

Kinematics and laxity in the knee, before and after Anterior Cruciate Ligament reconstruction

Evaluation using dynamic and static Radiostereometric analysis



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”Aut vincere aut mori”

*Order from Demaratus, King of Sparta, to his troops, in the summer of 480 B.C. during the Persians' invasion to Greece: -“their order are to remain at their posts and there, **Conquer or die**”*

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Introduction: Whether full active and passive extension training, started immediately after an Anterior Cruciate Ligament (ACL) reconstruction, will increase the post-operative A-P laxity of the knee has been the subject of discussion. For many years, many protocols have included full extension with full weight bearing after an ACL reconstruction. This is, however, based on empirical facts and has not been studied well in randomised studies. The A-P laxity of the knee joint is an important parameter when evaluating ACL-injured knees. For instance, it is difficult to find a study dealing with ACL insufficiency or post-operative follow-up after an ACL reconstruction, which does not use the KT-1000 as an evaluation instrument to assess objective outcome. The question of whether the results of KT-1000 measurements are sufficiently accurate and the extent to which they are clinically relevant still remains. Previous studies have shown abnormal kinematics in knees with chronic ACL insufficiency and reconstruction of the ligament using bone-patellar tendon-bone (BPTB) or hamstring autograft has not normalised the kinematics. The aim of *Study I* was to evaluate whether a post-operative rehabilitation protocol, including active and passive extension without any restrictions in extension immediately after an ACL reconstruction, would increase the post-operative A-P laxity. The aim of *Study II* was to compare the KT-1000 arthrometer with RSA, a highly accurate method, to measure A-P laxity in patients with ACL ruptures, before and after reconstruction. The aim of *Studies III and IV* was to evaluate whether early ACL reconstruction (8-10 weeks after injury) would protect the knee joint from developing increased external tibial rotation. Twenty-two consecutive patients (14 men, 8 women, median age: 24 years, range: 16-41) were included in *Studies I-II* and were randomly allocated to two groups in *Study I*. Twenty-six consecutive patients (18 men, 8 women; median age 26, range 18-43) were included in *Studies III and IV*. All the patients had a unilateral ACL rupture and no other ligament injuries or any other history of previous knee injuries. One experienced surgeon operated on all the patients, using the BPTB or hamstring autograft. We used RSA with skeletal (tantalum) markers to study A-P laxity and knee kinematics. Dynamic RSA was performed to evaluate the pattern of knee motion during active and weight-bearing knee extension. For A-P laxity, we used static RSA and the KT-1000. Clinical tests were conducted using the Lysholm score, Tegner activity level, IKDC, one-leg-hop test and ROM. The patients were evaluated pre-operatively and up to two years after the ACL reconstruction.

Results: The KT-1000 recorded significantly smaller side-to-side differences than RSA, both before and after the reconstruction of the ACL using a BPTB autograft. There were no significant differences in A-P laxity between early and delayed extension training after ACL reconstruction, up to two years post-operatively. Neither ROM, Lysholm score, Tegner activity level, IKDC nor the one-leg-hop test differed. Before surgical repair of the ACL and at the two-year follow-up, there were no significant differences between the injured and intact knees in internal/external tibial rotation or abduction/adduction, when the ACL reconstruction was performed within 8-10 weeks from injury.

Conclusion: Early active and passive extension training, immediately after an ACL reconstruction using BPTB autografts, did not increase post-operative knee laxity up to two years after the operation. The KT-1000 recorded significantly smaller side-to-side differences than the RSA, both before and after the reconstruction of the ACL. Before surgical repair (8-10 weeks after injury) of the ACL, the knee kinematics remained similar on the injured and normal sides. Two years after the reconstruction, the kinematics of the operated knee still remained normal, after using either BPTB or hamstring autografts.

Key words: ACL, KT-1000, early reconstruction, early extension, kinematics, laxity, RSA

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LIST OF PAPERS

This thesis is based on the following studies, which will be referred to in the text by their Roman numbers.

I: Early active extension after Anterior Cruciate Ligament reconstruction does not result in increased laxity of the knee

Jonas Isberg, Eva Faxén, Sveinbjörn Brandsson, Bengt I Eriksson, Johan Kärrholm, Jon Karlsson. *Knee Surg Sports Traumatol Arthrosc* 2006;14:1108-1115.

II: KT-1000 records smaller side-to-side differences than radiostereometric analysis before and after an ACL reconstruction

Jonas Isberg, Eva Faxén, Sveinbjörn Brandsson, Bengt I Eriksson, Johan Kärrholm, Jon Karlsson. *Knee Surg Sports Traum Arthrosc.* 2006;14:529-535.

III: Can early ACL reconstruction prevent the development of changed tibial rotation? Kinematic RSA study of 12 patients undergoing surgery with bone-patellar tendon-bone autografts, with a two-year follow-up.

Jonas Isberg, Eva Faxén, Sveinbjörn Brandsson, Bengt I Eriksson, Johan Kärrholm, Jon Karlsson. *Submitted.*

IV: Will early reconstruction prevent abnormal kinematics after ACL injury? Two-year follow-up using dynamic radiostereometry in 14 patients operated with hamstring autografts.

Jonas Isberg, Eva Faxén, Gauti Laxdal, Bengt I Eriksson, Johan Kärrholm, Jon Karlsson *Submitted.*

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ABBREVIATIONS

ACL	Anterior Cruciate Ligament
A-P	Antero-Posterior
BPTB	Bone-Patellar Tendon-Bone
LFFC	Lateral Flexion Facet Centre
MFFC	Medial Flexion Facet Centre
MRI	Magnetic Resonance Imaging
PCL	Posterior Cruciate Ligament
ROM	Range Of Motion
RSA	RadioStereometric Analysis
SD	Standard Deviation
SEM	Standard Error of the Mean
ST/G	SemiTendinosus/Gracilis
3D	Three-Dimensional
UmRSA	Umeå RSA (RSA software developed in Umeå, Sweden)

INTRODUCTION

The Anterior Cruciate Ligament

The cruciate ligaments (Figure 1) are often regarded as the nucleus of the knee joint kinematics and the primary restraints to anterior-posterior translation and rotation of tibia. The Anterior Cruciate Ligament (ACL) passes from the anterior part of the spina intercondyloidea on the tibial plateau to the posterior part of the medial side of the lateral femoral condyle. ACL injuries (Figure 2) are very common in athletes. Even though its natural history is not known, this injury is often disabling. It increases the risk of further injuries and predisposes to the early onset of osteoarthritis. The articulation of the knee displays a complex pattern of motion. This motion is guided not only by the ACL, but also by the menisci and other ligaments that bridge the knee. The ACL is not only the primary restraint to anterior displacement of the tibia relative to the femur; it also acts as a restraint to internal-external rotation and varus-valgus angulation.

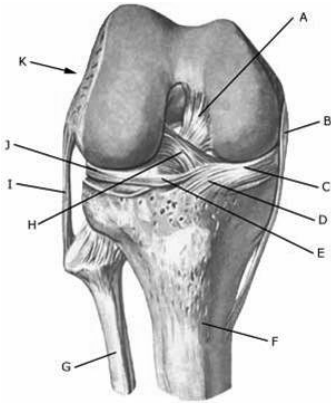


Figure 1. Right knee: A) Posterior Cruciate ligament. B) Medial Collateral ligament. C) Medial Meniscus. DE) Ligamentum Genu Transversum. F) Tibia. G) Fibulae. H) Anterior Cruciate Ligament. I) Lateral Collateral Ligament. J) Lateral Meniscus. K) Femur (© J Karlsson)



Figure 2. Rupture of the Anterior Cruciate Ligament (© J Karlsson)

Anterior Cruciate Ligament rupture

Rupture of the ACL is a common and severe injury during sports and leisure time activities (11,68). It is more common in females than in males. In soccer, for example, the risk of ACL injury is three to four times higher per game hour in female players than in male players (58,82) and female players sustain their injuries at a younger age than men, with an increased risk of developing osteoarthritis at a younger age. In overall terms, the risk of female athletes suffering/sustaining a tear in the ACL is between 2.4 and 9.7 times higher compared with men when practising similar activities (9).

The treatment alternatives are surgical or non-surgical. There is a definite place for non-surgical treatment, but it is extremely difficult exactly to determine the role of non-surgical treatment and for whom it should be used. An almost universally accepted indication for ACL reconstruction is heavy demands on knee function during work or leisure time and/or repeated episodes of giving way in spite of compliant rehabilitation training (9,10). According to the Swedish registry of ACL injuries, approximately 3,000 ACL reconstructions are performed in Sweden each year.

Laxity and kinematics

Chronic ACL insufficiency is associated with recurrent giving way. Several studies have reported that, in addition to increased anterior-posterior laxity (A-P laxity), these knees suffer from a change in kinematics (13,50,52,53).

The surgical reconstruction of the ACL represents an attempt to re-establish physiological joint stability and kinematics. However, the geometry of the ACL is complex and is not duplicated using current reconstructive techniques. The most common grafts in use are the hamstring autograft and the bone-patellar tendon-bone (BPTB) autograft (9,10). The native ACL has two bundles, i.e. the anteromedial (AM) and the posterolateral (PL) bundles. Most anterior fibres are the longest and the posterior ones are the shortest. It is generally accepted that the AM and PL bundles are important from a functional point of view. Most probably, this design/shaping of the ACL is reflected in the kinematics of the knee. The distribution of strain between the bundles is not uniform throughout the arc of motion and the distribution of tension in the different ligament fibres is also influenced by the muscle contractions and external forces.

Several studies have reported that surgical treatment with the above-mentioned grafts is able successfully to restore anterior tibial translation (9,10,54), but it will not influence the increase in external tibial rotation observed after a chronic tear of the ACL (4,14,17,77,78). All these studies have only included patients with chronic ACL insufficiency, suffering from repeated episodes of giving-way. To the author's knowledge, the changes in knee kinematics in the acute phase after ACL rupture, or after reconstruction before the occurrence of giving-way episodes has not been studied.

Osteoarthritis

An ACL injury predisposes the knee to subsequent injuries to the menisci and cartilage and finally the early onset of osteoarthritis (57,82,103). Fifteen years after an ACL injury, 51% of female soccer players (57) and 41% of male soccer players had radiographic signs of osteoarthritis (103). There was no difference in terms of the risk of developing osteoarthritis between surgically or non-surgically treated patients.

The clinical effects of changes in knee kinematics in patients with chronic injury of the ACL are not known. They may have an influence on the risk of subsequent additional injuries to the knee and in the end also play a role in the development of osteoarthritis. At present, it is not known whether changes in kinematics observed in patients with chronic ACL injury develop over time or whether the early repair of the ligament can prevent this. One of the main purposes of this thesis was therefore to study this question/issue in greater detail.

REVIEW OF THE LITERATURE

Timing of reconstruction

The time limits classifying ACL injuries into acute, subacute and chronic are vague and there is no consensus regarding the optimum timing of an ACL reconstruction (9) 'Acute reconstruction' implies variations between days to weeks after the injury; subacute could mean several months and chronic from three months to more than a year after the injury. In this context, strict definitions of timing may be difficult because of individual biological variations in terms of muscle strength, range of motion, pain and effusion. Approximately 20-30 years ago, it was customary to perform the ACL repair/reconstruction within days – in most cases within the first week after injury – as this was believed to be correct, without any real scientific basis. Many of these patients developed post-operative arthrofibrosis with reduced range of motion (ROM). Surgeons therefore suggested that delaying surgery would minimise this risk. Indeed, the loss of extension is often more devastating for the patient than the functional instability. Some researchers have mentioned that early ACL reconstruction after the acute phase might lead to more normal knee laxity and less risk of meniscal and cartilage damage. Given fewer problems with secondary meniscal and cartilage damage, the risk of osteoarthritis in the long run should also be less.

Mayr and co-workers (61) reported that, if the patients had synovitis in their injured knee when the ACL reconstruction was performed, 70% developed post-operative arthrofibrosis. Shelbourne and Patel (91) stated that, if the patient had good (normal) range of motion, little swelling, good leg control and a stable mental state before surgery, a predictable, smooth post-operative course could be expected. It thus appears that the time interval from the ACL injury is less important than the condition of the knee at the time of surgery. Range of motion, effusion and pain are probably most important. There is no optimum time at which the ACL reconstruction should preferably be performed, nor is there any corresponding period when it should not. The most important issue related to early ACL reconstruction is the opportunity to reduce the risk of additional damage to menisci and cartilage, caused by repeated giving-way episodes, with the potential to reduce the risk of osteoarthritis developing in the long term. It remains to be proven in

well-conducted studies with a long-term follow-up whether an early repair of the ACL will have this effect.

Post-operative rehabilitation

A well-planned and supervised post-operative rehabilitation protocol is probably as important for the final outcome after ACL reconstruction as the surgery itself. Early joint motion is also beneficial when it comes to avoiding capsular contractions and reducing swelling and pain, i.e. to avoid arthrofibrosis. Post-operative immobilisation of the knee may contribute to limited range of motion, muscular hypotrophy and inferior knee function (92). Rehabilitation protocols aim to restore the normal range of motion, muscle strength, co-ordination and full function as soon as possible, without damaging the graft (43,88-90,92,93).

In 1990, Shelbourne and Nitz (89) presented their accelerated post-operative rehabilitation protocol after ACL reconstruction, in which they allowed immediate full active extension of the knee and emphasised early accelerated rehabilitation. In 1995, Shelbourne and Klootwick (88) presented a favourable outcome two to six years after ACL reconstruction using BPTB autografts and an accelerated post-operative rehabilitation programme. Three years later, Muneta and co-workers (67) presented the outcome after an ACL reconstruction with multi-strand semitendinosus tendon, in which they also emphasised early accelerated rehabilitation.

Several studies have compared the effect of open and closed kinetic-chain training during post-operative rehabilitation (16,63,65,66,105). Most of the post-operative rehabilitation protocols used today include a combination of both methods. However, only a few studies have addressed the question of whether early active and passive extension immediately after the ACL reconstruction (89) affects the anterior-posterior knee laxity (A-P laxity) of the knee.

It is also thought that there are two post-operative periods during which the ACL graft and its fixations are most vulnerable. The first period starts immediately after the reconstruction (65,66,80), while the second one begins when the graft becomes weaker

due to graft revitalisation, until it reaches its weakest point, which is probably approximately 12 weeks after the reconstruction (67,80).

In a randomised study with a six-month follow-up, Shaw and co-workers (87) evaluated whether early quadriceps exercises affected the outcome of ACL reconstruction. The experimental group (n=47) performed straight leg raises and isometric quadriceps contractions throughout the first two post-operative weeks. The control group (n=44) did no quadriceps exercises during the same period. At six-months follow-up there was no significant difference in the average knee laxity between the groups. Quadriceps exercise performance was associated with a significantly lower incidence of abnormal knee laxity in the experimental group (3 of 47) than in the control group (12 of 44). The patients in the quadriceps training group also had significantly higher Cincinnati scores for symptoms and less problems with sports. No other statistical differences were found between the two groups.

Evaluation of Anterior-Posterior laxity after ACL reconstruction

The A-P laxity of the knee joint is an important parameter for evaluating ACL insufficiency. Clinical grading is, however, very difficult and may not be meaningful. The reason is the low correlation between the A-P laxity measurements and symptoms of ACL insufficiency. The Lachman, anterior drawer and pivot-shift tests are less reliable, due to the considerable variations between examiners (7). To obtain more objective evaluation methods, non-invasive arthrometers such as the KT-1000 have been developed. The reproducibility of the KT-1000 has been regarded as good in some studies (2,6,18,60,104), but it has been questioned by others (23,28,34,41,86,96). It is often used as a complement to clinical examination to establish the diagnosis of ACL rupture and during the follow-up after ACL reconstruction (1,3,9,10,27,54,60). In fact, the KT-1000 is included in most follow-up studies after ACL reconstructions in order to measure the objective benefit of the procedure.

The KT-1000 is widely used by knee surgeons and physiotherapists because of its many advantages in the clinical setting. It is non-invasive, can be used in a standard examination room and is easy to handle. This method has therefore become the standard

method for clinical evaluations of A-P knee laxity before and after surgical treatment (1,3,9,10,27,54). In spite of its widespread use, the question of whether the results of KT-1000 measurements are sufficiently accurate and clinically relevant still remains to be answered. The validity and reliability of the instrument are also under discussion.

If the KT-1000 measurements show small side-to-side differences in A-P laxity during the follow-up after ACL reconstruction, it is logical to draw the conclusion that the A-P laxity has normalised after surgery. However, Jonsson and co-workers (41) showed that the KT-1000 recorded less A-P laxity in injured knees after ACL rupture and after ACL reconstruction than RSA. Moreover, the KT-1000 side-to-side differences were smaller than those based on RSA measurements, both before and after ACL reconstruction. However, according to the current standard at that time, these authors used a smaller anterior traction force (89N) with KT-1000 than RSA (150N).

Knee kinematics

Knee kinematics have frequently been studied (15,21,36,106). These observations may not mimic the clinical situation sufficiently well, due to the lack of muscle action and gravity. New techniques have been developed, but very few of them can be used to study the true dynamic movement with weight bearing in vivo. Goniometers are often too inexact to measure either longitudinal rotation or varus/valgus angulations as reflected by a high coefficient of variation. Instrumented goniometers and reflective markers attached to the skin have problems associated with movements of the markers against the skin and between the skin and the bones, which also induces error (76). In order to increase the reliability of these methods and to overcome the skin-to-bone movements, the reflective markers and goniometers have been fixed to pins driven into the skeletal bones (35), but this will inevitably limit the patient population. Moreover, reflective markers with pins fixed to bone will never be used in a clinical setting. Dynamic MRI can only be used to study static or quasi-static knee joint motion (24). During the last few years, the combination of cine-PC and MRI has been developed (8). The investigation is performed with the patient lying down and actively moving the knee between full extension and 30 degrees of flexion, but without weight bearing.

Different methods have been developed to measure the fine-tuned knee kinematics during active motion and in-vivo A-P laxity. Radiostereometry (RSA) is one such method, which is accurate enough to study skeletal and implant motions with high resolution (13,14,36,39,40,45,47,48,50,52,53,69,84,99-102). This method is able to measure motions down to 0.1 mm and 0.1-0.3 degrees and can be used for three-dimensional (3D) recordings (12,45,48,100). Thirteen years ago, this method was developed to enable dynamic recordings during continuous motion and weight bearing. One of the main aims of this thesis was to use this method to study the kinematics of knees after ACL injury and after surgical repair of this ligament.

AIMS OF THE INVESTIGATION

Study I

To study whether full extension training immediately after an ACL reconstruction would increase the post-operative A-P laxity and subsequently lead to an inferior clinical outcome.

Study II

To compare the KT-1000 arthrometer and RSA measurements of A-P laxity in the intact knee joint, as well as after an ACL rupture, pre-operatively and two years after an ACL reconstruction in a group of patients who were as homogeneous as possible. We also evaluated the side-to-side differences in these patients. A secondary aim was to analyse the ability of the KT-1000 to establish a diagnosis of ACL rupture, using RSA as a reference.

Study III

To perform an ACL reconstruction, using a patellar tendon autograft, in the early phase and to investigate the dynamic kinematics before and two years after the reconstruction. The study comprised a consecutive series of patients who had not had any pivoting episodes between the injury and the reconstruction.

Study IV

To perform an ACL reconstruction, using a hamstring autograft, in the early phase and to investigate the dynamic kinematics before and two years after the ACL reconstruction. The study comprised a consecutive series of patients who had not had any pivoting episodes between the injury and the reconstruction.

PATIENTS

Study I

Twenty-two consecutive patients (14 men, 8 women) with a unilateral ACL rupture and an uninjured contralateral knee were included. Multiple knee ligament injuries and/or a history of knee injuries were the main exclusion criteria.

The median age at the ACL reconstruction was 24 (16-41) years. The time period between the index injury and the ACL reconstruction was 16 (4-45) weeks. The ACL reconstruction procedure was identical in all patients. One experienced surgeon performed the operation, using a patellar tendon autograft. The patients were randomly allocated to post-operative rehabilitation programmes either allowing (Group A, n=11) or not allowing (Group B, n=11) full active extension (30--10°) immediately after the operation. The patients were evaluated pre-operatively and two years after the operation.

Study II

The same twenty-two consecutive patients as in *Study I* (14 men, 8 women) with a unilateral ACL rupture and an intact contralateral knee were included. The exclusion criteria were a history of any previous knee injury and the involvement of other ligaments. The median age at the time of ACL reconstruction was 24 (16-41) years. The time period between the injury and the ACL reconstruction was 16 (4-45) weeks. One experienced surgeon performed the operation, using a patellar tendon autograft.

The patients were evaluated pre-operatively and two years after the ACL reconstruction. All the patients were evaluated using RSA and KT-1000 measurements for A-P laxity. All the patients were examined both pre-operatively and at follow-up by the same independent observer, who did not participate in the surgical procedure.

Study III

Between December 2000 and September 2002, twelve consecutive patients (10 men, 2 women) with a median age of 26 years (20-38), who had sustained a complete, isolated unilateral ACL rupture, were included in this prospective study (nine right knees and three left) after informed consent. All the ACL ruptures were diagnosed clinically by an

orthopaedic surgeon and confirmed by manual laxity testing (Lachman, KT-1000) and arthroscopy. The exclusion criteria were previous knee surgery or conservatively treated knee injuries and multiple knee ligament and cartilage injuries in either the injured or the intact knee. The presence of a concomitant meniscal tear, which was treated with a partial resection during the primary arthroscopy, was accepted.

All the patients participated in athletic activities, which imposed heavy demands on knee function. They were recruited to the study on a volunteer basis on their first visit to the emergency department after the injury. The time from the index injury to inclusion varied between 0-6 days. The time period between the injury and the ACL reconstruction was nine (8-10) weeks.

Arthroscopy of the injured knee was performed in all patients, confirming the diagnosis of a total rupture of both bundles of the ACL ligament. Two patients had a minimal lateral meniscal injury and one had a small medial meniscal injury, all of which were treated with a partial resection. All the patients were examined both pre-operatively and two years after the operation by the same independent observers who did not participate in the surgical procedure.

Study IV

Between March 2002 and April 2003, fourteen consecutive patients (8 men, 6 women) with a median age of 24 years (18-43) presented with a complete, isolated unilateral ACL rupture and were included in this prospective study after informed consent. All the patients imposed heavy demands on their knee function, during leisure time, athletic activities, or work. They were recruited on a volunteer basis on their first visit to the emergency department after the injury, 0-6 six days after the index injury. The exclusion criteria were multiple knee ligament and cartilage injuries, a history of previous knee surgery and conservatively treated knee injuries in either the injured or intact knee. The presence of a meniscal tear, which was treated with a partial resection during the primary arthroscopy, was accepted.

All the ACL ruptures were diagnosed clinically by an orthopaedic surgeon and confirmed by manual laxity testing (Lachman, KT-1000 arthrometer) and arthroscopy.

Arthroscopy was performed on the injured side in all patients, to confirm the diagnosis and to evaluate the menisci and cartilage. Two patients had a lateral meniscus injury, which was treated with a partial resection. All the patients were examined both pre-operatively and two years after the operation by the same independent observers who did not participate in the surgical procedure. The time period between the injury and the ACL reconstruction was nine (8-10) weeks.

METHODS

Surgical procedure

A standard arthroscopic one-incision technique was used. One experienced surgeon performed the operation, using a bone-patellar tendon-bone (*Studies I-III*) and a four-strand semitendinosus/gracilis (ST/G) autograft (*Study IV*). The procedure was identical in all patients.

Bone-patellar tendon-bone (BPTB) autograft: The mid-third of the patellar tendon was harvested through a 7-8 cm vertical incision and the graft was 8-10 mm, depending on the size of the patellar tendon. The proximal bone block was sized to 9 mm and the distal to 10 mm. The tibial tunnel was placed just anterior to the posterior cruciate ligament (PCL). A small notchplasty was performed to avoid any graft impingement. The graft was placed at approximately the 10.30 (right knee) or 01.30 (left knee) positions in the posterior intercondylar notch and was drilled transtibially. The fixation was performed using metallic interference screws (Cannu-flex silk screws 7x20 mm in the femur and 7-9x20 mm in the tibia, Acufex, Microsurgical Inc., Mansfield, MA, USA) (Figure 3).

Semitendinosus/gracilis (ST/G) autograft: The graft was harvested through a 25-35 mm incision over the pes anserinus. The sartorius fascia was incised and the vinculae were cut under visual control. The semitendinosus and gracilis tendons were harvested with a semi-blunt, semi-circular open tendon stripper (Acufex, Microsurgical Inc., Mansfield, MA, USA). The tendons were prepared to create a quadruple graft. To pull the graft, we used two no. 5 non-resorbable Ticon® (Sherwood Medical, St Louis, MO, USA) sutures in the proximal and distal end. Both ends of the graft were prepared with modified baseball stitches with resorbable no. 1 Vicryl® (GmbH & Co. KG, Norderstedt) sutures. A small notchplasty was performed to avoid any graft impingement. The femoral tunnel was drilled through a medial portal and the graft was placed at approximately the 10.30 (right knee) or 01.30 (left knee) positions in the posterior intercondylar notch. The fixation of the graft was performed using metallic interference screws (7 mm soft-threaded RCI®, Smith and Nephew, Inc, Andover, MA 01810, USA) on both the femoral and tibial side (Figure 4).

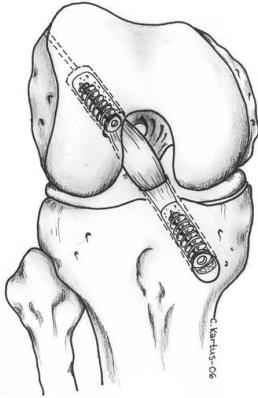


Figure 3. The BPTB autograft. Interference screw was used on the femoral and tibial side respectively (© C.Kartus)

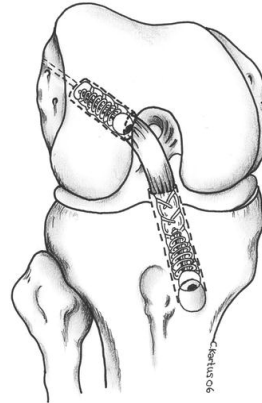


Figure 4. The ST/G autograft. A soft-threaded-RCI interference screw was used on the femoral and tibial side respectively (© C.Kartus)

Rehabilitation

The rehabilitation training was started the day after the operation. A physiotherapist supervised the training three times a week during the first four weeks and then twice a week during the remaining rehabilitation period. During the first four post-operative weeks, the rehabilitation protocols differed between study *Study I-II* and *Studies III-IV*. From the fifth post-operative week and onwards, the patients in *Studies I-IV* followed the same rehabilitation protocol.

In *Study I*, the patients were randomly allocated to two different rehabilitation protocols, which continued for the first four post-operative weeks. In *Studies III-IV*, the patients were treated according to a rehabilitation protocol allowing full extension and full weight bearing immediately post-operatively and no brace was used.

Study I-II

The same rehabilitation brace was used in both groups and it allowed 10° of hyperextension. The patients were randomly allocated to two groups, either without (Group A) or with (Group B) restricted active and passive extension between 30° and minus 10°.

Weeks 0-2: Full weight bearing was allowed in both groups immediately post-operatively, but crutches were allowed for 10 days in both groups. The same model of rehabilitation brace was used in both groups, either without (Group A) or with (Group B) restricted active and passive extension between 30° and minus 10°. The training programme, including active and passive extension and flexion exercises, closed-kinetic-chain (CKC), was started immediately post-operatively in both groups.

Weeks 3-4: The two groups still used their rehabilitation brace. The training programme continued with or without restricted extension according to the initial protocol. CKC exercises for hamstrings and quadriceps were continued. Gait, stationary cycling, proprioception and balance training were started. Open-kinetic-chain (OKC) training was started in both groups.

The brace was removed at the end of the fourth week in both groups.

Studies III-IV

Weeks 0-2: Full weight bearing was allowed immediately post-operatively, but crutches were allowed for 10 days. The training programme, including active and passive extension and flexion exercises, CKC, was started immediately post-operatively (Figure 5).

Weeks 3-4: CKC exercises for hamstrings and quadriceps were continued. Gait, stationary cycling, proprioception and balance training were started. OKC training was started in both groups.

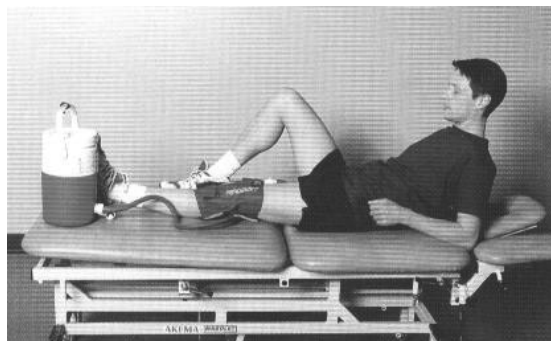


Figure 5. The training programme, including active and passive extension and flexion exercises, CKC, was started immediately post-operatively (© J Karlsson)

Studies I-IV

Weeks 5-6: Active and passive extension without any restrictions was allowed. Isokinetic concentric and eccentric OKC quadriceps training was initiated in week 6, together with isokinetic hamstring training.

Weeks 7-12: Functional exercises, such as stair walking and rope-skipping exercises were started. Slideboard exercises were initiated in week 12.

Weeks 13-17: Straight ahead jogging was permitted on an even surface. Eccentric and concentric muscle training was continued with increasing weight and speed.

Weeks 18-24: Sport-specific training, jogging on an uneven surface and with 90-360° turns was initiated.

Week 25: The patient was allowed to return to sports activities, if his/her muscle strength was 90% or more of that of the intact leg.

The clinical examination tests

In Studies I-IV, one experienced physiotherapist, who was not involved in the rehabilitation, performed all the pre- and post-operative clinical examination tests at follow-ups.

The IKDC knee examination form

The IKDC knee examination form is based on both the patient's subjective evaluation and knee evaluation by an independent examiner (30). The patient ranks his/her symptoms and activity level and the examiner ranks the measurements included such as ROM, laxity, crepitus and so on. The results were graded as A (normal), B (nearly normal), C (abnormal) and D (severely abnormal). The lowest grade within the subgroup gives the subgroup ranking and the lowest subgroup ranking gives the final evaluation ranking. The final ranking at the two-year follow-up is reported.

The Lysholm knee scoring scale

The modified Lysholm knee scoring scale was used (97). It consists of eight items, such as pain and instability, and the maximum score is 100 points.

The Tegner activity level

The Tegner activity level score is graded from 1-10 (97). Scores between 1-4 cover activities of daily life and work, while 5-10 cover recreational or competitive sports activity.

Range of motion (ROM)

A standard hand-held goniometer was used. The measurement was performed on both the injured and intact side pre-operatively and at follow-up. The patient started with an active maximum extension, followed by a maximum flexion. The extension measurements were performed with the patient in the supine position and flexion was measured when the patient slid his/her heel as close to the buttocks as possible without any help from the arms. Values were rounded off to the nearest increment of 5°. A side-to-side difference of more than 5° was registered as a deficit (Figure 6).



Figure 6. The ROM measurement was performed with a standard hand-held goniometer (© N. Sernert)

The one-leg-hop test

The one-leg-hop test was performed by jumping and landing on the same foot with the hands behind the back. Three attempts were made for each leg and the longest hop was registered for each leg separately. A quotient (%) was calculated between the intact and the injured knee (98) (Figure 7).

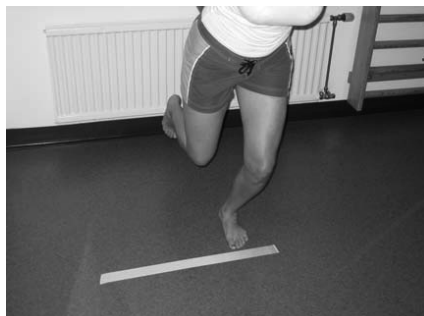


Figure 7. The one-leg-hop test was performed by jumping and landing on the same foot with the hands behind the back (© N. Sernert)

KT-1000 arthrometer test

We used a standard KT-1000 arthrometer (MEDmetric Corp., San Diego, Ca, USA) (2,3,18,23,28,34,41,75,79). One experienced observer performed all the measurements (7). The values are presented as the side-to-side differences (the difference between the injured and uninjured knees). The patients were evaluated pre-operatively and at the two-year follow-up.



Figure 8. For the KT-1000 arthrometer measurements we used a standard KT-1000 arthrometer (MEDmetric Corp., San Diego, Ca, USA) (© J Isberg)

The anterior-posterior displacement of the tibia in relation to the femur was registered

at; 134 N anterior and 89 N posterior (18) in *Study I* and 89 N anterior and posterior in *Studies II-IV*. The patients were asked to place both their legs on a thigh support with the knees in 30° of flexion, and with the arms along the sides of their body. They were then instructed to relax. Before each test, the instrument was calibrated to zero. The intact knee was always tested first. The median value of three measurements for each knee was registered (Figure 8).

Radiostereometric analysis (RSA)

RSA was introduced in 1974 (85) and has been widely used since then. The basis of the technique has been described in several articles and theses (45,48,49,85,101). Some 400 scientific papers have been published. RSA has mainly been used for evaluating arthroplasties, but it has also been used for more than a decade to evaluate the laxity and kinematics of ACL-injured knees (13,14,25,33,34,37-41,45,48,50,52,53,101). It is a highly accurate method that is frequently used to measure joint motion, motion between bony structures, motion between an implant and the host bone and wear. Provided that at least three well-spaced, stable bone markers are present, three-dimensional (3D) measurements (85) can be made. The method can be used in a static or dynamic setting. RSA is accurate and precise down to 0.1 mm and 0.1-0.3 degrees (12,72,99,100). Its accuracy is also similar when it comes to measuring A-P laxity for repeated testing over

time (22). In this setting, other factors such as muscle tension, reproducibility of the application of the external forces used to provoke A-P translation and the positioning of the joint have a decisive impact on the reproducibility of the measurements. Since the measurement error is small, it is possible to use a comparatively small number of subjects to draw relevant conclusions (46,83).

RSA includes the following steps

Implantation of tantalum markers: An arthroscopy of the injured knee was performed in all patients one to three weeks after they were recruited to confirm the diagnosis. During the same session, the tantalum markers (diameter 0.8 mm) were inserted percutaneously in both the injured and the intact knee (Figure 9). Four to five tantalum markers were implanted into the distal femur and proximal tibia on the injured and intact knees. For the RSA measurements, at least three non-linear markers are needed in each segment. They should be as well spaced as possible within each bone. To ensure this and to compensate for any loosening of a single marker, four to five tantalum markers were implanted.

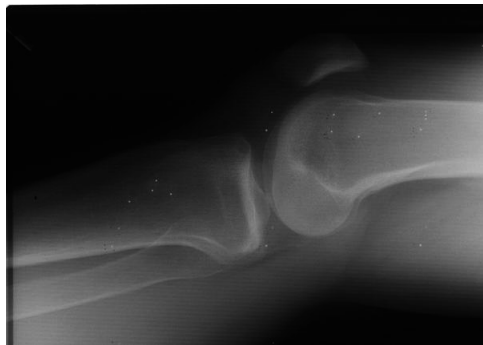


Figure 9. The tantalum markers can be seen in an intact knee, in both the tibia and femur. The markers located outside the skeletal structure are located in the Plexiglas® calibration cage (© Knee Surg Sports Traumatol Arthrosc)

Static radiographic examinations: Two ceiling-mounted radiographic tubes, one anterior-posterior and one lateral, connected to two separate generators, were used to obtain simultaneous exposures. The patients were examined in the supine position with

the knee in a Plexiglas® calibration cage (85) (Figure 10). The distal femur was fixed with an adjustable frame to minimise femoral movements. Anterior and posterior loads were applied approximately 7 cm distal to the joint line (Figure 11). The same set-up was used as previously described by Brandsson and co-workers (14) and Kärholm and co-workers (52,53).



Figure 10. The RSA lab with two ceiling-mounted radiographic tubes (© Knee Surg Sports Traumatol Arthrosc)

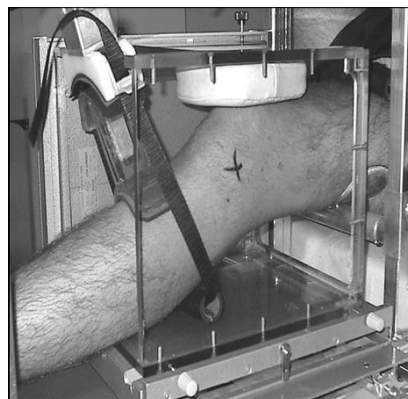


Figure 11. The plexiglass cage with a posterior pushing force of 80 Newtons. (© Knee Surg Sports Traumatol Arthrosc)

The following positions were tested:

- Extended knee (0 degrees) (Figure 12)
- 30 degrees of flexion
- 30 degrees of flexion with an anterior traction of 150 Newtons
- 30 degrees of flexion with a posterior force of 80 Newtons



Figure 12. Reference position with an extended knee (© J Isberg)

The mean intra-articular displacement of the two tips of the intercondylar eminence along an anterior-posterior axis of the knee represented the A-P laxity. The femoral markers were used as fixed reference segments. The median value (range) of the “mean errors of rigid body fitting” and condition numbers (85,101) representing marker stability and scatter are presented in the study. During the pre-operative examinations, both the injured and the uninjured side were examined. At follow-up, the post-operative side-to-side differences in displacement were compared with the pre-operative measurements of the intact knee, i.e. the baseline examination. Measurements of digital radiographs and computations of three-dimensional co-ordinates (85) were performed using a software package (UMRSA 6.0, RSA Biomedical, Umeå, Sweden).

Dynamic radiographic examinations:

All the examinations were made by one experienced examiner. The patients were examined in a specifically designed radiographic laboratory for RSA examinations. Two ceiling-mounted radiographic tubes and two film-exchangers connected to two separate generators were used to obtain simultaneous exposures, one anterior-posterior and one lateral (Figures 13).



Figure 13. The radiographic set-up in film-exchanger examination. (© J Isberg)

The film-exchangers were used to enable sequential exposure of radiographs during a continuous joint motion performed by the patient (dynamic examinations). The film-exchangers can be adjusted upwards/downwards and in the transverse direction depending on the height and size of the patients.

The radiographic examination started by recording a reference/starting position. A pair of simultaneous exposures, stereoradiographs, was obtained in accordance with a standardised method (69). We used a standard biplane calibration cage (cage 10, RSA

Biomedical, Umeå, Sweden) equipped with tantalum markers, which defined the laboratory co-ordinate system. This examination was performed in the supine position at 0° extension and with the knee aligned to the cage. The supine position minimises the side-effects of malalignment, i.e. kinematic cross-talk (74). All subsequent stereoradiographs were related to this straight position. Reference plates and a calibration examination were used to obtain a sufficient amount of space during knee motion (45,50,99,100). Both the injured and the uninjured sides were examined in a standardised manner.

During the examination of active weight-bearing extension, the patient placed his/her foot in a neutral position on a 16 cm high platform (Figure 14) and performed an extension of the knee from 90° of flexion to maximum extension (Figures 15a and b). Before the radiographic recordings were started, the patients performed five to seven trial extensions, until they had obtained a reproducible speed, i.e. three to four seconds from 90° of knee flexion to full extension. During the active knee extension, the two roentgen tubes exposed 13-16 pairs of radiographs during the active knee motion from flexion to extension. The reproducibility of knee motions during a step-up has previously been determined as 1.6-2.3° and 1.2-2.2 mm (one standard deviation (SD)) (100).

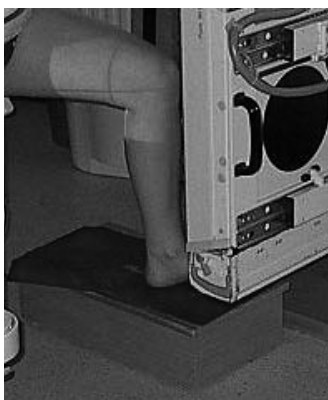


Figure 14. At the examination of active weight-bearing extension the patient placed his/her foot in neutral position on a 16 cm high platform (© J Isberg)



Figure 15. Film exchanger examination
a) starting position
(© J Isberg)



b) final position

Computation: All measurements of digital radiographs and computations of three-dimensional co-ordinates were performed using a software package (UmRSA 6.0, RSA Biomedical, Umeå, Sweden). The UmRSA system includes quality control of the scatter of tantalum markers expressed in the condition number of each segment. To control the stability, the mean error of rigid body fitting was calculated. It assesses the changes in distance between tantalum markers placed in one segment (distal femur or proximal tibia) between two examinations. Optimally, this value should be zero, but it rarely is, due to measurement errors and any marker instability. It is suggested that the upper limit should be 0.35 mm (101), for the femoral and tibial segments respectively.

The condition numbers indicate the quality of tantalum marker distribution. It should be as low as possible and preferably smaller than 150 (101). The marker stability is related to the distribution of the markers. The lower the mean error of rigid body fitting, the higher the condition number that can be accepted. The median value (range) of the “mean errors of rigid body fitting” and condition numbers in each study are presented.

The mean displacement of the two tips of the intercondylar eminence along an anterior-posterior axis of the knee represented the A-P laxity. The femoral markers were used as fixed reference segments.

To evaluate the internal/external tibial rotations and the adduction/abduction (varus/valgus) angulations of the tibia, the femoral markers were used as a fixed reference segment (70,99,100). To evaluate the anterior/posterior (A-P) translations of the medial and lateral femoral condyles (MFC, LFC), the tibial markers were used as a fixed reference (13,47).

Femoral translations were represented by the displacement of the posterior circular centre of the medial and lateral femoral condyles (the medial and lateral flexion facet centres). The centres of the condyles were identified, marked and measured using circular templates on the lateral reference radiograph with the knee in 0° extension. The distance between these circular centres to the distal edge of each femoral condyle was measured. In addition to the sclerotic lines corresponding to the medial and lateral walls of each condyle, these distances were used to identify the condylar centres on the A-P view of the reference stereoradiographs. These plotted points were measured on both the A-P and

lateral view and their three-dimensional co-ordinates were computed. The tips of the tibial condylar eminence were marked on the A-P view of the reference position. These co-ordinates, in the tibia and femur, were then mathematically transformed to the subsequent examinations using the rigid body (defined by the tantalum markers) in the distal femur (99,100) and the proximal tibia respectively. Once plotted and measured, the precision of the location of these “fictive points” is related to the stability, configuration and location of the tantalum markers in the same segment. This means that, within one and the same knee, the location of the points representing translation will be high and in most instances higher than they would have been if a single tantalum marker had been used. Between knees, the variation could be expected to be higher due to plotting inexactness and individual variations in the condylar anatomy. This means that there is a small variation in the position of the point of measurement between knees, which could be expected to have a very small effect on the resulting recording of translations.

STATISTICAL METHODS

Studies I-II

All the values are presented as the median and (range). The Mann-Whitney U-test was used in the independent comparison of the two groups for non-parametric data and Wilcoxon's signed-rank test was used to evaluate changes in parameters over time. A p-value of less than 0.05 (two-sided test) was regarded as statistically significant.

Study III

The observed motions were interpolated at 5° intervals of extension. Repeated measures analysis of variance (ANOVA) was used to compare the groups. The interval of 55° to 10° was used for the statistical analysis. Observations from twelve patients, both intact and injured knees, were available from 55° to 10°. Probability values lower than 0.05 were regarded as representing a significant difference. Alignment parameters were compared using the Mann-Whitney U-test.

The Mann-Whitney U-test was used in the independent comparison of the two groups for non-parametric data and Wilcoxon's signed-rank test was used to evaluate changes in parameters over time. A p-value of less than 0.05 (two-sided test) was regarded as statistically significant. Data are presented as median and (range) or mean and SE.

Study IV

The observed motions were interpolated at 5° intervals of extension. Repeated measures analysis of variance (ANOVA) was used to compare the groups. The interval of 60° to 10° was used for statistical analysis. Observations from fourteen patients, both intact and injured knees, were available from 60° to 10°. Probability values lower than 0.05 (two-sided test) were regarded as representing a significant difference. Alignment parameters were compared using the Mann-Whitney U-test.

The Mann-Whitney U-test was used in the independent comparison of the two groups for non-parametric data and Wilcoxon's signed-rank test was used to evaluate changes in parameters over time. A p-value of less than 0.05 (two-sided test) was regarded as statistically significant. Data are presented as median and (range) or mean and SE.

ETHICS

The Human Ethics Committee at the Sahlgrenska Academy, Göteborg University, approved all the studies.

SUMMARY OF THE PAPERS

Study I

Introduction

To our knowledge, there are no randomised studies which have studied the influence of allowing full active extension immediately after an ACL reconstruction and evaluated A-P laxity with a highly accurate method. Despite this, many rehabilitation protocols include immediate early full active and/or passive extension training after an ACL reconstruction. We investigated whether a post-operative rehabilitation protocol including active and passive extension without any restrictions in extension immediately after an ACL reconstruction would increase the post-operative A-P laxity of the knee. We used RSA to evaluate the A-P laxity.

Twenty-two patients (14 men, 8 women), median age: 24 years, were included and randomised into two groups with 11 patients in each group – Group A (allowing full extension) and Group B (not allowing extension from 30–10°). All the patients had a unilateral ACL rupture.

The hypothesis was that full active and passive extension immediately after an ACL reconstruction would have no negative effects on A-P laxity and the clinical results up to two years after the operation.

Results

Pre-operatively, the side-to-side difference using RSA was 8.6 mm (2.3-15.4) in Group A and 7.2 mm (2.2-17.4) in Group B, while it was 2.0 mm (0-8.0) in Group A and 4.0 mm (0-10.0) in Group B using the KT-1000 (Tables 1 and 2), without any statistical differences between Groups A and B (RSA: $p=0.51$, KT-1000: $p=0.90$).

At the two-year follow-up; the side-to-side difference using RSA was 2.7 mm (0-10.7) in Group A and 2.8 mm (-1.8-9.5) in Group B. The difference using the KT-1000 was 1.0 mm (-1.5-3.5) in Group A and 0.5 mm (-1.0-4.0) in Group B (Tables 1 and 2), without any differences between Groups A and B (RSA: $p=0.58$, KT-1000: $p=0.93$).

Table 1. A-P laxity (side-to-side difference) with RSA. All the measurements are median (range).

RSA	GROUP A (mm)	GROUP B (mm)	GROUP A vs. B
Pre-operatively	8.6 (2.3-15.4)	7.2 (2.2-17.4)	p=0.51
24 months post-op	2.7 (0-10.7)	2.8 (-1.8-9.5)	p=0.58
Pre-op vs. 24 months	p=0.005	p=0.005	

Table 2. A-P laxity (side-to-side difference) with KT-1000. All the measurements are median (range).

KT-1000	GROUP A (mm)	GROUP B (mm)	GROUP A vs. B
Pre-operatively	2.0 (0-8.0)	4.0 (0-10.0)	p=0.90
24 months post-op	1.0 (-1.5-3.5)	0.5 (-1.0-4.0)	p=0.93
Pre-op vs. 24 months	p=0.01	p=0.004	

Both groups displayed a significant reduction in A-P laxity between the pre-operative examination and the two-year follow-up for both the RSA and KT-1000 measurements (Tables 1 and 2), in Group A (RSA: p=0.005 and KT-1000: p=0.01) and in Group B (RSA: p=0.005 and KT-1000: p=0.004).

Conclusion

We conclude that it appears to be safe to start early active and passive extension training without any restriction in extension immediately after an ACL reconstruction with a patellar tendon autograft.

Study II

Introduction

A-P knee laxity is an important parameter for evaluating knees with ACL insufficiency and after an ACL reconstruction. Clinical grading is, however, difficult. The KT-1000 and similar non-invasive arthrometers are used as a complement to clinical examination in the diagnosis of ACL rupture and during the follow-up after surgery. The reproducibility of the KT-1000 has been regarded as good in some studies, but it has been questioned by others. With our equipment, similar but not equal to that used in an earlier study (41), we wanted to evaluate whether these previous results could be reproduced. In contrast to this earlier investigation, we also wanted to evaluate a more homogeneous group of patients.

We compared two methods, the KT-1000 and RSA. The A-P laxity of the knee was measured on both sides in patients with a unilateral ACL rupture, before and after the reconstruction of this ligament.

Twenty-two patients (14 men, 8 women), median age: 24 years, were included. All the patients had a unilateral ACL rupture.

The hypothesis was that the KT-1000 and RSA have equal diagnostic accuracy. The A-P laxity was evaluated in terms of side-to-side difference before and after reconstruction of the ACL.

Results

Pre-operatively, we found a median (range) side-to-side difference of 4.0 (0-10.0) mm, using the KT-1000 in ACL-injured knees. The corresponding RSA value was 7.4 (2.2-17.4) mm ($p < 0.0001$). An individual patient evaluation revealed that 11/22 patients (50%) had a cut-off value, for side-to-side difference, higher than 3.0 mm using the KT-1000, but, using RSA, 21/22 patients (95%) had a cut-off value higher than 3.0 mm, indicating an ACL rupture.

Separate measurements for intact and injured knees revealed an A-P laxity with the KT-1000 of 8.0 (6.0-10) mm in the intact knee. The corresponding RSA value was 3.1 (0.2-8.6) mm ($p<0.0001$). In the injured knee, the KT-1000 value was 11.0 (6.0-18.0) mm. The corresponding RSA value was 10.9 (6.2-19.6) mm ($p=0.88$), (Table 3).

Table 3. A-P laxity in injured and intact knees, KT-1000 and RSA. Pre-operative and two-year follow-up values, n=22; mm: median (range)

	KT-1000 arthrometer			
	Injured knee	Intact knee	Side-to-side difference	KT-1000/ RSA side-to-side diff
Pre-op	11.0 (6.0-18.0)	8.0 (6.0-10.0)	4.0 (0-10)	$p<0.0001$
Two-year	9.5 (7.5-14.0)	9.0 (7.0-10.5)	0.5 (-1.5-4.0)	$p<0.0001$
p=pre/ two-year	$p<0.0001$	n.s	$p=0.0001$	
	RSA			
	Injured Knee	Intact knee	Side-to-side difference	KT-1000/ RSA side-to-side diff
Pre-op	10.9 (6.2-19.6)	3.1 (0.2-8.6)	7.4 (2.2-17.4)	$p<0.0001$
Two-year	6.5 (2.4-14.1)	3.0 (0.2-7.8)	2.8 (-1.8-10.7)	$p<0.0001$
p=pre/ two-year	$p<0.0001$	n.s	$p<0.0001$	

Table 4. Clinical outcome

		Pre-op	Two year
Tegner activity scale		3 (2-9)	7 (4-10)
Lysholm knee scoring scale		75 (25-99)	95 (79-100)
One-leg-hop test (%)		82 (0-96)	97 (85-100)
IKDC	A (normal)	0	8
	B (nearly normal)	0	12
	C (abnormal)	10	2
	D (serverely abnormal)	12	0
ROM	Intact knee, extension	-5 (-15-0)	
	Injured knee, extension	0 (-10-15)	0 (-10-5)
	Intact knee, flexion	150 (125-160)	
	Injured knee, flexion	140 (85-160)	150 (135-160)

At the two-year follow-up; a side-to-side difference of 0.5 (-1.5-4.0) mm using the KT-1000 was found. The corresponding RSA value was 2.8 (-1.8-10.7) mm ($p<0.0001$). Both methods revealed a significant reduction in A-P laxity between the pre-operative examination and the two-year follow-up (KT-1000; $p=0.0001$, RSA; $p<0.0001$), but the KT-1000 measurements showed a significantly smaller difference than the RSA measurements ($p<0.0001$).

Separate measurements for injured knees revealed an A-P laxity with a KT-1000 value of 9.5 (7.5-14.0) mm. The corresponding RSA value was 6.5 (2.4-14.1) mm ($p<0.0001$), (Table 3). Significantly higher values were recorded with the KT-1000 compared with RSA when injured and uninjured knees were analysed separately. However, the side-to-side differences were significantly lower when measured with the KT-1000 as compared with RSA, which was mainly an effect of larger A-P laxity recordings with the KT-1000 on the intact side.

There were significant improvements in the Lysholm score, Tegner activity level, the one-leg-hop quotient and the IKDC between the pre-operative measurements and the two-year follow-up (Table 4).

Conclusion

Significantly smaller side-to-side differences were recorded with the KT-1000 as compared with RSA, both before and after the reconstruction of the ACL using a bone-patellar tendon-bone autograft. These results were mainly an effect of larger A-P laxity recordings with the KT-1000 on the intact side.

Study III

Introduction

Recent in-vivo studies (14,17,77,78) report that ACL reconstruction does not restore tibial rotation in chronic ACL-insufficient knees. Using the RSA technique, we investigated whether early ACL reconstruction (8-10 weeks after injury) would maintain normal knee kinematics, with specific emphasis on tibial rotation and concomitant translation of the femoral condyles. RSA has been used to study the kinematics of normal knees with osteoarthritis, knees with arthroplasty and knees with chronic ACL insufficiency. To our knowledge, this is the first study to measure the dynamic in-vivo kinematics as early as eight weeks after the injury, with a two-year follow-up after the operation. We also performed a clinical evaluation in addition to the kinematics.

Twelve consecutive patients (10 men, 2 women) with a median age of 26 years were included. All the patients had a unilateral ACL rupture.

The hypothesis was that early ACL reconstruction, using BTB autografts, before pivoting episodes had occurred, would protect the knee joint from developing abnormal kinematics in terms of increased external tibial rotation at flexion.

Results

Internal (+)/external (-) tibial rotation: During the active and weight-bearing extension, both the intact and the injured knees (before and after the ACL reconstruction) started in an internally rotated position and rotated externally during the extension. There were no significant differences between the injured and intact knee before or two years after the operation respectively or between the two evaluations of the injured side before and two years after the operation ($p=0.19-0.65$), (Figure 16).

Figure 16. Internal (+)/external (-) tibial rotation during active weight-bearing knee extension. Injured side examined before and two years after reconstruction of the ACL. Mean values and standard error of the mean

Translation of medial (MFC) and lateral (LFC) femoral condyles: During the active extension, the MFC started in a slightly anterior position and translated posteriorly in the intact and the injured knee (before and after the ACL reconstruction), without any significant differences between the injured and uninjured knee, pre-operatively or at the two-year follow-up respectively ($p=0.44$ and 0.61). Nor did the anterior-posterior translations of the MFC differ on the injured side between the pre-operative and the follow-up examination ($p=0.75$) (Figure 17).

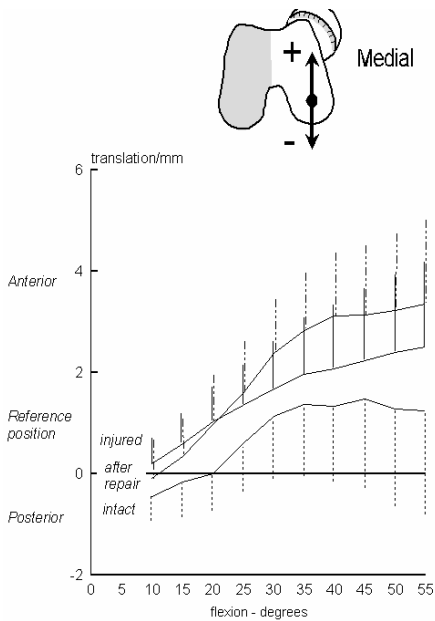


Figure 17. Anterior (+)/posterior (-) translation of the medial femoral condyle during active weight-bearing knee extension. Injured side examined before and two years after reconstruction of the ACL. Mean values and standard error of the mean

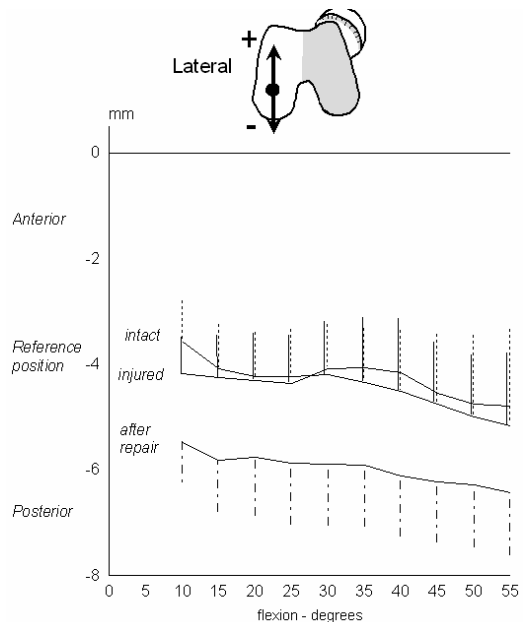


Figure 18. Anterior (+)/posterior (-) translation of the lateral femoral condyle during active weight-bearing knee extension. Injured side examined before and two years after reconstruction of the ACL. Mean values and standard error of the mean

The LFC started in a posterior position and ended up in almost the same position, without any significant differences between the injured and uninjured knee, pre-operatively or at the two-year follow-up respectively ($p=0.96$ and 0.31). At two years, these translations remained almost identical on the operated side when compared with the pre-operative examination ($p=0.24$), (Figure 18).

Tibial varus (+)/valgus (-) angulations: During the active extension, tibial rotations into varus or valgus were small, without any significant differences between the injured and uninjured knee, pre-operatively or at the two-year follow-up, or on the injured side before and two years after the reconstruction ($p=0.19-0.69$), (Figure 19).

Figure 19. Tibial varus (+)/valgus (-) angulations during active weight-bearing knee extension. Injured side examined before and two years after reconstruction of the ACL. Mean values and standard error of the mean

Conclusion

The normal fine-tuned kinematics between the tibia and femur may have a considerable impact on the function of the knee and on the risk of damaging the secondary restraints, as well as menisci and cartilage. The findings in the present study indicate that early ACL reconstruction could be beneficial by preventing these detrimental effects.

Before surgical repair of the ligament, the knee kinematics were similar on the injured and normal sides. Two years after the reconstruction, the kinematics of the operated knee were still normal.

Study IV

Introduction

During the last few years, increasing interest has been shown in investigating the effect of an ACL reconstruction on resisting anterior and rotatory loads. Most studies have been conducted on cadavers, using either BPTB or ST/G grafts, and most of these studies have shown that these grafts are successful in restoring anterior tibial translation but have limited effect on rotational stability. Much less is known about rotational stability in vivo, for instance, during walking or step-ups. We studied 14 consecutive patients (8 men, 6 women) with a median age of 24 years (18-43), all with a complete, isolated unilateral ACL rupture. They were all operated on using the quadruple hamstring autograft. We used dynamic RSA with tantalum markers to study the pattern of knee motion during active and weight-bearing knee extension. The patients were evaluated pre-operatively and followed for two years after the ACL reconstruction. A-P laxity was measured using the KT-1000.

The hypothesis was that early ACL reconstruction, using quadruple hamstring autografts, before pivoting episodes had occurred, would protect the knee joint from developing abnormal kinematics with increased external tibial rotation at flexion.

Results

Internal (+)/external (-) tibial rotations: During the active and weight-bearing knee extension, both the intact and the injured knees (before and after the ACL reconstruction) started in an internally rotated position and rotated externally during the extension movement. There were no significant differences between the injured and intact knees, either before or two years after the ACL reconstruction ($p=0.13$ and 0.54), (Figure 20). Two knees (one injured and one intact) started (at 60° of flexion) with the tibia in a slightly externally rotated position (-1.1° , -3.3°). During extension, they rotated slightly internally but remained in slight external rotation at 10° of flexion (-0.31° and -1.8°).

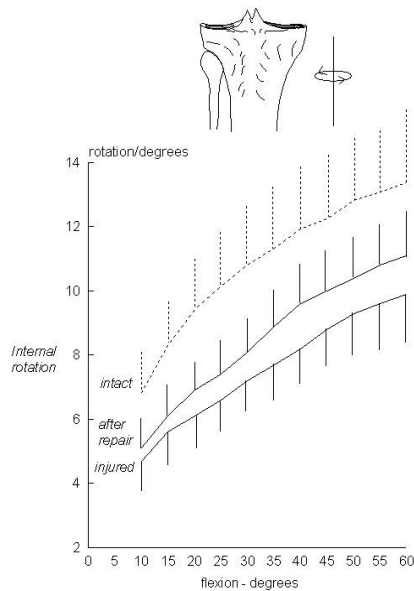


Figure 20. Internal (+)/external (-) tibial rotation during active weight-bearing knee extension. Injured side examined before and two years after reconstruction of the ACL. Mean values and standard error of the mean are shown.

Translations of the medial (MFC) and lateral (LFC) femoral condyles: During the active and weight-bearing knee extension, the MFC started in a slightly anterior position and translated posteriorly on both sides, without any significant differences between the injured and uninjured knees, either pre-operatively or at the two-year follow-up ($p=0.59$ and 0.97), (Figures 21).

The LFC started in a posterior position and ended in almost the same position, without any significant differences between the injured and uninjured knees, either pre-operatively or at the two-year follow-up ($p=0.21$ and 0.96), (Figures 22).

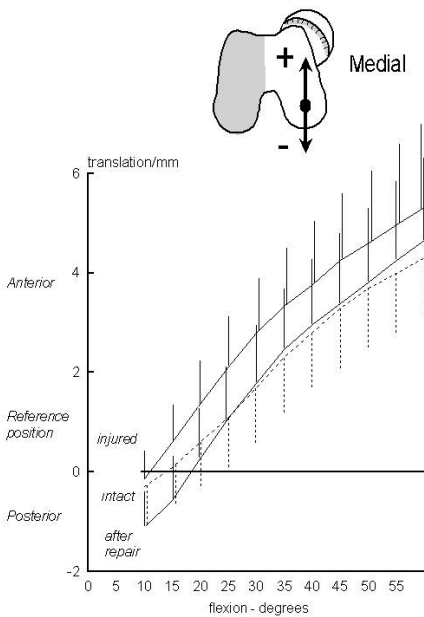


Figure 21. Anterior (+)/posterior (-) translation of the medial femoral condyle

Figure 22. Anterior (+)/posterior (-) translation of the lateral femoral condyle during active weight-bearing knee extension. Injured side examined before and two years after reconstruction of the ACL. Mean values and standard error of the mean are shown.

Tibial varus (+)/valgus (-) angulations: During the active and weight-bearing knee extension, tibial rotations into varus or valgus were small, without any significant differences between the injured and uninjured knees, either pre-operatively or at two-year follow-up ($p=0.59$ and 0.91) (Figure 23).

Figure 23. Tibial varus (+)/valgus (-) angulation during active weight-bearing knee extension. Injured side examined before and two years after reconstruction of the ACL. Mean values and standard error of the mean are shown.

Conclusion

Before surgical repair of the ACL, the knee kinematics was similar on the injured and uninjured sides. Two years after the reconstruction, the kinematics of the operated knee was still normal. Our findings indicate that previously observed changes in knee kinematics after ACL rupture develop gradually after the injury. Early surgical repair using quadruple hamstring autografts appears to be just as effective as previously observed for the BPTB graft (Study III) in protecting the knee from developing abnormal knee kinematics after ACL rupture.

GENERAL DISCUSSION

New surgical techniques and rehabilitation regimens should be evaluated scientifically. This should preferably be done using methods with high accuracy to expose a minimum of patients to new and unproven treatments before they are taken into clinical practice. In the history of ACL surgery and rehabilitation, there are many examples of the opposite, such as the transition from open to mini-open to arthroscopic ACL reconstruction; the change from bone-patellar tendon-bone grafts to hamstring grafts; the use of double-bundle grafts; allowing early extension after ACL reconstruction; the timing of surgery, acute or delayed, and finally the use of different fixation methods.

RSA is a method with high accuracy, which has been used for more than 20 years to evaluate new hip and knee arthroplasties. The accuracy of the RSA technique makes it possible to draw conclusions from a limited cohort. It is, however, of great importance that these studies follow the standardisation recommendations for RSA studies (101).

Rehabilitation after an ACL reconstruction

Allowing full active and passive extension immediately after an ACL reconstruction has been the subject of discussion, since it might increase the post-operative A-P laxity of the knee. For a long time now, many protocols have encouraged early full active and/or passive extension with full weight bearing after an ACL reconstruction. This opinion has, however, not usually been based on controlled clinical studies. Instead, most clinicians who have encouraged and allowed immediate full extension, including active extension training, have only followed the trends of time.

Beynon and co-workers (10) found only five randomised, controlled studies comparing immediate and delayed knee motion after an ACL reconstruction. Almost 30 years ago, Häggmark and Eriksson (29) published the first prospective, randomised study of rehabilitation after ACL reconstruction with a patellar tendon graft. All their patients were treated with a dorsal plaster splint during the first week after surgery. They were then randomly allocated to two groups with different rehabilitation protocols for four weeks. The first group used a hinged cast, which allowed knee motion, and the second group used an ordinary cylinder cast, without any motion. All the patients were followed up for one year, including muscle biopsies. The group treated with a cylinder cast had

significant hypotrophy of the slow-twitch fibres of the vastus lateralis, whereas the group with a hinged cast had no such hypotrophy of slow- or fast-twitch fibres. At the final follow-up, there were no differences between the two rehabilitation groups in terms of knee laxity, knee motion, subjective knee function and activity level.

Noyes and co-workers (71) compared continuous passive motion with immobilisation in 18 patients randomised into two groups. The first group started continuous passive motion of the knee on the second post-operative day. The second group was immobilised in a brace for six days in 10° of flexion and started with continuous passive motion on the seventh post-operative day. The authors found no differences between the two groups in terms of anterior knee laxity as measured with the KT-1000, flexion-extension, joint effusion, use of pain medication and length of stay in hospital. They concluded that a start of continuous passive knee motion immediately after ACL reconstruction did not lead to an increase in anterior knee laxity. However, only a few patients were studied without using the most accurate methodology, extensor muscle activity was not allowed and the differences between the protocols were minor.

Recently, Henriksson and co-workers (31) published a randomised study including 50 patients undergoing ACL reconstruction with a BPTB graft. After the reconstruction, the patients were randomly allocated to two groups. The first group started early range of motion training using a brace and the second group were immobilised in a cast for five weeks. At the two-year follow-up, there were no differences between the two groups in terms of knee laxity, knee motion, subjective knee function and activity level. The results of these studies indicate that early training of range of motion after an ACL reconstruction might not be detrimental to the graft.

The relevance of these results for the rehabilitation protocols used today can be questioned. Häggmark and Eriksson (29) studied open ACL reconstruction, while Noyes and co-workers (71) studied open and arthroscopic reconstruction, but the difference between the groups was only five days of immobilisation. Henriksson and co-workers used a cast and brace. Neither open ACL reconstructions nor casts are used any longer.

In a randomised study with a six-month follow-up, Shaw and co-workers (87) evaluated whether early quadriceps exercises affected the outcome of ACL reconstruction. The experimental group (n=47) performed straight leg raises and isometric quadriceps contractions throughout the first two post-operative weeks. The control group (n=44) did no quadriceps exercises during the same period. At six-months follow-up there was no significant difference in the average knee laxity between the groups. Quadriceps exercise performance was associated with a significantly lower incidence of abnormal knee laxity in the experimental group (3 of 47) than in the control group (12 of 44). The patients in the quadriceps training group also had significantly higher Cincinnati scores for symptoms and less problems with sports. No other statistical differences were found between the two groups.

In *Study I*, no difference was found in A-P laxity between the two groups at the two-year follow-up. One limitation in this study is the comparatively small number of patients. Based on the observed median/mean values in the two groups that were studied and the observed data scatter, it is most likely that a similar outcome would have been found, even with a larger number of patients. Since the measurement error is small, it is possible to use a small number of patients to draw relevant conclusions using RSA (46,83). The most important conclusion from *Study I* is that early extension training between 30--10° is a safe rehabilitation regimen when BPTB autografts with secure fixation are used.

Instrumental evaluation after ACL reconstruction

The A-P laxity of the knee joint is an important parameter when evaluating the ACL-injured knee. Almost all studies dealing with ACL insufficiency or post-operative follow-up after an ACL reconstruction use the KT-1000 as part of the outcome analysis. Non-invasive arthrometers are often used as a complement to establish the diagnosis of an ACL rupture. However, to be clinically relevant, the results from such measurements must be sufficiently accurate. The instrument that is chosen must be easy to handle and adapted for use in a standard examination room. The KT-1000 is often used by knee surgeons and physiotherapists and has become one of the most widely used non-invasive

arthrometers. In spite of its widespread use, the question of whether the results of KT-1000 measurements are sufficiently accurate and clinically relevant still remains.

The reproducibility and/or sensitivity of the KT-1000 has been regarded as good in some studies (2,6,18,60,104) but has been questioned by others (23,28,34,41,86,96), but Malcolm and co-workers (60) evaluated 19 patients with chronic ACL insufficiency and 24 with an acute ACL rupture, using the KT-1000. In the chronic group, they found a mean laxity of 15.3 mm in the injured knee and 8.5 mm in the uninjured knee. In the acute group, the corresponding measurements were 11.3 mm and 7.3 mm respectively. The mean side-to-side difference was 6.8 mm in the chronic group and 4.0 mm in the acute group. They found a pre-operative side-to-side difference of > 3 mm in 18/19 in the chronic group and in 22/24 in the acute group. They stated that the KT-1000 is a valuable and important part of the post-operative evaluation.

In a study of the reproducibility of the KT-1000, Sernert and co-workers (86) studied 20 patients with chronic ACL insufficiency. Two experienced investigators evaluated the KT-1000 in a group of 20 patients with chronic ACL injury. Using a cut-off value of > 3 mm for side-to-side difference, the two investigators identified 10 (50%) and 11 (55%) true positive ACL ruptures respectively. These researchers stated that the KT-1000 was not useful for diagnosing an ACL rupture in each individual patient but could be useful at group level.

In a prospective study, Graham and co-workers (28) compared the accuracy of the Lachman test, anterior drawer test and KT-1000. They used a force of 89N for the KT-1000 and tested 21 patients with a chronic ACL rupture. They found that 10/21 patients were true positive with the KT-1000 and stated that “the KT-1000 knee arthrometer was found to be totally inaccurate”. Strand and co-workers (96) evaluated patients with an acute ACL rupture and found 25/42 true positive. Jonsson and co-workers (41) compared the KT-1000 with RSA and found 28/39 true positive for the KT-1000, using a 3 mm cut-off value, and 38/39 true positive when using RSA with a 2.5 mm cut-off value. Several authors have also found differences between investigators, when evaluating the same cohort of patients on two occasions (7,86).

In *Study II*, the pre-operative A-P laxity, using the KT-1000, showed that 11/22 (50%) patients had a cut-off value of > 3 mm, while the corresponding number for RSA was 21/22 (95%) patients. The reason for this discrepancy is not quite clear, but one important factor is the observation that the KT-1000 appears to overestimate the A-P laxity on the intact side. This might in turn be an effect of soft-tissue compression, which is probably unavoidable when using external recorders of skeletal translations applied to the skin. Not surprisingly, the KT-1000 still recorded larger A-P laxity on the intact side. On the injured side and before reconstruction, the KT-1000 recordings were similar to those observed with RSA. Provided that the amount of soft tissue compression included in the KT-1000 measurements is similar on both sides, this observation can be interpreted as the failure of the KT-1000 to identify the true extent of the instability caused by the absence of the ACL itself. If so, this theory will also explain the smaller side-to side difference after reconstruction. The KT-1000 measures the same soft tissue compression on both sides and is not sensitive enough to detect a slight remaining increase in the A-P translation caused by the slight elongation of the graft or any other reason.

Our observations concerning the diagnostic sensitivity of the KT-1000 confirm a number of previous studies (23,34,41,86). In our hands, its sensitivity was 50%, which is similar to tossing a coin. We think it is important to be aware of these limitations of the KT-1000, not least for knee surgeons and physiotherapists, who may use this device in their daily clinical work. The low sensitivity of the KT-1000 is certainly an important explanation of the low correlation between laxity values and giving-way symptoms (23,34,41,86).

Timing of the ACL reconstruction

There is no consensus concerning an optimum time period between injury and subsequent repair of the ACL (9). Mayr and co-workers (61) reported that, if the patients had synovitis in their injured knee when the ACL reconstruction was performed, 70% developed post-operative arthrofibrosis. Shelbourne and Patel (91) stated that, if the patient had normal range of motion, minor swelling, good muscle control and a stable

mental state before surgery, a predictable, smooth post-operative course could be expected.

In a prospective study, Hunter and co-workers (32) studied the impact of surgical timing on post-operative motion and laxity following ACL reconstruction. One hundred and eighty-five patients with an acute ACL rupture, sustained during downhill skiing, were included and divided into four groups. Group 1 underwent surgery within 48 hours, Group 2 between three and seven days after injury, Group 3 between one and three weeks after injury and Group 4 more than three weeks after injury (the maximum time in Group 4 is not stated). The post-operative rehabilitation included a hinged brace with full range of motion. Motion measurements were taken every day for the first post-operative week, then weekly until six weeks and at three, six and 12 months. The authors found no differences in terms of restoration of extension and flexion in any of the groups at any time. The KT-1000 showed no differences between any of the groups. At the 12-month follow-up, a side-to-side difference of ≤ 3 mm was found in 94% of the patients. Hunter and co-workers concluded that surgical success was independent of the timing of surgery, all the patients were classified as acute ruptures and none of the patients included could be regarded as having a chronic injury.

The patients in *Studies III* and *IV* underwent an early ACL reconstruction (8-10 weeks after injury), before they had experienced pivoting episodes, and the results of the RSA measurements demonstrated normal kinematics. Two years after the ACL reconstruction, they had maintained normal kinematics in their injured knees. Even if our results are encouraging and support an early repair, further studies with a randomised design and, if possible, including cases with a favourable outcome after conservative treatment are desirable in order to evaluate this issue further.

Kinematics of the normal knee

In a review article, Freeman and Pinskerova (24) described the kinematics in the normal knee and subdivided the arc of flexion into three sub-arcs; i.e. (1) “terminal extension” from full extension to 10° ; (2) “the active functional arc”, which is the arc from 10° to about 120° ; and (3) “the arc of passive flexion”, which is from 120° to full passive flexion.

During flexion from 10° to 120°, the tibia rotates approximately 30° internally (externally during extension). There is very little varus/valgus motion unless there is lift-off, which may occur laterally, because the femoral surfaces are circular and the lateral tibial articular surface is essentially flat and parallel to the varus/valgus axis.

Freeman stated that “the medial femoral condyle can be viewed as a sphere which rotates to produce a variable combination of flexion and longitudinal rotation”. The medial femoral condyle translates a maximum of ±1.5 mm antero-posteriorly. The lateral femur condyle rolls and slides antero-posteriorly on the tibial plateau and rotates around an axis passing through the centre of the medial condyle. During flexion, it translates posteriorly about 15 mm by a combination of rolling and sliding.

Jonsson and Kärrholm (39) showed, in a three-dimensional in vivo study, using RSA, that the tibia rotated about 20° externally during extension from 100-0° and about 15° from 60-10° of extension. They also found that the femoral condylar centre translated about 15 mm during extension from 100-0° and about 5 mm from 60-10° of extension. Saari and co-workers (84) found, in a dynamic RSA study with full weight bearing, that the tibia started in 5.6° of internal rotation at 50° of flexion and rotated externally 1.4° up to 20° of flexion.

Kinematics in chronic ACL-insufficient knees, before and after ACL reconstruction

Chronic ACL insufficiency is associated with recurrent pivoting phenomena, i.e. “giving way”, which leads to an increased load on the secondary restraints, such as the joint capsule, and the collateral ligaments. Several authors (4,8,13,14,17,77,78) have studied the kinematics in the chronic ACL-insufficient knee.

Using dynamic RSA, Brandsson and co-workers (13,14) evaluated 11 patients with chronic ACL instability, who were all suffering from recurrent pivoting. They found that the “normal” internal tibial rotation accompanying flexion was reduced in these patients, before the ACL reconstruction, but that it also persisted after the ACL reconstruction. Ristanis and co-workers (77,78) used a six-camera optoelectronic system to study patients with chronic ACL insufficiency. They also found that excessive tibial rotation

remained one and two years after reconstruction of the ligament. Barrance and co-workers (8) recorded a significant anterior translation and external tibial rotation accompanying knee extension using cine-PC and MRI in patients who had sustained an ACL rupture up to six months prior to testing. This implies that patients with chronic ACL insufficiency are unable to regain normal kinematics, i.e. normal tibial rotation relative to the femur, in spite of seemingly successful ACL reconstruction and a clinically well-functioning knee.

It is, however, not known whether a change in knee kinematics after tearing the ACL is an obligatory effect of loss of tension in the ligament, or develops gradually after the injury. It is also not known whether the time between the injury and ACL reconstruction affects the kinematics after an ACL reconstruction.

Interestingly, Saari and co-workers (84) observed reduced or absent external tibial rotation with flexion in patients who had medial osteoarthritis. This abnormality was similar to the one observed in knees with chronic insufficiency after tearing the ACL. Even if this could be a coincidence, it is tempting to speculate that the loss of normal internal rotation with flexion is an effect of the chronic rupture of the ACL and actually indicates that the knee joint has started to undergo degenerative changes.

Can an early ACL reconstruction prevent the knee from developing increased external tibial rotation?

To our knowledge, there are no studies which have measured the kinematics before an early ACL reconstruction (within eight weeks after the injury) and a follow-up investigation two years after the reconstruction using a highly accurate method such as RSA.

In *Studies III* and *IV*, the ACL reconstruction was performed in the early phase. The reason for selecting the timing of 8-10 weeks after the ACL rupture for the reconstruction was that we wanted the patients to be in optimal physical and psychological condition at the time of the ACL reconstruction, in order to minimise the risk of arthrofibrosis (9). The dynamic kinematics before an early ACL reconstruction and two years after the reconstruction were studied. This meant that no pivoting episodes between the injury and the ACL reconstruction had occurred. The rehabilitation started immediately after the

injury. None of the patients had any knee swelling and all the patients had good leg control, including muscle control and ROM, at the time of ACL reconstruction. Before the ACL reconstruction, the tibial internal/external rotation and abduction/adduction did not differ between the injured and intact knees. Nor did studies of the translations of the medial and lateral femoral flexion facet centres (MFC and LFC) relative to a fixed tibia reveal any differences between the injured and intact sides. At two years, the knee kinematics were unchanged and there was still no difference compared with the intact side. Pre-operatively, the difference in side-to-side A-P laxity as measured with KT-1000 arthrometer was 2.0 mm and it decreased significantly to 0.5 mm at two years.

High prevalence of knee osteoarthritis after ACL injury

Lohmander and co-workers (57) evaluated 84 female soccer players 12 years after an ACL injury with a questionnaire and 67 of them were also radiographed. The mean age at injury was 19 years, while it was 31 years at the follow-up assessment. Of these 67 females, 41 had undergone an ACL reconstruction. The average time from injury to reconstruction was three (0-11) years. Among these 41 patients, 23 (56%) had radiographic patello-femoral or tibio-femoral osteoarthritis (OA) in the reconstructed knee. In the contralateral knee, radiographic tibio-femoral OA was present in five of 65 knees (8%).

Recently, von Porat and co-workers (103) presented a follow-up of male soccer players 14 years after an ACL injury. One hundred and fifty-four men were evaluated; 65 of them had been treated without reconstruction and 89 with an ACL reconstruction. One hundred and twenty-two of 154 were evaluated with knee radiographs. Of these 122 patients, 50 had radiographic signs of osteoarthritis. No differences were found between those treated with or without an ACL reconstruction.

There are reasons to believe that changes in the kinematics of the knee over a long period of time might have secondary effects and may predispose to the development of degenerative changes in the knee joint. According to our knowledge, no such evidence has, however, been found to date. As mentioned above, other factors such as repeated giving-way episodes and secondary effects such as injuries to the knee will more definitely contribute to the development of osteoarthritis (9,10,57,103), which will

obscure a more precise evaluation of the change in knee motion during daily activities in the long term.

Repeated giving-way episodes may distend and damage the secondary restraint structures such as the collateral ligaments, the menisci, the posterior cruciate ligament and the postero-lateral corner. This may result in changes in the pattern of knee motion and joint contact, increased laxity and symptoms of instability and an increased risk of developing osteoarthritis.

Strengths and limitations

There are some disadvantages to using RSA. It is an invasive method and each patient and investigation will take a long time and is extremely labour intensive. A specially designed laboratory is needed. Even if the radiation is lower than that in an ordinary radiographic examination, the examinations add to the total radiation burden. A second limitation is the fact that, despite being extremely accurate and reliable, RSA will never be used in everyday clinical work.

There are also advantages to using RSA. It is a highly accurate method for quantifying motion between bony structures and motion between an implant and the host bone and for measuring wear. It is a true three-dimensional method and can be used as both static and dynamic. It can provide important information from a relatively small patient cohort and after a comparatively short period of time. This means that the number of patients exposed to a new and unproven treatment or implant can be limited.

A further limitation in the present thesis is the limited number of patients that were included. This makes it more difficult to draw firm clinical conclusions, e.g. using more traditional outcome measures, like the Lysholm, Tegner and IKDC scores. On the other hand, this shortcoming is partly compensated for by the benefits of the method, which reduces the data scatter. The high accuracy of RSA is of particular importance in kinematic studies, where variations in muscular activity and positioning may cause true deviations of a few degrees in the pattern of motion, according to the tests of reproducibility.

One of the strengths of the present thesis is the RSA method, which has been tested for reliability and validated in patients who undergo surgery for hip and knee replacements. To the best of our knowledge, this is also the first study to investigate dynamic knee kinematics in vivo pre- and post-operatively in patients undergoing early-phase ACL reconstructions.

CONCLUSIONS

- The KT-1000 recorded significantly smaller side-to-side differences in terms of A-P laxity, both before and after the ACL reconstruction, compared with RSA.
- The KT-1000 recorded significantly larger A-P laxity in the intact knee and larger A-P laxity in the ACL-reconstructed knee compared with RSA.
- It appears to be safe to start early active and passive extension training without restrictions in extension immediately after the ACL reconstruction with a bone-patellar tendon-bone autograft.
- Eight to ten weeks after rupture of the ACL, the knee kinematics remained similar on the injured and normal sides. Consistent observations were made in two consecutive studies, before and after surgical repair.
- Two years after the reconstruction with a bone-patellar tendon-bone autograft, the kinematics of the operated knee were still normal.
- Two years after the reconstruction with a quadruple hamstring autograft, the kinematics of the operated knee were still normal.

CLINICAL RELEVANCE

According to the findings in the present thesis, full active and passive extension training immediately after an ACL reconstruction did not increase the post-operative A-P laxity, which could have an important clinical impact on the rehabilitation programme and facilitate accelerated training.

The KT-1000 is one of the most widely used non-invasive arthrometers. The convenience of this instrument is probably responsible for its popularity. However, to be clinically useful, the results from its measurements must be accurate. Using a 3 mm cut-off value for the side-to-side difference in AP-laxity implies that the KT-1000 measurements result in a correct diagnosis of an ACL rupture in approximately 50% of injured knees. This method also overestimates the effect of ACL reconstruction regarding the A-P laxity of the knee.

According to our observations, ACL reconstruction should be performed at an early stage to minimise any adverse development in knee kinematics. There is reason to believe that a change in the kinematics of the knee over a long period of time will have secondary effects and may predispose to the development of degenerative changes in the knee joint. However, there is as yet no clear evidence of this. As mentioned above, other factors might play an important role; they include repeated (giving-way) pivoting episodes resulting in secondary injuries to other ligaments, capsules or menisci, as well as chondral lesions, which could obscure a more precise evaluation of changes in knee kinematics during daily activities in the long term. On the other hand, changes in the kinematics of the knee may facilitate the occurrence of further knee injuries.

The normal fine-tuned kinematics of the knee may be of considerable importance for the function of the joint. Abnormal kinematics might increase the risk of damaging the secondary restraints, as well as the menisci and the cartilage. Our findings could indicate that previously observed changes in knee kinematics after ACL rupture develop gradually after the injury. The findings in the present study could be interpreted in such a way that

early surgical repair of the ACL might protect the knee from developing abnormal kinematics, which could be beneficial by preventing subsequent detrimental effects.

THE FUTURE

One main purpose of this thesis was to assess new methods and techniques in surgery and rehabilitation, in order better to evaluate these methods before they are introduced into clinical use. It is also important to perform long-term follow-ups of existing models in a similar way. With its high accuracy and potential for use in small numbers of subjects, RSA is an appropriate method well suited to this mission.

One important step in the future is a randomised study using the double-bundle, double-tunnel technique for reconstruction, using RSA as part of the clinical outcome evaluation, with A-P laxity and kinematics.

The next dynamic RSA project is to compare the kinematics in a dynamic knee extension with a dynamic knee flexion analysed using dynamic weight-bearing RSA. The reason is that, to date, it has only been possible to study one activity. Increased knowledge of the kinematics of the knee during different types of activity and the development of any changes in joint motion over time has the potential to increase our understanding of the effects of knee injuries. This knowledge could also be of some importance for their prevention. If longitudinal recordings of this kind are combined with simultaneous observations of any degenerative changes, any association between changes in knee kinematics and osteoarthritic development might be better understood.

The first step in a project of this kind is to analyse the knee kinematics shortly after the ACL rupture and then perform repeated measurements at comparatively short intervals to record if and when any irreversible changes in knee kinematics occur. An approach like this requires observations of a group of patients treated conservatively without ACL reconstruction.

Our ambition is to develop the dynamic RSA technique still further in order to supplement gait analysis during walking and possibly even running.

SUMMARY IN SWEDISH

Bakgrund

Det främre korsbandet (Figur 24) har en viktig betydelse i knäledens rörelsemönster och laxiteten framåt-bakåt. Slutresultatet efter en främre korsbandsoperation är beroende av många olika faktorer. En mycket viktig faktor är det post-operativa rehabiliteringsprogram. Sedan många år har de flesta rehabiliteringsprogrammen tillåtet att patienterna sträcker fullt omedelbart efter operationen. Det har spekulerats att det skall kunna öka A-P laxiteten (instabiliteten framåt-bakåt i knäleden). Det har dock saknats randomiserade studier med noggranna mätmetoder för att studera om så är fallet. Det anses betydelsefullt att utvärdera knäledens laxitet efter en främre korsbandsoperation, med ett reliabelt mätinstrument. Det vanligaste mätinstrumentet på marknaden idag för att mäta A-P laxiteten är KT-1000. Tidigare studier har visat att en knäled, som utvecklat kronisk instabilitet efter en främre korsbandsskada har ett avvikande rörelsemönster, som inte normaliseras av en rekonstruktion av det främre korsbandet. Rörelsemönstret = kinematiken analyseras utifrån de tre rörelseaxlarna i ett tredimensionellt koordinatsystem: x,y,z (Figur 25).

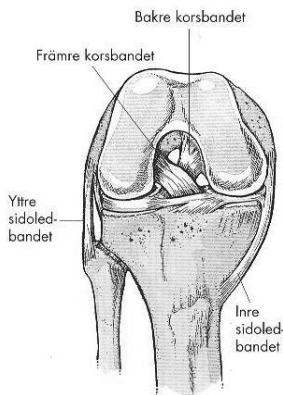
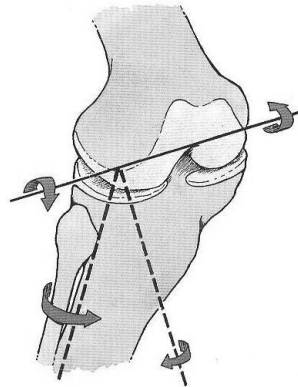


Figure 24. Anatomi höger knä. (© J Karlsson)



Figur 25. Rörelsemönstret = kinematiken analyseras utifrån de tre rörelseaxlarna i ett tredimensionellt koordinatsystem: x,y, z (© J Karlsson)

Syftet med *Studie I* var att i en randomiserad studie undersöka om ett rehabiliteringsprogram, som tillåter full aktiv och passiv sträckning i knäleden omedelbart efter en främre korsbandsrekonstruktion påverkar A-P laxiteten upp till två år efter operationen.

Syftet med *Studie II* var att jämföra KT-1000 mot en mätmetod med hög noggrannhet och precision. Radiostereometrisk analys (RSA) är en mycket noggrann metod för att mäta A-P laxiteten i knäleden hos friska, och främre korsbandsskadade knän, före och efter operationen. Tjugo två patienter (14 män, 8 kvinnor) med en median (min-max) ålder på 24 (16-41) inkluderades och randomiserades till två grupper. Grupp A tilläts sträcka fullt omedelbart efter operationen och Grupp B fick inte under de fyra första veckorna sträcka de sista 30 graderna. Syftet med *Studie III* och *IV* var att utföra en främre korsbandsrekonstruktion tidigt efter skadan och utvärdera om tidig operation skulle kunna förhindra utvecklingen av ett felaktigt rörelsemönster. Tidigare studier har visat att om patienterna redan utvecklat en kronisk instabilitet, inkluderande felaktig underbensrotation, i sin skadade knäled, så normaliseras inte rörelsemönstret efter en främre korsbandsrekonstruktion. Vi utförde främre korsbandsrekonstruktionen 8-10 veckor efter skadan. 26 patienter inkluderades; 12 i *Studie III* och 14 i *Studie IV*. Samtliga patienter hade en akut ensidig främre korsbandsruptur. Alla inkluderade patienter var innan studien helt friska i båda sina knäleder. Samtliga patienter opererades av en och samma erfarna knäkirurg, som använde ett graft från knäskålssenan i *Studie I-III* och från hamstring musklernas senor i *Studie IV*. RSA med skelettmarkörer av tantalum användes för att studera rörelsemönstret i knäleden under en aktiv och belastad knästräckning. A-P laxiteten mättes med KT-1000.

Utvärdering med kliniska parametrar såsom Lysholm score, Tegner aktivitetsnivå, IKDC och en-bens-hopp utfördes i samtliga studier. Patienterna utvärderades prospektivt, dels före operationen och dels två år efter.

Resultat

Studie I: Det förelåg ingen signifikant skillnad mellan de båda grupperna (tidig eller sen extension) avseende A-P laxitet, två år efter korsbandsoperationen. Det fanns inte heller någon skillnad mellan grupperna avseende de kliniska testerna.

Studie II: KT-1000 mätte signifikant lägre sidoskillnad (skillnad mellan sjuk och frisk sida) än vad RSA gjorde, både före och efter korsbandsoperationen. I *Studie III* och *IV* visade det sig att patienterna inte hade utvecklat en kronisk instabilitet med sjukligt rörelsemönster innan främre korsbandsrekonstruktionen, som utfördes 8-10 veckor efter skadan. Patienterna behöll också det normala rörelsemönstret vid uppföljningen två år efter rekonstruktionen.

Konklusion

En tidig aktiv och passiv rörelseträning efter korsbandsrekonstruktion till full sträckning ökade inte A-P laxiteten upp till två år efter operationen. KT-1000 mätte signifikant lägre värden avseende A-P laxiteten jämfört med RSA. Främre korsbandsrekonstruktion 8-10 veckor efter skadan tycks hindra en utveckling av det sjukliga rörelsemönster som föreligger efter en rekonstruktion hos en patient med en kronisk främre korsbandsinstabilitet.

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