.** This program transforms the film coordinates to the laboratory coordinate system defined by the cage. The true cage coordinates are stored in the computer. The three-dimensional coordinates of the patient markers are computed.

**Segment motion.** This program calculates the absolute movements of each rigid body (here: distal femoral and proximal tibial markers) relative to a reference position (here: the extended reference position or the flexed reference position). The movements of one rigid body relative to another can be calculated. The choice of fixed and moving body segment can be set arbitrarily. In most evaluations the distal femoral markers were used as fixed segment and the proximal tibial markers as the moving one. The calculation of rotations is performed in the following order: flexion/extension, internal/external rotation and adduction/abduction.

**Point transfer.** Transforms fictive points to subsequent examinations provided that they are placed in a bone segment identified by at least three non-linear markers. In this thesis the positions corresponding to the two tips of the intercondylar eminence were transformed to the same location in proceeding examinations by using the known positions of the tibial bone markers.

**Rotate.** This program supports defined rotations of the laboratory coordinate system.
**Point motion.** This program calculates three-dimensional translations of real or transformed fictive points

**Parallel transformation.** The origo of the coordinate system can be transform to a chosen point with known three-dimensional coordinates. This program was used to transform the origo of the laboratory coordinate system to the calculated position of the femoral ACL insertion point (VI).

**Kinerr, Number correction.** An interactive program that detects incorrect marking on focus 1 (usually the AP view). The maximum tolerated marker instability (mean error of rigid body fitting, Selvik 1974, 1989) can be predetermined which means that poorly defined or loose markers are excluded from the calculations.

**Kinerr, Pairing.** Corrects erroneous identification of tantalum markers on the two images of one examination.

**Evaluation of AP laxity (I–IV).** Calculation of the AP-laxity included three steps. The absolute tibial rotation between the extended and flexed unloaded positions were recorded. These rotations were used to align the laboratory coordinate system with the tibia in the flexed position (see Rotate above). The second step was to transform the fictive point corresponding to the two tips of the tibial intercondylar eminence to the subsequent examinations (point transfer). Finally the mean three-dimensional displacements of these points were calculated at anterior and posterior traction using the flexed and unloaded examination of the knee as starting position. This thesis only accounts for displacements along the sagittal axis of the tibia corresponding to the true anterior–posterior translations.

**Evaluation of knee kinematics (V, VI).** Translations and rotations were calculated in relation to the extended reference examination. The tibial rotations (internal/external, adduction/abduction) and translations (medial/lateral, proximal/distal, anterior/posterior displacements) were plotted in relation to the degree of knee extension providing a total amount of 5 diagrams for each knee examined. In the study of extension during weight-bearing (VI) the tibial markers were used as moving segment at five of the evaluations. In further one these markers were fixed at the mathematical computations to record anterior–posterior translation of a central femoral point. The rotations and translations were interpolated at intervals of 5° (V) or 20° (VI) of knee extension from the diagrams.
Evaluation of helical axes (VI). The three dimensional positions of the helical axes (Selvik 1974, 1989) were reconstructed between subsequent positions of extension. The axes were sorted into one of six intervals of knee extension (>80, 80−60, 60−40, 40−20, 20−0 and <0 degrees) comprising the major part of its range of motion. To assure correct positioning in relation to anatomical landmarks the origo of the laboratory coordinate system was adjusted by parallel transformation to the femoral insertion of the anterior cruciate ligament. The reconstruction of this location was obtained from a cadaver study (see below). The three dimensional coordinates for the helical axis intersection with each cardinal plane (frontal, horizontal and sagittal) were calculated. The angle between the helical and the transverse (x−axis) axes in the frontal and horizontal planes were computed. Within each interval of extension the mean values of all paired observations were presented. The mean position of the axis intersection with a sagittal plane through the femoral insertion of the anterior cruciate ligament was also calculated at each of the six chosen intervals of extension.

Accuracy of the RSA examinations

The stability and the scattering of the bone markers were quantified by the calculation of the mean error of rigid body fitting (Selvik 1974, 1989, Nyström 1990, Söderkvist 1990) and the configuration number of the markers in each bone segment (Söderkvist 1990, Nyström et al. 1992). The size of the mean error of rigid body fitting and configuration number in this thesis were in most instances less than 0.25 mm and 90.

The reproducibility of the AP (anterior−posterior translation, I−IV) and the rotatory (rotations about the longitudinal axis, II) laxity has previously been calculated at 0.8 mm (Kärrholm et al. 1988) and 1.7° (one standard deviation, Kärrholm et al. 1989).

Three patients had their examination repeated on the intact side during active extension (V) resulting in 10 paired observations for each rotation and translation. The standard deviations for internal/external rotation and adduction/abduction were 1.9° and 0.3° respectively. For the medial/lateral, proximal/distal and anterior/posterior translations corresponding values were 0.2, 0.2, 0.3 mm.

During extension and weight bearing (VI) a corresponding test of three patients (injured side, 15 paired observations) revealed standard deviations of 1.1°
and 0.3° (internal/external rotation, adduction/abduction) and 0.3, 0.8, 1.2 mm (medial/lateral, proximal/distal and anterior/posterior translations).

The direction and position of the helical axis is more sensitive to landmark measurement errors than the corresponding evaluation of translations along and rotations about the axes in a coordinate system. To evaluate the reproducibility of the helical axes a computer simulation was performed (Nilsson 1992) based on the condition number and the mean error of rigid body fitting. Landmark positions were sampled from a uniform distribution in the range 0–45 mm resulting in a mean condition number of 59.5. Landmarks perturbations were sampled with an unbiased normal distribution causing a mean error of rigid body fitting of 0.09. The corresponding mean values for mean error and configuration number in study VI was 0.06 and 84.

The error in helical axis direction decreases with increasing size of the moving rigid body. For the marker distribution usually available in the knee joint the direction error is less important than the position error (De Lange et al. 1990). The position error is determined by the size of the helical axis rotations and translations. The influence of these two factors were evaluated in two steps with a fixed screw axis translation of 5 mm at the first computation and a fixed helical axis rotation of 5° in the second one.

The mean positioning error for a screw axis rotations of 5° was calculated at 2 mm (Figure 7). Based on these calculations examinations representing rotations less than 5° were excluded. A translation along the helical axis of 5 mm revealed a mean error of 2.5 mm. The maximum translation observed in any of the patients was 4.3 mm (Figure 8)
The relative femoral ACL insertion was determined in 10 specimen. The knee joint was approached through a medial arthrotomy. The anterior cruciate ligament was removed. Tantalum markers were placed centrally and at the anterior and posterior edges of the femoral insertion of the ligament. The wound was sutured. The knee was placed inside the calibration cage and a pair of radiographs was exposed with the knee in 0 degrees of extension. The knee was aligned to the cage coordinate system in the same way as the reference position in the patient study.

The joint line was marked on the AP radiographs (A) (Figure 9). Further one line parallel to the first one was drawn at the level of the medial epicondyle (B). A box was created by two more lines (C, D) perpendicular to lines A and B and tangential to the medial and lateral borders of the condyles. The projections of the center of the femoral ligamentous insertion (a) on lines B and C were identified to calculate the quotients E/B and F/C. On the lateral radiographs a transverse line (G)
joining the most distant points on the anterior and posterior contours of the femoral condyles and one line along the Blumensaats line (H) were drawn. The projections of the center of the ligamentous insertion were identified enabling the calculation of the ratios J/H and I/G.

Figure 9: The quotients measured in the cadaver study to reconstruct the femoral insertion of the anterior cruciate ligament (a). * denotes the reconstructed center of the femoral condyles.

Radiographic measurements of tunnel positions

The tunnel positions were measured on the frontal and lateral radiographs of the extended knee two years after surgery (IV). The two year observation was chosen because the sclerotic margins of the tunnels could be most easily observed at that time. Achievement of full knee extension also enabled a standardised radiographic examination in that position. A digitising table (Ortho–Graphics Inc.™) connected to a personal computer was used for these measurements and corresponded to conventional radiographic measurements.
In patients operated with isometric graft positioning (IV) the femoral tunnel entrance was measured on the lateral radiographs as the midpoint between its sclerotic margins intersecting the Blumensaat line. In the OTT group (IV) these measurements could not be done because of absent bony definition. The relative tibial tunnel position was calculated in both groups (Figure 1). The locations of the tibial and femoral tunnel midpoints were compared with the normal insertions of the anterior cruciate ligament as evaluated on radiographs of cadavers (VI).

**KT 1000 (I)**

Both knees were placed on a thigh support and a footrest providing an estimated knee flexion of 30± 5° The arthrometer was fixed to the tibia with two velcro straps. Firm pressure was placed on the patellar pad by one hand. Anterior traction with 89 N was applied. The reference position was achieved by repeated posterior loads of 89 N until a reproducible unloaded position was obtained (within 0.5 mm on the dial). Repeated anterior tractions were performed until a constant reading on the dial was recorded. All tests were performed by the same examiner.

To evaluate the reproducibility of the KT-1000 measurements sixteen patients were tested twice in a random order. The examination table was divided by a screen and the examiner could only see the lower legs.

**Functional tests(III,IV)**

*Isokinetic muscle strength.* The peak isokinetic muscle strength performance of the quadriceps was measured with a Cybex® II dynamometer (Lumex, Inc New York) with the angular velocities set at 30° and 180°/ second. The dynamometers were calibrated by applying known loads to the lever arms, and differences between measurements never exceeded 2 Nm. In Umeå the patients were examined in the supine position with the hips flexed about 20°. The examination started with the normal leg at the highest velocity. The patient performed repeated extensions until no further increase in strength was noted. The peak values were selected and the injured/normal ratios calculated. In Boden the patients sat and performed three extensions with an interval of 10 seconds. The peak value was recorded.

*Figure of 8 run.* The patients ran in a figure of 8 track (Tegner et al. 1986B). They ran the track 3 times and rested one minute. This procedure was repeated three
times. The running times for the 2:nd to 5:th curves were added and the mean values calculated. The absolute running times were compared to a normal material (Elmqvist et al. 1988) previously examined in the same track (III). Patients operated in Boden and Umeå ran on different tracks (IV). The absolute values for the turn times were not comparable. Therefore the relative improvement in running time was calculated [Preop running time− 2 years postop running time/ preop running time].

**One leg hop.** The patients started to jump with the normal leg and jumped three times with each leg. The hands were placed on the back. The mean (III) or peak (IV) values were used to calculate the injured/intact ratio. (Tegner et al. 1986B)

**Functional and activity scoring.** Lysholm score and Tegner activity scales were used to estimate the subjective function and activity level before and after surgery. The first 11 patients in study III were preoperatively evaluated according to the original Lysholm score (Lysholm and Gillquist 1982) whereas all other evaluations were done according to the modified score (Tegner and Lysholm 1985). Preoperatively the patients were evaluated by the surgeons. In study III the two year examinations made by myself were used at the statistical calculations. In study IV all patients operated in Umeå were evaluated by me and those operated in Boden by the surgeon (YT).

**STATISTICS**

The statistical methods used are accounted for separately for each study in the results. For continuous variables the mean values and standard deviations are given. For the Lysholm and Tegner scores the median values and ranges are given. P−values less than 0.05 were regarded as significant.
SUMMARY OF PAPERS I–VI AND RESULTS

I. Knee laxity after cruciate ligament injury. The KT–1000 arthrometer versus roentgen stereophotogrammetry in 86 patients.

Patients and methods
Thirty-nine patients with unilateral chronic anterior cruciate ligament tears and 55 patients that had been surgically reconstructed were studied. Eight of these patients were assessed both before and after surgery. The examinations were performed on the same day except for the RSA measurements of the intact knees in the operated patients. They were radiographed once prior to surgery. In addition, the AP laxity was investigated in 100 consecutive patients with an unilateral ACL tear to determine the side to side difference injured–intact knees. The reproducibility of the KT–1000 was tested in 16 patients with unilateral old tear of the ACL.

Student’s paired T–test, Chi² test and Pearsons correlation coefficients were used at the statistical evaluation.

Results
In normal knees, the KT–1000 recorded about the same mean displacement as the RSA (5.9 and 5.5 mm respectively, r²= 0.3, p<0.001). In the injured knees the KT–1000 measured smaller laxity values than the RSA (10.5 and 12.8 mm respectively) without any correlation. Smaller displacements were also recorded with the KT–1000 in the ligament reconstructed knees ( 7.5 and 9.5 mm respectively, r²=0.2 ,p<0.01). The side to side difference before and after surgery revealed 2.8 and 2.4 mm smaller values when evaluated with the arthrometer. No correlation between the methods was observed (Figure 10 and 11).

The 100 unilateral ACL injured patients had an AP laxity of 5.3±2.1 mm in the normal knees and 12.8±3.8 mm in the injured knees with the RSA set–up. Cut off values of 2, 2.5 or 3 mm for the side to side difference corresponded to a sensitivity of 98%, 97% and 93% respectively in diagnosing ACL injuries.

A side to side difference of 3 mm for the KT–1000 and 2.5 mm for the RSA set–up was used to discriminate injured from normal knees. Fewer patients were
classified as ACL injured with the KT-1000 (28 patients, 72%) than with the RSA set-up (38 patients, 97%, KT-1000 vs. RSA p<0.01). More patients had their sagittal laxity reduced to "normal" according to the KT-1000 (35 patients, 64%; cut-off value of 2.5 mm: 33 patients 60%) than with the RSA set-up (16 patients, 29%, KT-1000 vs. RSA p<0.01).

The mean differences (first and second examination) and standard deviations in the reproducibility test of the KT-1000 were, -0.2 ± 1.1, -0.7±1.6 and 0.5± 1.5 mm for normal knees, injured knees and the side to side difference.

Figure 10,11 KT-1000 vs. RSA side to side knee difference in the ACL injured (left) and in the ACL reconstructed patients (right)

Conclusions

The KT-1000 measured smaller translations than RSA in injured and operated but not in normal knees resulting in smaller side to side differences. This arthrometer overrates the stabilising effect of reconstructive surgery using 89 N anterior traction compared to the RSA (150/ 80N force). A threshold value for the side to side difference with the RSA set-up separating about 95% of the ACL injured from normal patients would be about 2.5 mm. The reproducibility for the KT-1000
corresponded to values previously reported in the literature.

II. Brace effects on the unstable knee in 21 cases. A roentgen stereophotogrammetric comparison of three designs.

Patients and methods

Each of the three brace designs (SKB, ECKO and the modified Lenox-Hill) examined, were tested on seven ACL injured knees. Nineteen patients with unilateral and one with bilateral chronic ACL injuries were included in the study. The contralateral intact knees were also examined (SKB: n=7, Lenox Hill and ECKO n=6 for each). The AP displacement, rotatory laxity with and without anterior traction was examined. Both the intact and injured knees were evaluated.

Student’s t-test was used.

Results

The injured knees displayed an increase in AP laxity. The ECKO and the Lenox Hill braces reduced the AP instability in the injured knees with about one third but not to normal levels (Figure 12, Table 4). External or internal rotatory laxity did not differ between ACL injured and normal knees. None of the braces influenced the internal rotatory laxity (Table A–1, appendix). Only the Lenox Hill brace reduced the external rotation (Table A–2, appendix). At simultaneous anterior traction less external rotation (1.4°) was observed in the injured than in the normal knees (10.3°), (Table A–4, appendix). When analysing all three brace designs together they increased the external rotation (4.1°) but not to normal levels. Separately, none of the designs affected external rotatory laxity at simultaneous anterior traction. The internal rotatory laxity during concomitant anterior traction was about the same in the injured, normal and braced knees (Table A–3, appendix).

Conclusion

The modified Lenox Hill and the ECKO designs reduced AP laxity but not to normal levels. The braces had no or minimum effect on tibial rotations.
Table 4 AP Laxity in normal, injured and braced knees

<table>
<thead>
<tr>
<th></th>
<th>AP Laxity Difference</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mm (SD)</td>
<td></td>
</tr>
<tr>
<td>All cases</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Normal (N)</td>
<td>5.4 (2.1)</td>
<td>N-I -8.9</td>
</tr>
<tr>
<td>Injured (I)</td>
<td>14.6 (3.9)</td>
<td>I-IB 4.8</td>
</tr>
<tr>
<td>Braced (B)</td>
<td>9.8 (3.1)</td>
<td>N-IB -4.2</td>
</tr>
<tr>
<td>SKB</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Normal (N)</td>
<td>4.2 (1.4)</td>
<td>N-I -10.6</td>
</tr>
<tr>
<td>Injured (I)</td>
<td>14.8 (4.3)</td>
<td>I-IB 3.8</td>
</tr>
<tr>
<td>Injured-braced (IB)</td>
<td>10.1 (4.6)</td>
<td>N-IB -5.9</td>
</tr>
<tr>
<td>ECKO</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Normal (N)</td>
<td>5.8 (2.6)</td>
<td>N-I -5.9</td>
</tr>
<tr>
<td>Injured (I)</td>
<td>12.3 (3.9)</td>
<td>I-IB 3.8</td>
</tr>
<tr>
<td>Injured-braced (IB)</td>
<td>8.5 (2.3)</td>
<td>N-IB -2.3</td>
</tr>
<tr>
<td>Lenox Hill</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Normal (N)</td>
<td>6.4 (1.6)</td>
<td>N-I -9.9</td>
</tr>
<tr>
<td>Injured (I)</td>
<td>16.7 (2.2)</td>
<td>I-IB 6</td>
</tr>
<tr>
<td>Injured-braced (IB)</td>
<td>10.7 (1.8)</td>
<td>N-IB -4.3</td>
</tr>
</tbody>
</table>

Figure 12 Plotting of the AP laxity with (x-axis) and without brace (y-axis). Diagonal lines represent the difference with and without brace. O = SKB, □ = ECKO, △ = Lenox Hill.
III. Lengthening of anterior cruciate ligament graft. Roentgen stereophotogrammetry of 32 cases 2 years after repair

Patients and methods

Thirty-two consecutive patients with old ACL tears were operated on using the over the top technique. The first 19 patients had no augmentation (the NA group, Marshall et al. 1979). The following 13 patients had their grafts augmented with a polypropylene braid. The AP laxity was measured preoperatively, at 6, 12 and 24 months after surgery with RSA. The first 7 patients in the non augmented group were examined only with anterior traction at the preoperative examination. At the two-year follow-up subjective knee function and activity levels were recorded. The muscle strength and functional performance were also examined.

Quantitative continuous variables in the total material were analysed with Student’s t-test and Pearson’s coefficient of correlation. For sub-materials and qualitative variables the sign test and Spearman’s rank correlation coefficient were used.

Results

AP laxity. Six months after surgery the AP displacements were reduced with 5.4 mm (p<0.05) in the NA group (Figure 13), but it was still 2.4 mm larger than on the intact side. Eight of the 12 patients had their laxity returned within normal levels (side to side difference< 2.5 mm). During the following 18 months the AP laxity increased and at two years only two patients had a side difference of less than 2.5 mm.

Six months after surgery the A group (Figure 14) had less AP laxity (1.9 mm, p<0.01). Only one patient had a laxity within normal limits. At two years the AP laxity had returned to the preoperative level without any patients having normal side difference.

Functional scores and tests. The Lysholm score and Tegner activity level improved in both the non augmented and augmented groups. According to Lysholm 28 of the 32 had reached a level regarded as good or excellent (≥ 84). The injured knees had 0.82 to 0.89 of the intact knee muscle strength depending on the angular velocity at the examination. Using a ratio of 0.9 (Tegner et al. 1986A) or more as the goal for
the rehabilitation 16/32 reached that level at the fastest and 7/32 at the slowest angular speed. Patients with high activity levels (≥6) had greater muscle strength (180°/s, injured/intact: 0.94) than patients with lower activity levels (<6: 180°/s, injured/intact 0.81, p<0.05).

Both groups had longer turn times compared with a normal reference group (Elmqvist et al. 1988). Fifteen of the 32 patients had a turn time within +2 standard deviations of the reference population. The mean value of one leg hop quotient was 0.92. Twenty-five of the patients had a quotient being within 2 standard deviations of the reference group. There were no correlation between the translations recorded at the laxity tests (difference injured−normal) and function score, activity level, performance, or muscle strength.

Figure 13,14  AP laxity in the Non augmented group (NA) (left) and the Augmented group (A) (right). Triangles in the lower left corners of the diagrams denote the intact contralateral knees.
Figure 14, 15, 16 Scattergram of the side to side difference, injured–intact knees and the Lysholm score (left above), turn time (right above) and isokinetic muscle strength (right). O = NA group, Δ = A group. \( \bar{X} \) and +2sd denote the mean value and 2 standard deviations for a normal population (Elmqvist et al. 1988).
Conclusions

Two thirds of the patients with non-augmented and one patient with augmented repair had AP laxity within normal limits 6 months after surgery. An increasing AP laxity was noted six to twenty-four months postoperatively, suggesting inappropriate graft strength after the early remodelling and rehabilitation phase. Two years after surgery no correlation was observed between the laxity (side difference) and subjective or objective functional evaluations. Other factors than static stability may influence the subjectively evaluated knee function and functional performance.

IV. Over the top vs. tunnel technique reconstruction of the anterior cruciate ligament. A prospective randomised study.

Patients and methods

Fifty-four patients with chronic ACL rupture were operated on with patellar-quadriceps tendon graft augmented with a polypropylene braid (Kennedy-LAD). The femoral placement of the graft was randomised to either a modified over the top (OTT) or a tunnel position obtained by an isometric drill guide (ISO). Four patients could not participate in the standardised postoperative rehabilitation program because of additional surgical procedures leaving 24 in the ISO and 26 in the OTT group to be evaluated. The AP laxity was measured with RSA preoperatively and after 6, 12, and 24 months. Subjective evaluation of knee function, activity level, muscle strength tests and functional tests were done preoperatively and at the 2–year follow-up. The relative tibial (both groups) and femoral (ISO group) tunnel positions were measured on the RSA radiographs.

To decrease the number of statistical tests the Hotellings T2 test was used to evaluate continuous variables preoperatively and at 2 years (AP laxity, muscle strength, one leg jump, turn time ratio, age, duration, tunnel position). Complete follow up data was necessary to be included in this test. If a significance was observed separate analysis of the variables included in the test was performed with a univariate F-test. Pearson’s coefficient of correlation was also used. The non continuous quantitative (subjective) and qualitative variables were evaluated with the Wilcoxon rank sum and the chi² test. Changes within the groups (preoperative – 2 years) were evaluated with the paired Student’s t test or Wilcoxon signed rank test.
Results

No difference was observed between the ISO or OTT group regarding AP-laxity, muscle strength, one leg hop, improvement in turn time or activity level two years after surgery. The OTT group had a higher Lysholm score than the ISO group (p<0.04, Table 5). The AP laxity was reduced in both groups at 6 months. No increase in laxity was observed in either of the groups during the following 18 months.(Figure 17).

Tunnel position. The tibial tunnel position in anterior–posterior direction slightly influenced ($R^2=0.11$, $p<0.05$) the improvement in laxity, i.e., an anterior position revealed less improvement. In the ISO group the femoral and tibial tunnel positions on the lateral view were anterior to the anatomical insertion center of the ACL in relation to data from a cadaver study. No correlation was observed between the femoral position and the improvement in laxity.

![Figure 17 Changes of mean AP laxity for the ISO (triangle) and OTT (square) during follow-up. The AP laxity of the contralateral intact knees to the lower left.](image-url)
Table 5 Pivot shift and subjective scores and functional tests. 30°/s, 180°/s indicate isokinetic muscle strength. a: Ratio injured/intact knee b: Improvement in turn time: (Preop time–Postop time/ preop time). Median (range) and mean (SD) values are reported.

<table>
<thead>
<tr>
<th></th>
<th>OTT 2-years</th>
<th>ISO 2-years</th>
</tr>
</thead>
<tbody>
<tr>
<td>n=25</td>
<td>n=22</td>
<td></td>
</tr>
<tr>
<td><strong>Pivot shift –/+</strong></td>
<td>16/9</td>
<td>17/5</td>
</tr>
<tr>
<td>Lysholm</td>
<td>90 (56–100)</td>
<td>81.5 (34–100)</td>
</tr>
<tr>
<td>Tegner</td>
<td>7 (0–9)</td>
<td>6 (0–10)</td>
</tr>
<tr>
<td>30°/s</td>
<td>0.87 (0.2)</td>
<td>0.83 (0.1)</td>
</tr>
<tr>
<td>180°/s</td>
<td>0.91 (0.1)</td>
<td>0.86 (0.1)</td>
</tr>
<tr>
<td>One leg Hop (^a)</td>
<td>0.94 (0.1)</td>
<td>0.86 (0.1)</td>
</tr>
<tr>
<td>Fig 8 run (^b)</td>
<td>0.06 (0.1)</td>
<td>0.07 (0.2)</td>
</tr>
</tbody>
</table>

**Function and stability.** No correlation was observed between functional scores, tests, muscle strength and the side to side difference at two years except for the Tegner score ( R\(^2\)=0.1). Separating the patients into stable and unstable showed that the stability affected knee function. (Table 6)

Table 6 Stability and function. \(^a\) indicate the p-value for the Hotellings T2 test for the continuos variables (muscle strength and one leg jump). Median (range) and mean (SD) are given.

<table>
<thead>
<tr>
<th></th>
<th>AP laxity</th>
<th>Pivot Shift</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Difference operated–intact</td>
<td></td>
</tr>
<tr>
<td></td>
<td>&lt;2.5 mm</td>
<td>≥2.5 mm</td>
</tr>
<tr>
<td>Lysholm</td>
<td>85 (56–100)</td>
<td>86 (34–100)</td>
</tr>
<tr>
<td>Tegner</td>
<td>7 (4–10)</td>
<td>6 (0–9)</td>
</tr>
<tr>
<td>30°/s</td>
<td>92 (18)</td>
<td>82 (12)</td>
</tr>
<tr>
<td>180°/s</td>
<td>93 (12)</td>
<td>86 (12)</td>
</tr>
<tr>
<td>One leg hop</td>
<td>0.9 (0.1)</td>
<td>0.9 (0.1)</td>
</tr>
</tbody>
</table>

**Conclusions**

Both the OTT and the ISO group displayed decreased AP laxity 6 months after surgery without any difference. No increase in laxity was observed during the
following 18 months. Less than one third of the patients displayed values within normal limits two years after surgery. Despite the isometric drill guide the femoral and tibial tunnels were positioned too far anterior. The theoretical advantages of using the drill guide aiming for an isometric graft placement could not be verified. Patients with AP laxity within normal limits displayed better functional outcome.

III+IV. Postoperative examination of AP laxity

Patients and Methods

The AP laxity was measured the day after surgical reconstruction, after 3, 6, 12 and 24 months in eight patients. Seven patients were operated with the OTT and one with the ISO technique. Patients operated under epidural anaesthesia and the catheter left in place for the postoperative analgesia were asked to participate. Two patients from study III and six patients from study IV agreed. The postoperative brace was removed during the examination.

Results

The day after surgery the mean side difference (operated-intact knee) was close to normal (1.7±3.6 mm). An increase in laxity was observed during the first three months but not thereafter. Individual analysis displayed an improvement for all patients. Two patients seemed to be too tight (side difference <-2.5 mm), two had AP laxity within normal limits and four had the side difference reduced without reaching normal limits (Figure 18,19)

Conclusions

Surgery reduced AP laxity in all patients but were within "normal" in only two of them. The laxity increased during the first three months of the rehabilitation period.
Figure 18, 19 The eight patients examined the day after surgery. To the left the mean values and standard deviations. To the right the individual values. Seven patients were operated with the OTT and one (open square) with the ISO technique.

V. Kinematics of active knee extension after tear of the anterior cruciate ligament.

Thirteen patients with unilateral ACL injuries were examined during active extension of the knee with a load of 30 N at the ankle.

At the statistical calculations Student's t-test were used. Only paired observations were evaluated. To compensate for unequal number of measurements from different patients the mean differences (intact–injured) were computed throughout the range of extension in each patient and thereafter in the total material. Thus each patient constituted one observation. When a difference was found further calculations were performed to evaluate if these variations were unevenly distributed between the
separate intervals of 5° of extension.

Results

Rotations: (Figure 20, 21). In the starting position at about 30° of flexion the tibia had an internally rotated and an adducted position. Extension was associated with external rotation and abduction without any significant difference between the two sides.

![Diagram showing tibial rotations about the longitudinal axis (internal-external rotation) during active extension. Numbers of paired observations for each 5° interval of extension at the top.](image)

![Diagram showing tibial rotations about the sagittal axis (adduction-abduction).](image)

Figure 20 (left) Tibial rotations about the longitudinal axis (internal-external rotation) during active extension. Numbers of paired observations for each 5° interval of extension at the top.

Figure 21 (right) Tibial rotations about the sagittal axis (adduction-abduction).

Translations. (Figure 22, 23, 24) During extension the tibial intercondylar eminence displaced laterally, distally and anteriorly. The amount of lateral translation was
about the same on the two sides. The distal translation was more pronounced in the injured knees (0.8 mm, p<0.001). Separate analysis at each 5° interval of extension revealed an average increase of 1.9 mm at the beginning of the extension. The difference decreased with proceeding extension and disappeared at 5°. Increased anterior translation (mean 1.9 mm, p<0.05) was recorded on the injured side. Separate analyses revealed significant differences (p<0.01) only at 10° and 15° of knee flexion.

Conclusions

Absence of the anterior cruciate ligament was associated with increased anterior and distal displacements of the tibial intercondylar eminence. Close to full extension the tibial movements normalised.

Figure 22 (left) Translations of the tibial intercondylar eminence along the transverse axis (medially-laterally)

Figure 23 (right) Translations of the tibial intercondylar eminence along the longitudinal axis (proximally-distally).
VI. Three dimensional knee joint movements during weight-bearing

The kinematics of the knee was studied in thirteen patients with chronic unilateral anterior cruciate ligament injuries during weight-bearing.

For the statistical analysis a three factor ANOVA was applied. The patient was considered as random factor, the condition of the knee (healthy vs. injured) and the degree of flexion as fixed factors. Only paired observations were analysed.

Results

Rotations. From an internally rotated position the tibia rotated externally (screw home mechanism) without any difference between injured and the intact knees (Figure 25). There were almost no rotations about the sagittal axis (Figure 26).
Translations. From a medial (Figure 27) and proximal position (Figure 28) the tibial intercondylar eminence translated laterally and distally during the extension (injured vs. intact, n.s.). The tibial intercondylar eminence in the injured knee was up to 2.1 mm (mean value at 60° of flexion) more posterior displaced during the extension (p<0.05; Figure 29).

Helical axes. At the beginning of the extension the helical axes were positioned within or close to the femoral insertion of the anterior cruciate on both sides (Figure 30, 31). The mean axis was positioned distal to (all intervals) and in front of the center of the ligamentous insertion (past 80 degrees of extension). During the progress of the extension the inclination of the axis increased in the frontal plane from 1.2° to 20–26.6° close to full extension corresponding to distal displacement of the axis in the lateral condyle and proximal displacement in the medial one.

In the horizontal plane the mean axes on the intact side were almost parallel to the transverse axis of the coordinate system at 80 and 60 degrees of knee flexion. Between 60 and 0 degrees the inclination increased on the intact side corresponding to anterior displacement of the axis inside the medial condyle. On the injured side a corresponding obliquity was observed from the beginning of the extension. Both sides displayed a more transverse course at hyperextension.

Conclusions

In knees with absent anterior cruciate ligament the intercondylar eminence had a more posterior position during the extension. This may indicate compensatory muscular mechanisms. At the beginning of the extension the helical axes were close to the femoral insertion of the ACL and parallel to the joint line indicating some influence of the ligament for the tracking of knee motion or that the circular center of the posterior femoral condyle coincides with the insertion site. From this position the axes moved anteriorly and distally on the lateral side suggesting more translatory movements in the medial compartment. The changes in the three dimensional positions of the helical axes imply that limited conclusions can be drawn about knee kinematics based on two dimensional evaluations.
**Figure 25** Tibial rotation about the longitudinal axis (internal–external rotation) in the normal and injured knees. Number of paired observations for each degree of flexion at the bottom.

**Figure 26** Rotation about the sagittal axis (adduction–abduction).
**Figure 27** (left above) Translation of the two tips of the tibial intercondylar eminencia along the transverse axis (medial–lateral).

**Figure 28** (right above) Tibial translation along the longitudinal axis (proximal–distal).

**Figure 29** (right) Translation along the sagittal axis (anterior–posterior).
Figure 30 Mean positions of helical axes and angles relative the transverse axis in the frontal and horizontal planes. The origo is the reconstructed position of femoral insertion of the anterior cruciate ligament based on ratios obtained from the cadaver study. The numbers (1–6) indicate each interval of flexion from $100 - 80^\circ$ (1) to hyperextension $> 0^\circ$ (6). The knee contours were reconstructed from one of the patients in the study.

Figure 31 Intersections of the helical axes with a sagittal plane through the femoral insertion of the anterior cruciate ligament.
DISCUSSION

Measurement of knee laxity

Instruments measuring knee laxity have been developed to avoid the uncertainty of manual tests (Daniel et al. 1991). Numerous studies have reported good or acceptable reproducibility of commercially available arthrometers (Malcolm et al. 1985, Hanten and Pace 1987, Highgenboten et al. 1989, Bach et al. 1990, Steiner et al. 1990, Wroble et al. 1990, Anderson et al. 1992). In an autopsy study Daniel et al. (1985A) reported high correlations between the KT-1000 readings and measurements of skeletal displacements. Later, several authors have questioned these devices. In inexperienced hands it is difficult to separate ACL injured from normal knees (Stryker/OSI laxity tester, King and Kumar 1989). Even in skilled hands the clinical examination has been reported to be a better tool to diagnose ACL ruptures than arthrometers (Anderson et al. 1989, Graham et al. 1991). Forster et al. (1989) observed unexpected variability in the laxity measurements during the follow-ups after ACL surgery. After assessing the intra- and inter-examiner variability they were reluctant to use the KT-1000 as an unbiased arbiter of ACL surgery.

The measurements with the externally applied devices are distorted by the patello-femoral alignment and the soft tissues (Edixhoven 1987, Granberry et al. 1990, Shino et al. 1987, Fridén et al. 1992B). These sources of error are completely avoided using radiography. Some correlation between the KT-1000 and uniplanar radiographic techniques has been observed although the numerical values differed. The correlation coefficients has varied between 0.6–0.7 (Moyen et al. 1990, Stäubli and Jakob 1991). Almost the same correlation was recorded in our study (r=0.6), but only in the intact knees. Fridén et al. (1992B) compared their RSA set-up with the Stryker/OSI laxity testers in eleven injured or operated knees. They recorded a correlation of 0.8.

The relative femuro tibial position before the loads are applied may vary depending on several factors (Kärrholm et al. 1988, Jonsson and Kärrholm 1990). It is difficult to reproduce the same reference position for different arthrometers (Moyen et al. 1990, Stäubli and Jakob 1991) or for the same arthrometer in longitudinal studies. The anterior play varies depending on the knee flexion, whereas the AP laxity is less sensitive for the flexion angle (Andersson and Gillquist 1990). Thus, recordings of the laxity between anterior and posterior
endpoints seem to be superior in terms of reproducibility (Wroble et al. 1990). Further, measurements of the anterior play (e.g. stressradiography, KT–1000) or between anterior and posterior endpoints (e.g. RSA set-ups, the Stryker/OSI arthrometer) may be one important reason for absent or poor correlations between these techniques.

Normal side to side difference has been determined to establish the threshold value discriminating the ACL injured from the normal knee. This value is device specific and reflects the reproducibility of the arthrometer (Steiner et al. 1990). The RSA, being an invasive method has not been evaluated by bilateral measurements of healthy knees. Therefore, the side to side difference indicating rupture of the anterior cruciate ligament has been estimated indirectly. The chosen limit of 2.5 mm was more than two standard deviations of the reproducibility for two different RSA set-ups (Kärrholm et al. 1988, Fridén et al. 1992A). This limit could also correctly diagnose about 95% of the ACL injured patients.

The amount of displacement is influenced by the size of load applied (Bach et al. 1990, Steiner et al. 1990, Fridén et al. 1992A, B, Edixhoven et al. 1989, Shino et al. 1987). The rationale for using different loads in study I was that we were interested in the clinical implications the choice of method had. In the RSA set–up we used 150 N anterior traction and 80 N posterior tractions which were the largest loads that could be applied without discomfort to the patients. The KT–1000 was introduced with 89 N anterior traction, which is still the standard force in use. More patients had their ACL injury diagnosed and fewer patients had returned to normal stability after surgery according to the RSA set–up than the KT–1000 (I). Similar result was reported by Moyen et al. (1992). They examined ACL reconstructed patients two years or more after surgery with stressradiography and the KT–1000. The mean side to side differences measured with the arthrometer were within normal limits (<3mm) irrespective of the force applied. With the stressradiography (90 N, Moyen et al. 1990) the mean displacement of the medial and lateral tibial compartment exceeded 4 mm which is consistent with our findings.

In normal knees the higher force used with the RSA did not increase the displacement significantly, probably because of a rapid increment in stiffness in normal knees. In the injured knees the KT–1000 recorded smaller displacements, probably because of smaller loads and a more gradual increase in stiffness (Markolf et al. 1976, Edixhoven et al. 1989). Based on unequal reproducibility of the two methods and recommendations in the literature (Daniel et al. 1985B) we used
different threshold values to diagnose pathological laxity. When the same threshold value was used for the KT-1000 (2.5 mm, Steiner et al. 1990) the results were about the same.

Greater applied forces (maximum manual drawer, MMD, about 134–178 N, Daniel et al. 1985B) have been reported to improve the diagnostic accuracy of the KT-1000 (Anderson et al. 1992), but this observation has not been confirmed in other investigations (Bach et al. 1990, Steiner et al. 1990). Paper I was not designed to evaluate the reason for the diverging results of the two methods, but based on previous studies it is reasonable to presume that not only the size of the applied forces was important. Factors related to the technique of measurement and application of forces had most certainly an influence on the results.

Treatment of the anterior cruciate ligament injured knee

Braces. Braces are widely used to protect the ACL reconstructed knee and to restore stability after ACL rupture. Subjectively, they seem to improve performance (Colville et al. 1986, Cook et al. 1989, Mishra et al. 1989). Two of the braces in the present study (ECKO, modified Lenox Hill) reduced the AP laxity but not to normal levels. Forces acting on the ACL during daily activities peak up to 450 N (Morrison 1970, Grood et al. 1976, Noyes et al. 1984). The examinations in paper II were made with smaller loads (150N anterior/ 80 N posterior forces ) than would be expected during daily activities. This suggest that the mechanical effect of the braces was not underestimated.

Forced internal tibial rotation is a primary mechanism for ACL injury. Beynnon et al. (1992) noted that some braces reduced the strain in the ACL at an internal torque of 5 Nm, but this protecting effect disappeared with increasing torques. In paper II anterior traction (150 N) was added to the torque to mimic forces resulting in giving way episodes. The braces did not affect internal rotation with or without anterior traction. Thus, the tested braces did not appear to have any capability to protect the knee against dangerous internal rotations.

With simultaneous anterior traction and external torque the injured knees displayed decreased external rotatory laxity compared to the intact knee. Kärrholm et al. (1989) observed this phenomenon in a study including some patients in study II and believed that it was an effect of impingement of the posterior edge of the lateral tibial plateau on the lateral femoral condyle. A similar phenomenon may occur when the subluxated lateral tibial plateau is reduced after a giving way
episode (Galway and MacIntosh 1980). The braces in our study did not protect the knee against this impingement although some of them reduced the anterior tibial translation. Even if a brace has to resist small forces (Shino et al. 1993) to restore normal kinematics during the swing phase (Marans et al. 1989) the inability of the braces to completely reduce the pathological laxity (modified Lenox Hill, ECKO) with small forces make us reluctant to recommend them from a biomechanical standpoint.

**Surgery – AP laxity.** In some patients (III) the same or almost the same displacements were recorded before and six months after surgery, indicating insufficient stability at surgery, early graft elongation or rupture. Recent laboratory studies showed that neither the OTT nor isometric graft positioning can normalise the AP laxity (Brower et al. 1992). In the eight patients (III,IV) examined the day after surgery the mean side to side difference was 1.7 mm suggesting that normal or close to normal AP laxity could be obtained (Figure 18). It was noticed when analysing these patients separately that the early stabilising effect of surgery was variable (Figure 19). Other studies examining patients within a few days or immediately after surgery indicate that the operated knees tend to become tighter than the contralateral knees at surgery (Malcom et al. 1985, Moyen et al. 1992, Good 1993).

During the proceeding three months the AP-laxity increased to a level that remained almost the same throughout the observation period. Moyen et al. (1992) observed an increase in anterior laxity within the first two to three months in knees operated with the OTT technique with and without the Kennedy LAD augmentation. Almost no change in the side difference was observed during the following three years. Contrary to our observations the mean side to side differences were within normal limits (89 N, KT–1000 ). The time for the elongation coincides with the remodelling phase for the biological grafts, when their strength is reduced (Alm et al. 1974, Kennedy et al. 1980, Clancy et al. 1981). Increasing AP laxity during the postoperative months and the presence of abnormal laxity in most of the operated knees in papers III and IV support that the surgical procedure and the early rehabilitation period are major determinants for the long term outcome.

A progressive increase in AP laxity could be observed during the proceeding 18 months of observations in the non augmented group (NA, III) ending with none of the patients having AP laxity within normal limits. This graft has been found to
be one of the weakest structures used for ACL reconstructions (Noyes et al. 1984A). Animal studies (McPherson et al. 1985) have demonstrated that this weakness persists for a long time. Perhaps they never get a tensile strength exceeding 50% of the normal ACL. Good (1993) observed a corresponding increase in AP laxity during the two postoperative years with bone–patellar–bone, the strongest autograft available (Noyes et al. 1984A). This development calls for other explanations than ultimate graft strength at the time of surgery. In their study grafts that had been tightened at the flexion angle providing the shortest distance between the insertion sites were predisposed to failure.

The surgical treatments used in this thesis yielded small differences in the AP laxity at the follow-up examinations. The augmented group in study III displayed a small improvement in AP laxity six months after surgery. One year or later this improvement had disappeared indicating that the augmentation did not protect the graft from failure. The knees in study IV had almost the same AP laxity six months after surgery as the augmented group in study III, but during the following period no further lengthening occurred maybe reflecting improved surgical technique. The NA group (III) were about 1 mm tighter six months after surgery than any of the other groups. These variabilities in patterns of postoperative elongation might have been an effect of the graft used, but may also reflect different rehabilitation protocols.

In our study no difference in AP laxity was observed at two years between the groups. Inability to achieve a correct anatomical position despite the use of the drill guide might be one explanation. Good et al. (1987) evaluated the precision of the Stryker drill guide by measuring the femoral and tibial tunnel placement on lateral radiographs calculating ratios in a similar manner as in this study. They obtained a femoral position ratio coinciding with the anatomical ligament insertions observed in a cadaver study. According to their observations the average position of the femoral tunnel in our study was correct whereas the tibial tunnel was slightly more anterior than the ideal one. Our own specimen data (Jonsson and Kärrholm 1992) suggested a location of both tunnels which were anterior to the anatomical positions, indicating that isometry was not obtained. Aglietti et al.(1992) and Good et al. (1993) demonstrated that a too anteriorly positioned femoral ACL attachment predisposed for graft to fail. In study IV the femoral tunnel position did not correlate to the AP laxity at two years. Differences in the assessment of the tunnel position or the graft used (Agletti et al. 1992, Good 1993) might explain this
discrepancy. Weaker grafts (Noyes et al. 1984A) and early elongation (IV) might also have reduced the influence of a too anterior femoral attachment.

A source of graft failure is impingement at the notch because of a too anterior and lateral tibial tunnel placement (Yamamoto et al. 1992). Notchplasty can to some extent compensate for this malpositioning (Yaru et al. 1992, Howell et al. 1991). In our study the influence of the tibial tunnel position on the anterior-posterior stability was small. This could partly be due to the routinely performed notch plasty. Some degree of graft impingement can even exist without jeopardising stability (Howell et al. 1992). Increased laxity and slackening of the graft may have reduced the negative effects of subsequent impingement.

**Knee stability and function**

Lysholm and Gillquist (1982), Johnson et al. (1984) and Odensten et al. (1985) observed that knee laxity correlated to the patients evaluation of knee function. Noyes et al. (1984) emphasised that the subjective evaluation of knee function should be combined with activity level evaluation. They developed a scoring system with this purpose in mind (Cincinatti rating system). Harter et al. (1988) modified this rating scale but failed to find any relationship with objective laxity measurements (KT-1000).

In papers III-IV there were no or almost no correlation between injured-intact AP laxity difference and the subjective functional scoring, activity scaling, muscle strength, functional performance. Classification of the knees into stable and unstable knees according to RSA measurements or pivot shift (IV) indicated that instability was of importance, but should be decreased to normal or almost normal to have a significant effect on the results.

Many scores and tests have been used for the evaluation of ligament surgery. Some authors suggest a comprehensive evaluation including knee function, activity level, laxity examination and functional tests (Kdolsky et al. 1992, Müller et al. 1988, the IKDC form). Others favour separate evaluation of the different parameters (Tegner and Lysholm 1985). Clinical examinations of knee stability only evaluate passive knee restraints, whereas functional stability is a more compound entity (Noyes et al. 1980) also including factors such as muscle strength (Tegner et al. 1986A) and proprioception (Barrett 1991).

According to the Lysholm score most patients in study III and IV would be regarded as having good or excellent results whereas few had postoperative AP
laxity within normal limits. The Lysholm score classifies more patients as good or excellent compared to other combined evaluation forms (Howe et al. 1991, Engström 1993). This is not surprising in the light of the inconsistency between the Lysholm score and AP laxity found in our studies (III, IV).

**Knee Kinematics**

Skeletal motions and clinical tests of joint stability occur in three dimensions even if a specific component of the motion or stability usually is in focus. The anterior drawer and Lachman tests start with the tibia in a reference position (Lachman about 20° of knee flexion) and rotations and translations are defined according to a coordinate system (Daniel and Biden 1987) fixed to the tibia. Continuous joint motion is more complicated to assess or describe. The coordinate systems used, their positions in relation to skeletal landmarks and the precision of landmark identification (radiographs or external digitization) vary making comparisons between kinematic studies difficult (Penncock and Clark 1990, Kurosawa et al. 1985, Grood and Suntay 1983, Lafortune and Canavgh 1984, Huiskes et al. 1985). Further, three-dimensional movements with six degrees of freedom may be difficult to transform into anatomical terms. The motion can also be calculated as rotation and translation in relation to one helical axis. This method is less dependent on the coordinate system used (Huiskes et al. 1985).

Changes in the pattern of motion has been proposed to be responsible for knee deterioration (Berchuk et al. 1990, Marans et al. 1989). RSA examinations of controlled weight-bearing (VI) or active flexion and extension (V) without ground reacting forces do not mirror the complexity of the gait restricting the conclusions to be drawn. The multidirectional instability observed at active flexion (Kärrholm et al. 1988) was reduced at extension with (VI) and without (V) weight bearing or during gait (Marans et al. 1989).

Palmer (1938) and Van Dijk (1983) suggested that the screw home movement at the end of the extension was controlled by the ACL, muscle activity and joint geometry. Hallen and Lindahl (1966) questioned its existence and Marans et al. (1989) did not observe it during gait. During active knee extension (V) or extension and weight-bearing (VI) we observed a screw home motion. Contrary to the situation during active knee flexion (Kärrholm et al. 1988) there was no difference between the intact and injured knees, suggesting variable function of the ACL.
depending on the direction and presence of the muscular and ground reacting forces.

**Kinematics and physiotherapy after surgery.** In the immediate postoperative period the graft fixation (Kurosaka et al. 1987) and later the biological graft (Alm et al. 1974, Arnoczky et al. 1982, Kennedy et al. 1980, McPherson et al. 1985) restricts the rehabilitation protocol. Active knee extension with weights at the ankle is commonly used for knee rehabilitation. Indirect calculation during isometric or dynamic quadriceps contraction has revealed anteriorly directed shear forces in the knee at a flexion angle less than 30–45° peaking up to 600 N (Yasuda and Sasaki 1987 B, Nisell 1985). Recently Shino et al. (1993) assessed much lower loads (23N) in the reconstructed ACL grafts during active extension or straight leg raise in vivo. Beynnon et al (1992,1993) have documented increased strain the anterior cruciate ligament close to full extension. Grood et al. (1984) registered an increased mean anterior tibial displacement of 3.8 mm at 15° during extension after cutting the ACL in five cadavers knees. Under similar loading conditions we found mean distal and anterior displacements of about 2 mm in the injured knees that were reduced close to full extension. The difference between the cadaver study and ours may be due to synergistic activity by the hamstring muscles (Solomonow et al. 1987).

Simultaneous quadriceps and hamstring contractions reduce the anteriorly directed shear forces (Yasuda and Sasaki 1987A). Axial load stabilise the knee further (Markolf et al. 1981, Hsieh and Walker 1976). Quadriceps contractions in the standing position up to 15° of knee flexion has been suggested in the early rehabilitation because this activity does not produce anteriorly directed shear forces especially with the hips slightly flexed (Ohkoshi et al. 1991). Shino (1993) recorded peak values of 84 N in the ACL graft during gait and Beynnon et al.(1993) found a 4% increase in the strain during squatting. Contrary to an in vitro study by Reuben et al. (1989) we found that the tibia was more posteriorly displaced on the injured side than on the intact side during extension and weight bearing (VI).

Changed pattern of motion reducing quadriceps activity has been observed during gait (quadriceps avoiding gait, Berchuk et al. 1989). Altered movements and muscle activation patterns have been found to reduce anteriorly directed shear forces during one leg hop in well rehabilitated chronic ACL injured patients (Gauffin and Tropp 1992). Increased hamstring activity seems to be an important
part in this functional adaptation (Solomonow et al. 1987, Branch et al. 1989) and could also be responsible for our results (VI).

**Helical axes.** In the study of simultaneous weight-bearing and extension (VI) the helical axes intersected the lateral femoral condyle closer to the joint line on the lateral than on the medial side during the major part of the extension. This implicates more rolling on the lateral side and more gliding on the medial one. At about 90° of flexion the helical axes were approximately parallel to the joint line suggesting an even distribution of these motions. Blankevoort et al. (1988) found that passive knee motion was restricted by soft tissue stiffness enveloping a certain range of internal/external rotation and adduction/abduction. Inside this envelope axial loads were the main constrain to the motion. Therefore, it would be difficult to find any reproducible axes within the limits of normal rotational laxity. Van Dijk (1983) examined cadaver knees during flexion and found a similar pattern for the helical axes as in our study (VI). Flexion of the internally or externally rotated tibia resulted in changed positions of the helical axes and especially during external rotation. The variability of the axes positions in our study increased close to full extension. This might be due to that joint geometry enabled the patients to choose alternative patterns of motion close to full extension whereas the circular shape of the posterior femoral condyles (Kurosawa et al. 1985) restricted the motion to a defined path at 100 to 80 degrees of flexion. Probably this variability would have been less if continuous active motion had been recorded.

In study VI the mean helical axis was positioned close to the femoral insertion of the anterior cruciate ligament at about 90° of flexion moving anteriorly during extension in agreement with the femoral centrode and previous cadaver studies by van Dijk (1983). The pattern for the displacement of the helical axis in study VI displayed a more complex pattern that would be expected according to the four bar linkage model. This discrepancy can be explained by simultaneous rotations about the longitudinal axis. These rotations make a plane perpendicular to the femoral centrode not parallel to any sagittal plane. Further, the four bar linkage model requires two non elastic bars whereas the tension in the cruciates varies during motion (Kurosawa et al. 1991). The ACL injured knees revealed almost the same helical axis displacement in the sagittal plane suggesting other or supplementary explanations for the tracking of knee motion than the cruciates. Blascharski et al. (1975) concluded that joint geometry was the major determinant for knee
kinematics. The tracking of the knee motion is probably controlled by joint geometry, ligaments and muscle activity.
GENERAL CONCLUSIONS

Measurement of knee laxity

• When used with 89 N the KT-1000 measured smaller translations than RSA in injured and operated but not in normal knees resulting in smaller side to side differences. The diagnostic sensitivity of the KT-1000 is inferior and this arthrometer may overrate the stabilising effect of reconstructive surgery. (I)

• Using the RSA set-up a side to side difference between the knees of 2.5 mm would indicate a rupture of the anterior cruciate ligament in more than 95 of 100 patients (I)

• The reproducibility of the KT-1000 in our hands did not deviate from other studies. (I)

Knee stability and function

• Subjectively nine out of ten patients rated their knee function good or excellent two years after surgery and about half of them reached satisfactory results according to the functional tests. Only one out of ten patients had their knee laxity in the operated knee returned within normal limits. (III)

• No numerical correlation was observed between the AP laxity (side to side difference) and subjective or objective functional evaluation. If the laxity was reduced within normal limits the patients had higher activity levels or were stronger and performed better in the one leg hop tests. (III, IV)

Treatment of the anterior cruciate ligament injured knee

• Two of three braces investigated partially reduced the AP laxity. The internal rotatory laxity was not affected. The external rotatory laxity was reduced by one of the designs. (II)

• Six months after surgery about one third of the patients had an AP laxity within normal limits. Increasing AP laxity was observed after six months suggesting inappropriate graft strength even after the early remodelling and rehabilitation phase. (III)
• The isometric ACL placement with the aid of a drill guide did not offer any advantages compared to the over the top technique. (IV)

Knee kinematics

• Absence of the ACL ligament was associated with increased anterior and distal displacements of the tibial intercondylar eminence during active knee extension in the supine position. (V)

• During extension and weight-bearing lack of ACL was associated with posterior displacement of the tibial intercondylar eminence. (VI)

• Between 100° and 80° degrees of knee flexion during the extension and weight-bearing the helical axes were close to the femoral insertion of the ACL and parallel to the joint line. From this position the axes moved anteriorly and distally on the lateral side suggesting more translatory movements in the medial compartment. The changes in the three-dimensional positions of the helical axes observed imply that limited conclusions can be drawn from two dimensional models (VI).
ACKNOWLEDGEMENTS

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The MPC:s of Boden for fruitful discussions throughout the years

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APPENDIX

Tables A1 – 4. Rotatory laxity in normal and ACL injured knees with and without braces. Each brace design was tested on seven injured knees. Seven (SKB group) or six (ECKO, Lenox Hill) contralateral normal knees were used as controls.

### Table A–1 Internal rotation

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<th>p–value</th>
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### Table A–2 External rotation

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### Functional score

- **6m, 12m, 24 m**: 6, 12, 24 month examination of AP-laxity
- **2L**: 2 year Lysholm score
- **2T**: 2 year Tegner score

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**Sex**: M = male, f = Female  
**Dur**: Duration injury–examination or surgery  
**Surg**: Type of surgery  
**OTT**: over the top with Kennedy LAD  
**ISO**: isometric, with drill guide  
**NA**: Non Agmented over the top  
**NAP**: NA and pes anserine transposition  
**GOR**: Goretex graft

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**N**: Normal  
**I**: Injured  
**PL**: Preoperative Lysholm score  
**PT**: Preoperative Tegner score

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because of both ACL and PCL injury

Planter: Bilateral ACL injuries.

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