ANATOMIC ANTERIOR CRUCIATE LIGAMENT RECONSTRUCTION

aspects of surgical technique

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To my family

Anatomic anterior cruciate ligament reconstruction – aspects of surgical technique

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"If we all worked on the assumption
that what is accepted as true is really true,
there would be little hope for advance."

Orville Wright

Contents

Abstract 01

Anatomic anterior cruciate ligament (ACL) reconstruction is a concept that has gained in interest and it aims to more effectively restore native ACL anatomy and function. Despite extensive research on the topic, the optimal surgical technique to accomplish this is still the subject of debate.

Study I is a meta-analysis to determine whether anatomic double-bundle (DB) reconstruction compared with anatomic single-bundle (SB) reconstruction more effectively restores knee laxity, and reduces rates of graft failure. A total of 15 studies were included for analysis. The results revealed significantly less antero-posterior (AP) laxity after anatomic DB reconstruction. No statistically significant differences were seen between anatomic DB and SB techniques in terms of the pivot-shift test, Lachman test, anterior drawer test, total knee rotation or graft failure rates.

Study II is a systematic review including the implementation of the Anatomic Anterior Cruciate Ligament Reconstruction Scoring Checklist (AARSC) on studies comparing SB and DB reconstruction in order to evaluate the reporting of surgical details, and the degree to which these clinical studies fulfil the criteria of anatomic ACL reconstruction. Seventy-seven studies were included. Details of the surgical techniques used were more thoroughly reported for DB reconstructions than for SB reconstructions. There was substantial underreporting of surgical data for both the SB and DB groups in clinical studies.

Study III is a prospective randomised clinical trial comparing the outcomes of the anatomic DB technique and anatomic SB technique using hamstrings tendon autograft. A total of 105 patients were randomised and underwent ACL reconstruction. At five-year follow-up, no statistically significant differences were found between the groups in terms of subjective or objective outcomes, or in terms of the presence of osteoarthritis (OA).

Study IV is a cohort study with data from the Swedish National Knee Ligament Register with the focus on the risk of revision ACL surgery. A total of 17,682 patients were included. Surgical details pertaining to their primary ACL reconstruction were collected via an online questionnaire comprised of items from the AARSC, distributed to the surgeons. Non-anatomic bone tunnel placement via transtibial drilling resulted in the lowest risk of revision surgery. Non-anatomic surgical techniques in general were associated with a lower risk of revision. Anatomic techniques utilising several pertinent items from the AARSC were associated with a lower risk of revision compared with anatomic techniques utilising only some items.

Keywords: Knee, Anterior Cruciate Ligament, Anatomic, Reconstruction, Double-Bundle, Single-Bundle, Laxity, Register, Score, AARSC, Graft Failure, Revision, Outcome

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Swedish abstract 02

Främre korsbandet är ett av de viktigaste ligamenten i knäleden, och förbinder lårbenet (femur) med skenbenet (tibia) samt bidrar till stabilitet och normal rörlighet i knät. Skador på främre korsbandet är vanliga. Konsekvenserna av främre korsbandsskada innebär ökad instabilitet i knät, liksom skadliga effekter på andra strukturer i knät, t ex menisker och brosk. Det är inte ovanligt att detta leder till en nedsatt funktion och svårigheter vid idrottsutövning. Artroskopisk främre korsbandsrekonstruktion är en vanlig behandling för denna skada. 'Anatomisk rekonstruktion' av det främre korsbandet har de senaste åren uppmärksammats alltmer och bygger på att återställa knäledens normala anatomi och funktion. Trots omfattande forskning inom ämnet, förekommer fortfarande relativt stor debatt om vad som är den optimala kirurgiska tekniken för att åstadkomma detta. Hittills har de flesta använt sig av enkelskänkelrekonstruktion för att stabilisera knäleden, men en vidareutveckling av begreppet "anatomisk" rekonstruktion har lett till utveckling av dubbelskänkel tekniken. Dubbelskänkelteknik är dock inte synonymt med "anatomisk rekonstruktion" utan går att utföra "icke-anatomiskt", liksom enkelskänkelteknik.

Genom en meta-analys i **delarbete I** bedömdes studier som specifikt jämför "anatomisk" enkel- med dubbelskänkelrekonstruktion. Här påvisades minskad antero-posterior laxitet i knät till fördel för dubbelskänkelteknik. Inga signifikanta skillnader avseende rotationell laxitet eller grafthaveri kunde påvisas. I **delarbete II**, som är en systematisk litteraturöversikt utvärderades främre korsbandsrekonstruktion med enkelskänkelrekonstruktion och dubbelskänkelrekonstruktion genom tillämpning av en checklista (Anatomic Anterior Cruciate Ligament Reconstruction Scoring Checklist-AARSC) för att objektivt gradera kirurgiska tillvägagångssätt vid anatomisk korsbandsrekonstruktion. Det påvisades omfattande underrapportering av data för båda teknikerna, med rapporterade värden klart under en föreslagen miniminivå för vad som får betraktas som en "anatomisk rekonstruktion", vilket begränsar tolkningen av utfall i befintliga studier inom ämnet.

I **delarbete III**, som är en prospektiv randomiserad klinisk studie jämfördes patienter som behandlades med antingen anatomisk enkelskänkelrekonstruktion eller anatomisk dubbelskänkelrekonstruktion. Vid 5-årsuppföljning analyserades subjektiva och objektiva utfallsmått, samt radiologiska tecken till artrosutveckling. Inga signifikanta skillnader påvisades mellan grupperna avseende dessa utfallsmått.

I **delarbete IV** utvärderades potentiella prediktorer för revision efter främre korsbandsrekonstruktion utifrån data från en nätbaserad enkät skickad till korsbandskirurger i Sverige, med svaren kopplade till Svenska korsbandsregistret. Totalt 17,682 patienter ingick i studies. Yngre patienter samt patienter utan broskskador löpte större risk för revision. "Icke-anatomiska" korsbandsrekonstruktioner löpte generellt lägre risk för revision. De patienter som opererats

med strikt tillämpning av 'anatomisk rekonstruktion' enligt AARSC, uppvisar en lägre risk för revision än de som opererats men tekniker som endast tillämpar ett fåtal av checklistans variabler. Detta fynd skulle trots allt kunna tala för tillämpning av "anatomisk" korsbandsrekonstruktion, under förutsättning att den utförs strikt enligt checklistan.

List of papers 03

This thesis is based on the following studies, referred to in the text by their Roman numerals.

I. **Anatomic single- versus double-bundle ACL reconstruction: a meta analysis**
Desai N, Björnsson H, Musahl V, Bhandari M, Petzold M, Fu FH, Samuelsson K
Knee Surgery, Sports Traumatology, Arthroscopy. 2014; 22(5): 1009-1023
E-published 2013 Dec 17

II. **A systematic review of single- versus double-bundle ACL reconstruction using the anatomic anatomic anterior cruciate ligament reconstruction scoring checklist**
Desai N, Alentorn-Geli E, van Eck CF, Musahl V, Fu F Karlsson J, Samuelsson K
Knee Surgery, Sports Traumatology, Arthroscopy. 2016; 24(3): 862-872
E-published 2014 Oct 26

III. **Comparison of anatomic double- and single-bundle techniques for anterior cruciate ligament reconstruction using hamstring tendon autografts: a prospective randomized study with 5-year clinical and radiographic follow-up**
Karikis I, Desai N, Sernert N, Rostgard-Christensen L, Kartus J
The American Journal of Sports Medicine
E-published 2016 Mar 6, doi:10.1177/0363546515626543

IV. **Revision surgery in anterior cruciate ligament reconstruction - A cohort study of 17,682 patients using the Anatomic Anterior Cruciate Ligament Reconstruction Scoring Checklist applied to the Swedish National Knee Ligament Register**
Desai N, Andernord D, Sundemo D, Alentorn-Geli E, Musahl V, Fu F, Forssblad M, Karlsson J, Samuelsson K
Manuscript

Additional relevant papers by the author not included in this thesis:

Level of Evidence in anterior cruciate ligament reconstruction research: a systematic review

Samuelsson K, Desai N, McNair E, van Eck CF, Petzold M, Fu FH, Bhandari M, Karlsson J

The American Journal of Sports Medicine. 2013; 41(4): 924-934

Outcomes after ACL reconstruction with focus on older patients: Results from The Swedish National Anterior Cruciate Ligament Register

Desai N, Björnsson H, Samuelsson K, Karlsson J, Forssblad M

Knee Surgery, Sports Traumatology, Arthroscopy. 2014; 22(2): 379-386

Is double-bundle anterior cruciate ligament reconstruction superior to single-bundle? A comprehensive systematic review

Björnsson H, Desai N, Musahl V, Alentorn-Geli E, Bhandari M, Fu FH, Samuelsson K

Knee Surgery, Sports Traumatology, Arthroscopy. 2015; 23(3): 696-739

No difference in revision rates between single- and double-bundle anterior cruciate ligament reconstruction. A cohort study of 16,791 patients from the Swedish national knee ligament register

Björnsson H, Andernord D, Desai N, Norrby O, Forssblad M, Petzold M, Karlsson J, Samuelsson K

Arthroscopy. 2015; 31(4): 659-664

Patient predictors of early revision surgery after anterior cruciate ligament reconstruction: A cohort study of 16,930 patients with 2-year follow-up

Andernord D, Desai N, Björnsson H, Ylander M, Karlsson J, Samuelsson K

The American Journal of Sports Medicine. 2015; 43(1): 121-127

Predictors of contralateral anterior cruciate ligament reconstruction: A cohort study of 9,061 patients with 5-year follow-up

Andernord D, Desai N, Björnsson H, Gillén S, Karlsson J, Samuelsson K

The American Journal of Sports Medicine. 2015; 43(2): 295-302

A Randomized Trial with mean 16-years follow-up after Anterior Cruciate Ligament Reconstruction

Björnsson H, Samuelsson K, Sundemo D, Desai N, Sernert N, Rostgård-Christensen L, Karlsson J, Kartus J

Submitted to The American Journal of Sports Medicine

Abbreviations 04

AARSC	Anatomic Anterior Cruciate Ligament Reconstruction Scoring Checklist
ACL	Anterior Cruciate Ligament
ALL	Anterolateral Ligament
AM	Anteromedial
AP	Anteroposterior
BMI	Body Mass Index
CI	Confidence Interval
CS	Case Series
CT	Computed Tomography
DB	Double-Bundle
EBM	Evidence-Based Medicine
EMBASE	Excerpta Medica database
EMT	Electromagnetic Tracking
EQ-5D	European Quality of Life-5 Dimensions, Euroqol
HR	Hazard Ratio
HT	Hamstrings Tendon
IKDC	International Knee Documentation Committee
KOOS	Knee Osteoarthritis and Outcome Score
KPACLRR	Kaiser Permanente Anterior Cruciate Ligament Reconstruction Registry
LCL	Lateral Collateral Ligament
MA	Meta-Analysis
MARS	Multicentre Anterior Cruciate Ligament Revision Study
MCL	Medial Collateral Ligament
MOON	Multicentre Orthopaedic Outcomes Network

MRI	Magnetic Resonance Imaging
OA	Osteoarthritis
OARSI	Osteoarthritis Research Society International
PCL	Posterior Cruciate Ligament
PCS	Prospective Comparative Study
PL	Posterolateral
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
PROM	Patient-Reported Outcome Measure
QoL	Quality of Life
RCT	Randomised Clinical Trial
ROM	Range Of Motion
RR	Relative Risk
SB	Single-Bundle
SMD	Standardised Mean Difference
SR	Systematic Review
TP	Transportal
TT	Transtibial

Brief definitions 05

Accuracy	The proximity of the measured result to the true value.
Bias	A systematic error or deviation in results or inferences from the truth. The main types of bias arise from systematic differences in the groups that are compared (selection bias), the care that is provided, exposure to other factors apart from the intervention of interest (performance bias), withdrawals or exclusions of people entered into a study (attrition bias) or the way outcomes are assessed (detection bias).
Case series	A study reporting observations on a series of individuals, usually all receiving the same intervention, with no control group.
Cohort study	An observational study in which a defined group of people (the cohort) is followed over time. The outcomes of people in subsets of this cohort are compared, to examine people who were exposed or not exposed (or exposed at different levels) to a particular intervention or other factor of interest.
Confidence interval	A measure of the uncertainty around the main finding of a statistical analysis. Often reported as a 95% CI specifying the range of values within which one can assume with 95% certainty, that the true value for the whole population lies.
Construct validity	Inclusion of questions representative of the qualities that the test is attempting to measure.
Content validity	Denotes whether the measurement accurately assesses what it is purported to measure.
Coverage	The proportion of units that report to a register in relation to number of eligible units.
Internal consistency	Psychometric property of an outcome instrument regarding the degree to which individual items are related to each other.
Face validity	Denotes if the measurement appears to be intuitively correct.
Meta-analysis	A systematic review that uses quantitative methods to summarise results.
P value	The probability, under the null-hypothesis, of obtaining a result equal to or more extreme than what was actually observed.

Power	The probability of finding a significant association when one truly exists.
Precision	The degree to which repeated measurements under unchanged conditions yield the same result.
Predictor	A variable associated with an increased risk of an outcome.
Randomised clinical trial	A clinical trial in which patients are randomly assigned to groups and followed prospectively over time.
Reliability	The degree to which an assessment tool produces stable and consistent results.
Systematic review	A review of a clearly formulated question that uses systematic and explicit methods to identify, select, and critically appraise relevant research, and to collect and analyse data from the studies that are included in the review. Statistical methods (meta-analysis) may or may not be used to analyse and summarise the results of the included studies.
Validity	The degree to which a result is likely to be true and free from bias (systematic errors).

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06 Introduction

6.1 HISTORY

"*Ligament genu cruciata*", possibly the first description of the ACL, was coined by Claudius Galen of Pergamon in Greece (131-201 BC). [1] Galen was a physician for the gladiators in Rome and is credited with some of the first observations of the ACL and its injury.[2] In around 1836, the Weber brothers from Goettingen in Germany described abnormal AP movement of the tibia after transection of the ACL, what we now define as the "anterior drawer sign". In addition, they were the first to approach the concept of the ACL multi-bundle anatomy and tensile properties, and the way they interact during varying degrees of knee flexion. In 1938, Ivar Palmer pub-

lished his thesis, "On the Injuries to the Ligaments of the Knee Joint", a detailed study of anatomy, biomechanics, pathology and treatment. He described the ACL consisting of two distinct bundles. In his work, he also emphasised the importance of restoring the injured ACL to its native anatomic position and the reconstruction of each bundle separately.[3, 4] These were concepts and ideas that, it could be argued, received undeservingly little attention at the time but has attracted increased interest today. These are now concepts that often lie at the centre of the current debate and research on ACL reconstruction. Returning to as early as 1917, Hey Groves is accredited with performing the first ACL reconstruction.[5] He was also one of the first to advocate the placement of an obliquely oriented graft within the anatomic insertion sites on the tibia and femur, in order to ensure the prevention of anterior tibial displacement, a concept resembling what we today refer to *as anatomic ACL reconstruction*.

6.2 ANATOMY AND FUNCTIONAL PROPERTIES OF THE ACL

The ACL is an intra-articular extrasynovial ligament. The main part of the ACL is composed of type I collagen fibres surrounded by a vascularised synovial sheath made up of loose connective tissue and rich in blood vessels where the terminal branches of the middle and the inferior geniculate arteries meet. From the synovial sheath, the blood vessels penetrate the ligament in a horizontal direction and anastomose with a longitudinally orientated intra-ligamentous network.[6, 7] Several studies have demonstrated that the human ACL contains mechanoreceptors that are able to detect changes in tension, acceleration, direction of movement, and proprioception.[8-11]

The length of the ACL ranges from 22 mm to 41 mm with a mean of 32 mm. It passes distally from its origin on the posteromedial surface of the lateral femoral condyle, to its insertion between the medial and lateral intercondylar eminences on the tibia. The femoral attachment has an oval/crescent shape with a longitudinal diameter of approximately 18mm and a transverse diameter of approximately 11mm.[12] A bony structure on the medial wall of the lateral femoral condyle, known as the lateral intercondylar ridge (Resident ridge), demarcates the anterior border of the femoral ACL origins, and no ACL fibres insert anteriorly to this ridge. The tibial insertion site is approximately 3.5 times larger than the ACL diameter at mid-substance and it is roughly 1.2 times larger than the femoral origin site. The ACL fibres fan out as they insert on the tibia to form what Amis *et al*. have described as a "duck's foot" insertion pattern.[13] The ACL insertion begins approximately 10 to 14 mm behind the anterior border of the tibia and extends to the medial and lateral tibial spine. On average, it measures 11 mm in the coronal plane and 17 mm in the sagittal plane.[7, 14]

The shape of the ACL varies with the angle of flexion of the knee, increasing in cross-sectional area from the femur to the tibia, and smallest at approximately mid-substance. There has been disagreement on the actual anatomic division of the ACL. Odensten and Gillquist, for example, found no histological evidence of separate bundle structures making up the ACL.[15] Recent studies have contested the concept of the double-bundle

structure of the ACL and described it as a flat "ribbon-like" ligament without any clear separation of the bundles. They found no ACL fibre-insertions at the centre of its "C" -shaped insertion on the tibia and interestingly no PL-bundle insertion. On the femur, they describe this flat insertion along the intercondylar ridge, in direct continuity with the posterior femoral cortex.[16, 17]

Today, the general consensus is that the ACL has at least two distinct functional bundles, with varying tension among the fibres in the ligament with different ranges of motion.[12, 13, 18] From a clinical and functional standpoint, the ACL is believed to consist of the AM and the PL bundles, named after their insertion on the tibia. The AM bundle is approximately 35 mm long and the PL bundle is 17-19 mm long on average. Both bundles have a similar diameter, with a total average width of 11 mm.[19-21] On the femur, the AM bundle is located in the proximal and anterior aspect of the femoral insertion site, with the PL bundle in the anterior and inferior aspect of the femoral insertion site. The positions of these bundles are, however, dynamic and vary depending on the flexion of the knee considering that the femoral ACL origin is oriented vertically in extension and horizontally in approximately 110° of flexion. It is this varying orientation that gives the individual bundles their tensile properties during the range of motion of the knee. The femoral insertion sites of the AM and PL bundles are in turn separated by another bony landmark, known as the lateral bifurcate ridge.[22] With the emergence of the concept of anatomic ACL reconstruction, these anatomic landmarks, together with ACL remnants, are vital in order to ensure the accurate position of the femoral bone tunnel(s) when ACL reconstruction is performed.

On the tibia, the line of separation between the AM and PL bundles runs anterior to posterior. The centre of the AM bundle insertion is roughly 5mm medial and 3mm posterior to the anterior horn of the lateral meniscus.[23, 24] The centre of the PL bundle lies roughly 11mm posterior to the attachment of the anterior horn of the lateral meniscus, anteriorly adjacent to the tibial insertion site of the PCL and roughly 20-25mm posterior to the anterior edge of the tibia.[14, 25] As on the femoral side, the centres of the AM and PL bundles are approximately 8-10mm apart.[18] On average, the AM bundle covers approximately 56% and the PL bundle 44% of the entire tibial insertion area.[26]

A combination of the bony morphology of the femoral condyles and their articulation with the tibia, as well as the orientations and large areas of the bony attachments of the ACL, results in a dynamic relationship between the distances between the ACL attachment sites and the tensile properties of the ACL bundle fibres during knee extension or flexion. This leads to a range of tightening–slackening patterns across the range of motion.[13, 27] The complex geometric relationship of the articulation between the femur and the tibia results in the femur not only rolling backwards but also sliding forwards on the tibia during flexion and vice versa during extension. As a result, the ACL and the PCL guide the movements of the femur on the tibia during flexion/extension and resist movement away from the positions dictated by those geometric and biomechanical mechanisms.[28] The general result is that the AM bundle tightens as the knee flexes with peak tension at approximately 60°, during which the AM positions itself posterior to the PL and "spirals" around it.[29] At this point, the AM assumes the role of the primary restraint to anterior loads. As

the knee extends and/or rotates, the PL in turn tightens and is exposed to its highest tension at near full extension, assuming the role of primary restraint to anterior loads. Several studies have confirmed this tensile and length-change pattern during knee motion.[30-33] A similar synergistic relationship between the AM and PL bundles under combined rotatory loading (valgus and internal rotation) was reported by Gabriel *et al*. further illustrating the fact that both AM and PL bundles contribute to maintaining both anterior and rotational laxity but that their individual contribution varies with knee flexion angles.[34]

The biomechanical properties of the ACL are evidently complex but, for the convenience of describing this in the current literature, its biomechanical characteristics are often described separately in terms of the two bundles. However, model experiments studying elongation patterns, comparing a two-bundle ACL model with a ten-bundle ACL model, suggest that the native ACL has a much more intricate architecture. A complex distribution of elongation, deformation and "recruitment" of fibres within the ACL throughout the range of motion, as opposed to the somewhat simplified explanation of an "on-off" relationship between the AM and PL bundles, has been suggested.[27] The theory of fibre recruitment is not a novel one, but it can be used to describe the process by which parts of the ACL, previously rendered slack during a specific phase of the range of motion of the knee, are *progressively* recruited in response to both a change in flexion-extension angle and to applied loads, together offering a resistance to tibial translation. [27, 28]

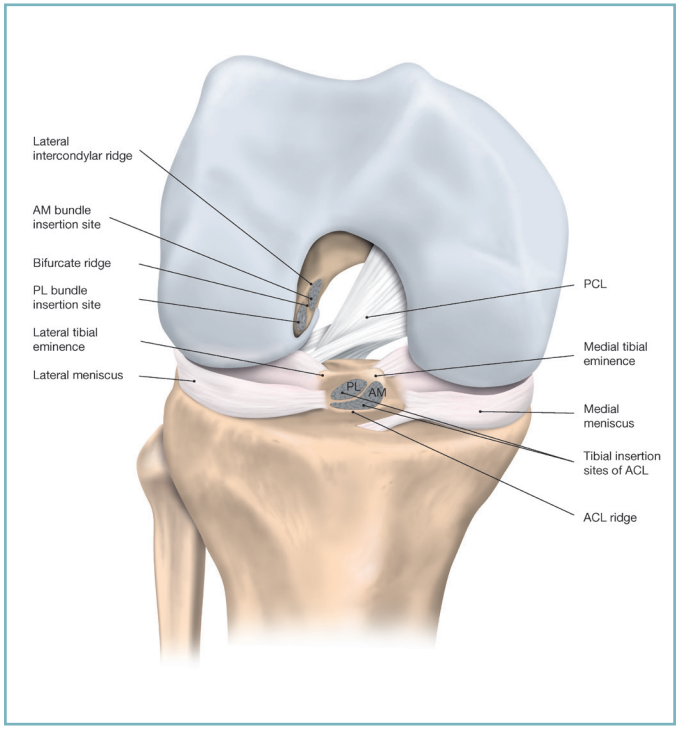


FIGURE 1

Image of the right knee at approximately 90° flexion, showing the locations of the AM and PL bundle insertion sites.

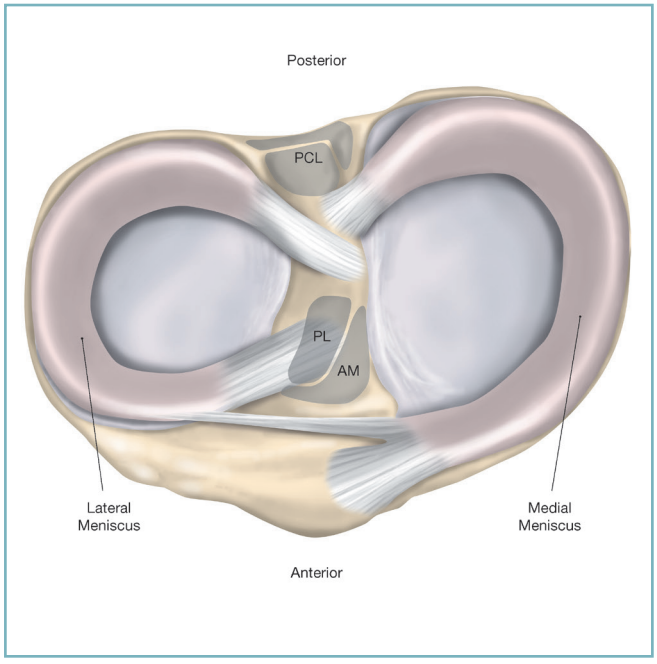


FIGURE 2

Image showing the AM and PL insertion site locations on the tibia.

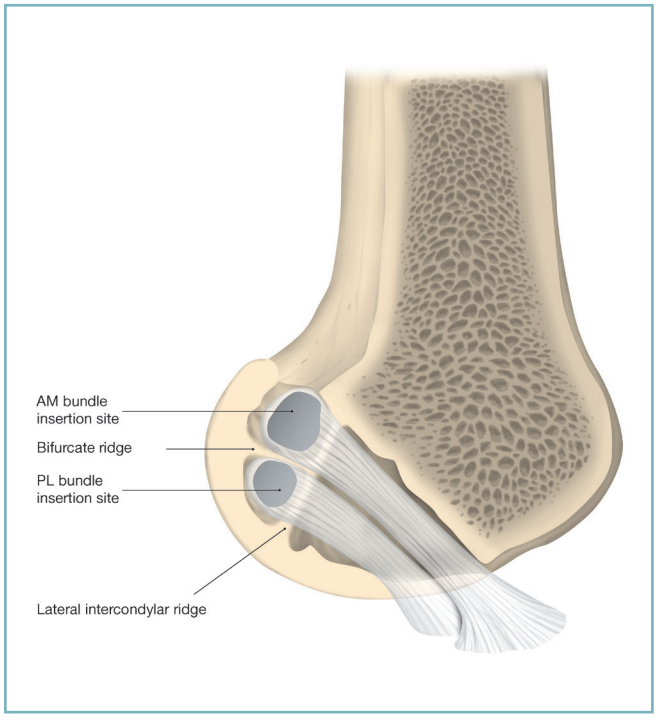


FIGURE 3

Image showing the lateral wall of the intercondylar notch with the knee in full extension. The AM and PL bundle's insertion sites, and their relation to the lateral intercondylar ridge and the lateral bifurcate ridge, are illustrated.

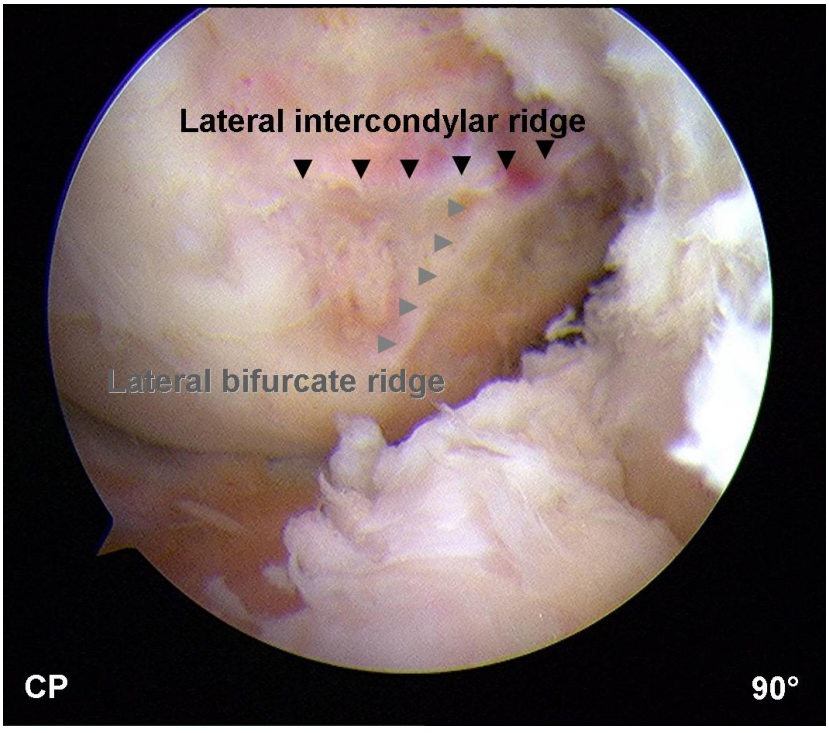


FIGURE 4

Arthroscopic image of the right knee in 90° flexion, showing the lateral intercondylar ridge that forms the anterior border of the femoral ACL insertion site and the lateral bifurcate ridge located between the AM and PL bundle insertions. (Image courtesy of the University of Pittsburgh Medical Center).

6.3 KNEE LAXITY

Knee laxity often refers to the movement of the proximal tibia in relation to the femur, be it translational or rotatory movement, in any of the six degrees of freedom of the knee. [35]

Knee motion and its kinematics are governed by active stabilisers, of which muscles are the predominant structures, and by passive stabilisers, primarily represented by the ligaments, menisci and joint capsule. The passive stabilisers can in turn be categorised into primary and secondary restraints. The ACL is an example of a primary restraint to anterior translation of the tibia relative to the femur. The ACL is aligned and positioned in such a way that it is optimised to resist this directional load. The MCL on the other hand, is an example of a secondary restraint to the anterior translation of the tibia relative to the femur, as it is able resist this force to a certain degree but is less optimised for the task, owing largely to its anatomic positioning

and alignment. It is important to recognise both primary and secondary restraints, as damage to one may place increased and potentially deleterious amounts of force on the other.

When attempting to describe knee laxity, we usually describe how the proximal tibia can be moved, from its native position, in relation to the distal femur. In other words, knee laxity refers to the ability/tendency of the knee to translate or rotate in a particular direction in response to an applied force. In the clinical setting, the evaluation of knee laxity is therefore a vital instrument in assessing the possible presence of injury to structures in the knee and/or evaluating the efficacy of the various reconstructive procedures that can be performed. There are a number of clinical tests exist for detecting the presence of knee laxity and they can generally be categorised as testing "static" laxity or "dynamic" laxity.

Static and dynamic laxity

Static laxity tests involve applying a load or force in a specified direction to the knee joint, often targeting a specific primary restraint of interest, and measuring the resulting displacement. These tests are often quick and easy to perform; however, they must be used with caution, as there is often more than one restraint (primary and secondary) in any specific direction that is being tested. They may not reflect the complex laxity envelope of the knee, and in turn not test the true functional behaviour of that structure in a dynamic situation of motion. Dynamic tests, on the other hand commonly reveal symptoms that patients experience during activities of daily living or sporting activities such as "giving way". Dynamic tests can be seen as a means of reproducing these symptoms in a clinical setting and involve applying a load with a specified direction, as well as incorporating movement.

One shortcoming of all manual laxity tests that it is important to remember is that the motions and loads induced by the examiner are appreciated and described in a subjective manner thereby proving difficult to quantify or grade. Secondly, the loads and displacements applied by the examiner are neither constant nor easy to measure.

Antero-posterior knee laxity

Injury to the ACL often results in anterior laxity, as it is the primary restraint to anterior loading of the tibia. The manual Lachman test has historically been the most commonly utilised manual test for suspected ACL injury, mainly due to its ease of use, reproducibility and high sensitivity, making it a consistent examination standard.[36] Instrumented manual systems, such as the KT-1000 arthrometer (MEDmetric corp, San Diego, CA, USA), provide a standardised means of non-invasively and relatively easily quantify this AP knee laxity.[37] AP laxity has, however, been shown to correlate poorly with subjective and objective function.[38]

Rotatory knee laxity and pivot-shift test

Static rotatory laxity measurements are possible, but they are complex and difficult to perform in the clinical setting, as are dynamic tests during functional activity, during running for example. Instead, manual dynamic tests for rotatory laxity are more commonly utilised. The most commonly cited example of dynamic laxity (involving a rotatory component) after ACL injury is the pivot-shift test. A common symptom experienced by the ACL-deficient patient often described as a "giving-away" or buckling of the knee and the pivot-shift test in part reflects this phenomenon.[36] The pivot-shift test begins with the anterior subluxation of the lateral tibial plateau near full extension and internal rotation of

the tibia (subluxation phase). The knee is then increasingly flexed from that position to approximately 30°, while a valgus stress is applied. This leads to the tilting of the posterior tibial margin, rising tension in the iliotibial tract, and contact between the posterior tibial margin and the lateral femoral condyle (tension phase). As flexion continues, the tibiofemoral contact point shifts, while the pull on the iliotibial tract is directed at a lower angle, causing the anteriorly subluxated lateral tibial plateau to reduce with a sudden "jerk" or "clunk" (reduction phase), which is often perceived by the patient and examiner.[39]

The pivot-shift test is the most specific test for ACL injury and correlates well with patient-reported instability, poor subjective and objective outcome scores [38, 40, 41] and the development of OA after ACL reconstruction.[42]

In addition, the pivot-shift test is widely used to evaluate the presence of residual postoperative dynamic laxity of the knee. Despite its widespread use, the execution of the pivot-shift test remains highly variable and its interpretation, highly subjective[43], prone to high inter-observer variability.[44]

6.4 EPIDEMIOLOGY

Anterior cruciate ligament injury is a common injury and one of the most commonly treated conditions of the knee.[45, 46] A recent systematic review presents data on the annual incidence of ACL injury from national population studies ranging from 0.01% to 0.05%, and when assessed for highly active groups (professional sporting groups) the annual ACL injury rate ranged from 0.15% to 3.67%, illustrating that ACL injury is a common injury among sporting individuals.[47]

The Swedish National Knee Ligament Register reports an annual injury incidence of approximately 80 per 100,000 inhabitants in Sweden. Of the subsequent 5,800 individuals suffering ACL injuries in Sweden every year, some 3,500 undergo surgery with an overall median age of 28 years at the time of surgery. Female patients account for approximately 43% and tend to undergo surgery slightly earlier than male patients (27 years and 28 years respectively). [48]

6.5 AETIOLOGY

The results of a national population-based study report that 80% of knee ligament surgery involved the ACL and that 65% of ACL injuries resulting in surgery occurred as a result of participating in a sports/recreational activity.[49] Among both men and women, football is the most common activity associated with an ACL injury in Sweden and this trend has remained fairly constant in recent years. In 2014, football was the "causative" activity at the time of ACL injury in 32% of women and 49% of men, followed by downhill skiing among women, and floorball among men. [48]

6.6 ACL INJURY MECHANISM

The majority of all ACL injuries are reported to occur in non-contact situations and mostly while taking part in sporting activities. Studies of the mechanics of ACL injuries have identified two predominant mechanisms.[50-52] The first entails a sudden pivoting movement, also known as a "plant-and-cut" manoeuvre, resulting in a deceleration, with high knee internal extension torque combined with dynamic valgus rotation and the foot fixed flat to the surface. The other, often resulting from landing on one leg from a jump, may represent the most detrimental force associated with ACL injury. In these cases the culprit is presumably an anterior translation force applied to the tibia via the rapid contraction of the quadriceps muscle, specifically at flexion angles around 20-30 degrees.[53, 54]

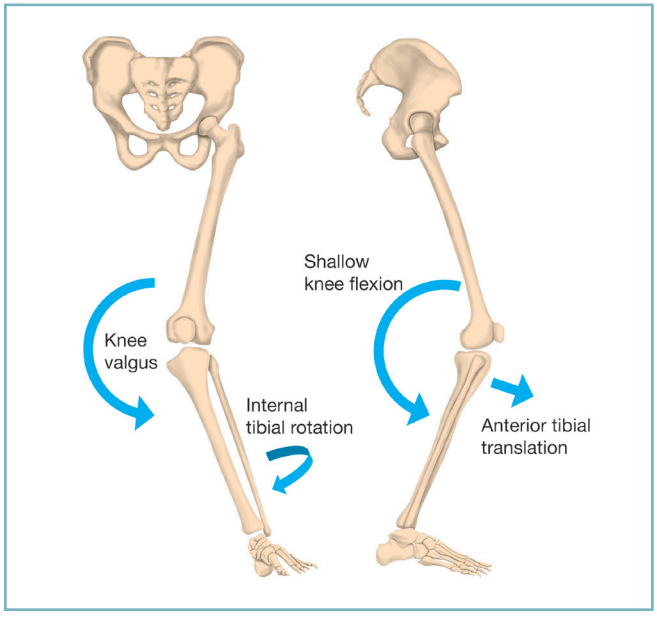


FIGURE 5

Image showing the common injury mechanisms leading to non-contact ACL injury. On the left, the "plant-and-cut" pivoting of the knee, with associated knee valgus and internal rotation of the lower leg. On the right, anterior translation of the tibia with slight knee flexion.

6.7 OSTEOARTHRITIS

Evidence to support the fact that injury to the ACL is associated with the increased development of OA is well established in the literature.[55-58]

The reported incidence of radiographic OA after ACL reconstruction, however, varies widely between reports as being between 10-90%. This existing evidence is largely based on data from heterogeneous populations with regard to choice of management, pre- and post-injury activity levels, the presence of concomitant injuries, age, patient sex and BMI, possibly explaining the variation in reported incidence.[57, 59] In addition, several different tibiofemoral

OA classification systems as well as radiographic modalities exist, and are all readily used and reported in the current literature, a factor that could account for the heterogeneity in reported OA incidence. The most commonly used OA classifications include Fairbank [60], Kellgren-Lawrence [61], Ahlbäck [62], IKDC [63], the the OARSI classification [64].

A comprehensive review of 31 studies by Øiestad *et al*. in 2009 concluded that the prevalence of osteoarthritis in knees after an isolated ACL injury was 0% to 13%. When associated with meniscal injuries, this number increased to 21-48%.[57] Several studies have echoed these results, indicating that meniscal injury and meniscectomy are significant risk factors for the development of OA.[57, 58, 65-67]

There is, however, conflicting evidence regarding the effect of ACL reconstruction in preventing OA.[56, 68] In addition, the correlation between the patients' subjective clinical symptoms and radiological evidence of OA is not convincing.[68-73] As in all cases of OA, it is important to evaluate the radiological signs in relation to clinical symptoms.

6.8 SURGICAL TREATMENT

6.8.1 Arthroscopic ACL reconstruction

David Dandy performed the first arthroscopically assisted ACL reconstruction at Newmarket General Hospital on 24 April 1980, using a carbon-fibre prosthesis and a MacIntosh lateral extra-articular substitution.[74] Despite the primitive instruments of the time, the arthroscopic methods reported less postoperative morbidity, increased postoperative ROM, quicker rehabilitation and improved cosmesis.[75] This novel procedure required two incisions, one through which the graft was harvested and the tibial tunnel drilled, and the other facilitating an "outside-in" drilling of the femoral tunnel.[76] This involved the use of a "rear-entry guide" being placed on the posterior aspect of the lateral femoral condyle, followed by the subsequent drilling of the femoral tunnel. Further advances in the development of the arthroscopic equipment led to the adoption of the single-incision all-inside technique using TT drilling. With this technique the tibial tunnel was drilled via one incision, and the femoral drilled via the tibial tunnel. This became the method of choice throughout most of the 1990's.

6.8.2 Isometry

The concept of *isometry* and isometric graft placement was introduced as the TT drilling technique established itself as the drilling method of choice when performing ACL reconstruction. Isometric placement entails the distance between ACL graft origin and the insertion remaining constant during flexion and extension. Biomechanical studies had shown irreversible elongation of the graft if stretched repetitively more than 4%. This was believed to have been avoided using isometric graft placement.[77] Graft placement was therefore aimed at a location that avoided this length

change and minimised potential graft impingement against the femur. The TT drilling technique thus gained increased popularity as a reliable method for achieving these objectives. As a result, surgeons placed the tibial tunnel more posteriorly and the femoral tunnel high and deep in the intercondylar notch of the femur close to the proximal limit of Blumensaat's line, outside the native femoral ACL insertion site. Biomechanical and clinical studies have shown the suboptimal restoration of knee kinematics and residual pivot-shift with isometrically placed grafts in comparison with those placed in the native ACL insertion sites.[78, 79] Today, it is known that the native ACL is not isometric, owing largely to its complex, non-uniform multiple-bundle anatomy, with each bundle exhibiting different tensile properties, and isometric graft placement is avoided in modern ACL reconstructive surgery.

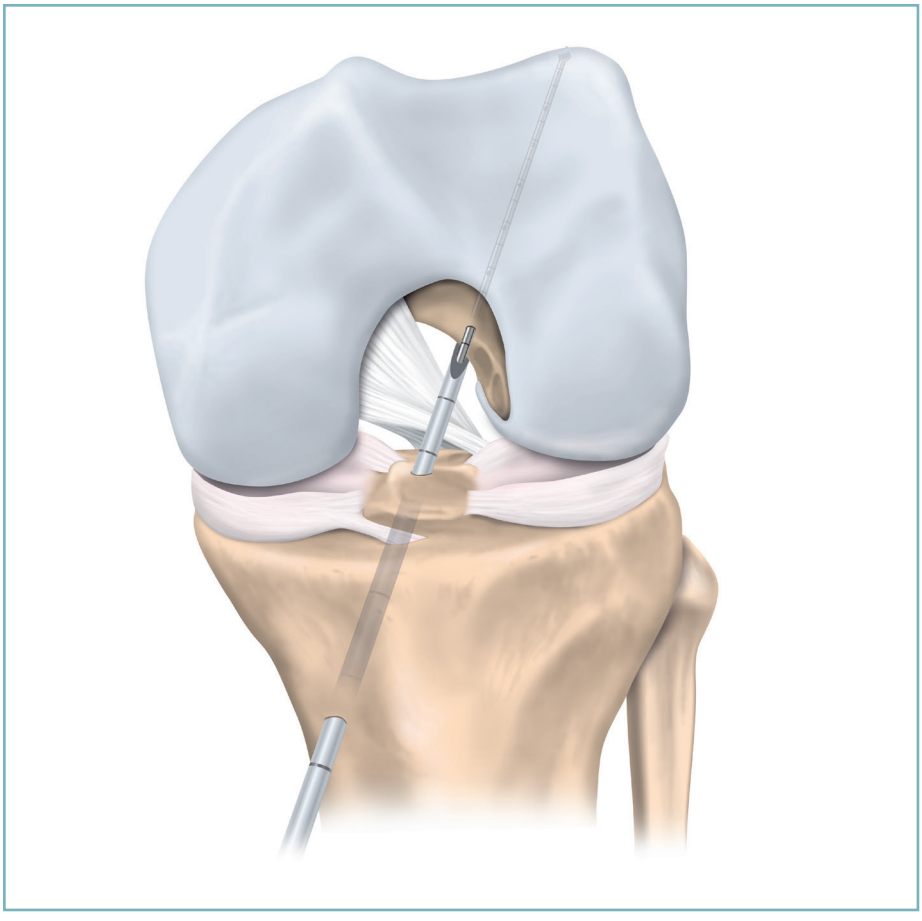


FIGURE 6

Image illustrating the transtibial drilling technique whereby the femoral bone tunnel is drilled via the tibial bone tunnel. The limitations of transtibial drilling technique are evident, with resultant non-anatomic femoral bone tunnel placement outside the native ACL insertion site.

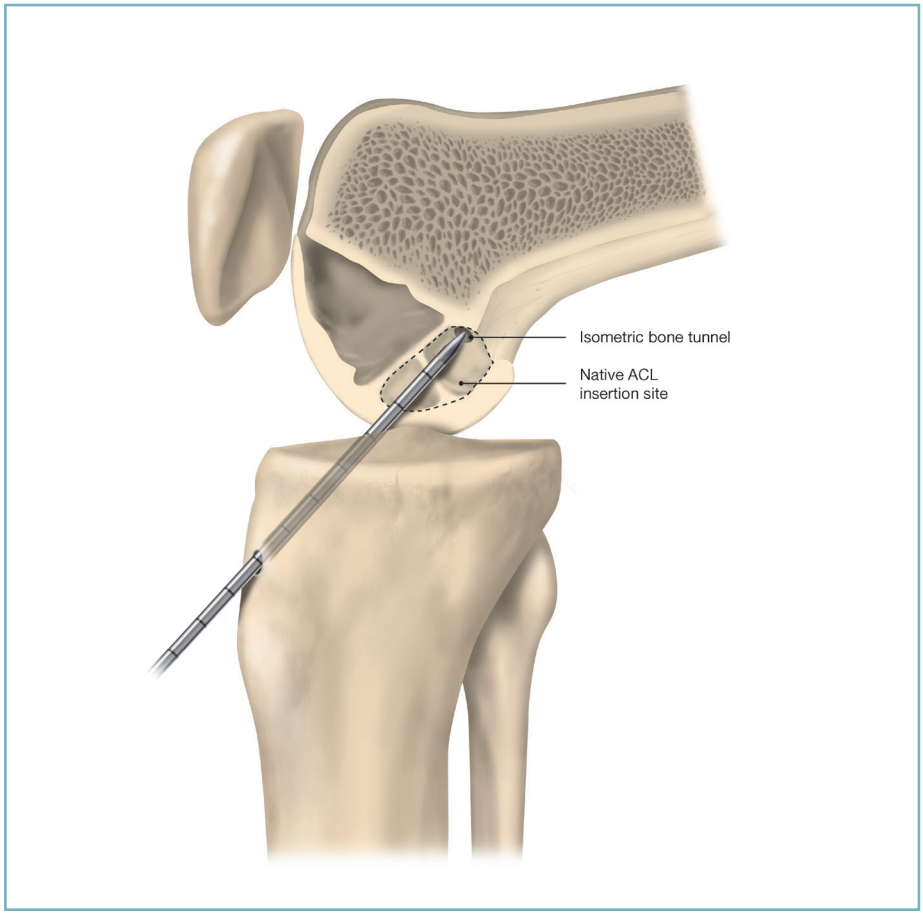


FIGURE 7

Image illustrating isometric bone tunnel placement using transtibial drilling. The bone tunnel is high and deep in the intercondylar notch, outside the native ACL insertion site.

One inherent limitation of the TT drilling technique is that the femoral tunnel position was ultimately dependent on the position of the tibial tunnel. Advocates of the TT drilling technique have, however, claimed that an anatomic femoral bone tunnel can be achieved by adjusting the tibial entry point to a more medial and proximal starting position or by drilling a tibial tunnel with a wide enough diameter to allow increased manoeuvrability when drilling the femoral tunnel.[80, 81] This may, however, be at the expense of an optimal tibial bone tunnel, resulting for example in a very short tibial tunnel, potentially compromising graft-bone or bone-bone interface fixation and incorporation and graft-tunnel length mismatch. [82, 83]

6.8.3 Notchplasty

A not uncommon consequence of non-anatomic tunnel placement on the tibia and femur was graft impingement.[84-86] Notchplasty may lead to abnormal knee kinematics by displacing the femoral insertion laterally.[87] In addition, it removes potentially pertinent osseous landmarks that can aid the surgeon in more anatomic orientation and graft placement, as well as a tendency towards regrowth at the notchplasty site.[88, 89]

Although notchplasty may be considered in cases of congenitally narrow notches, the presence of stenosing osteophytes, or if a graft is used that is wider than the native ACL was, it is not recommended as a means of increasing visualisation or alleviating graft impingement in otherwise normally configured knees. Notchplasty is regarded as non-anatomical, and it is often regarded nowadays as a corrective procedure indicative of misplaced portals and non-anatomically placed tibial and femoral bone tunnels.

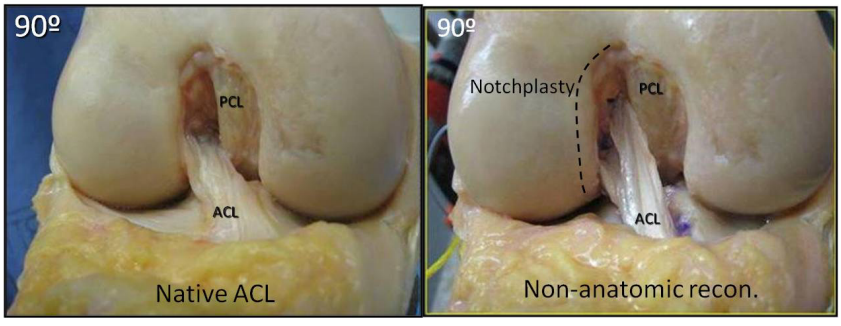


FIGURE 8

Image of native ACL on the left and a non-anatomic double-bundle ACL reconstruction to the right. The dotted area shows the area that is removed when performing a notchplasty. Notch- plasty can be necessary in a non-anatomic ACL reconstruction as it can impinge; however, this is not the case for the native ACL or in anatomic ACL reconstruction. (Image courtesy of the University of Pittsburgh Medical Center).

6.8.4 Clock-face reference

During this same period, a complement to this technique was the use of the clock-face method, whereby the tunnel placement is described in relation to a particular o'clock position. However there is no standardised location for the equator of the clock-face. [90] The clock-face method is primarily based on the morphology of the intercondylar notch, a notoriously imprecise arthroscopic landmark. Moreover, it is two-dimensional and does not take into account the depth of the intercondylar notch or the femoral insertion site. So, due to its variability in description and limited anatomic basis, the clock-face reference has no place in anatomic ACL reconstruction.

6.8.5 Anatomic ACL reconstruction

The past decade has seen a shift in interest towards using anatomic ACL reconstruction techniques with the emphasis on graft placement within the native femoral ACL insertion site. A recent study revealed that, in at least 50% of revision cases, technical error was either a predominant or contributing factor. Of these technical errors, at least 80% are due to malpositioning of the femoral and/or tibial tunnels.[91]

In an attempt to further improve knee kinematics and postoperative knee laxity after ACL reconstruction, there has been an evolution towards positioning the tibial and femoral bone tunnels within the native ACL insertion sites. This general principle has been termed *anatomic ACL reconstruction*. These advances in surgical technique have largely come about from a better understanding of the ACL anatomy, its multiple-bundle anatomy and inherent anisometry, the morphology of their bony insertions and how these relate to surrounding structures in the knee.[12, 13, 92, 93]

The cornerstones of anatomic ACL reconstruction are the functional restoration of the ACL to its native size and dimensions, collagen orientation, tension patterns and insertion sites, not forgetting the individualisation of the procedure for each individual patient. A prerequisite is the visualisation of the native ACL insertion sites, measuring the dimensions of the knee and the ACL itself, appropriate graft tensioning, a critical evaluation of tunnel and graft positioning and a comprehensive understanding and appreciation of the patients and their expectations. Encompassed in the concept of anatomic ACL reconstruction are both anatomic SB and anatomic DB reconstruction techniques. Both techniques aim to recreate the native ACL function through graft placement within the native ACL insertion sites.[25, 88, 94] One common misconception is that anatomic ACL reconstruction implies DB ACL reconstruction and vice versa. Anatomic ACL reconstruction should be regarded as a concept and not a specific surgical procedure, a concept that can be applied in addition to SB and DB reconstructions, to the augmentation of partial ACL tears, and revision ACL reconstruction. The specific surgical procedure should be based on the ACL injury pattern: complete ACL tear, partial ACL tear, intact ACL remnants, the size of the native ACL attachment sites and the degree of rotational instability. Several biomechanical studies have shown that anatomic graft placement within the native ACL insertion sites is more effective in controlling anterior tibial translation and rotational laxity, and more closely reproduces normal knee kinematics.[79, 95-101]

6.8.6 Transportal drilling

The use of TT drilling has subsequently decreased and there has been an increased in the adoption of more "independent" drilling techniques.[102] Using this technique, the femoral bone tunnel is drilled independently of the tibial tunnel through a separate portal, which allows more manoeuvrability and subsequent precision in placing the bone tunnel within the femoral insertion site. One significant advantage of this TP technique is the improved face-on visualisation of ACL insertions and/

or pertinent landmarks, facilitating all aspects of anatomic ACL reconstruction ranging from primary cases to augmentation and revision.

The clinical benefits of TP drilling for the patient are still the subject of debate, however. A recent retrospective study of 94 patients reported that the TP technique provided superior rotational and anterior translational stability compared to the TT drilling technique.[103] In their prospective study of 436 patients, Duffee *et al*. report no difference in the KOOS between the two drilling techniques, but significantly higher odds of repeat ipsilateral knee surgery in patients who underwent surgery with the TT technique.[104] A recent study reporting on prospectively collected data from the Danish Knee Ligament Reconstruction Register demonstrated an increased risk of revision ACL reconstruction when the antero-medial portal technique was compared with the TT technique [RR 2.04 (95% CI: 1.39-2.99)].[105] The reasons for these findings have been the subject of debate and the answer may lie in the fact that these observations were made on patients undergoing surgery during an era in which the technique of medial portal drilling was a novel one and may reflect an element of surgical inexperience with that specific method. Another possible cause is that anatomically placed grafts are subjected to larger in-situ forces than their non-anatomic counterparts [96, 106, 107], subjecting these grafts to an increased loading and subsequent increased risk of failure. This could indicate that grafts of increased strength capable of withstanding these increased loads are preferable when performing anatomic reconstructions, in order to reduce the risk of graft re-rupture. Future research has yet to confirm this however. In the case of non-anatomically placed grafts, they may be spared these excessive in-situ forces and may thus also be spared the risk of re-rupture, but possibly at the expense of rotatory control. This should not however, deter surgeons from attempting to achieve an anatomic position of their ACL reconstruction. The increased load on the anatomically placed graft may protect other structures in the knee, such as the menisci and cartilage from progressive degeneration, but the higher load on the graft must be considered during postoperative recovery and rehabilitation while the graft is still healing.

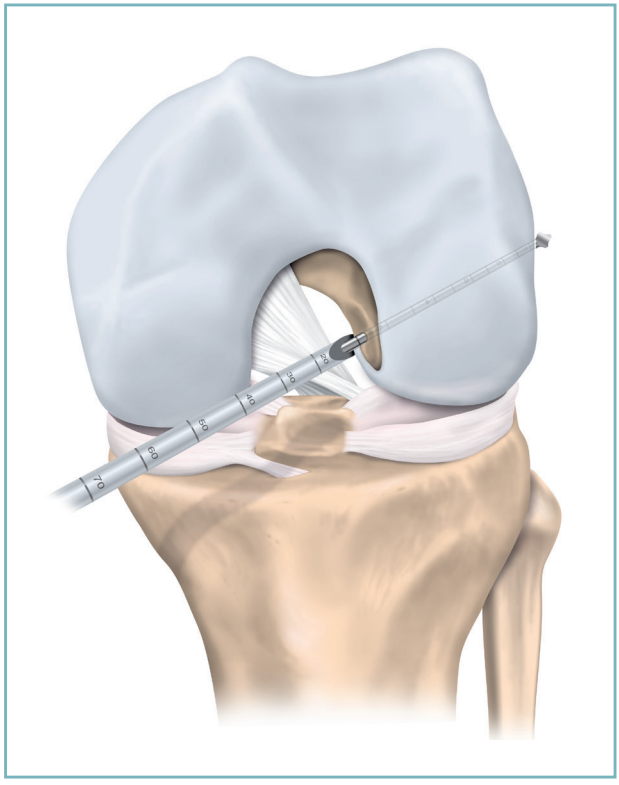


FIGURE 9

Image illustrating the approach to the femoral ACL insertion site on the lateral wall of the intercondylar notch using an independent transportal drilling technique.

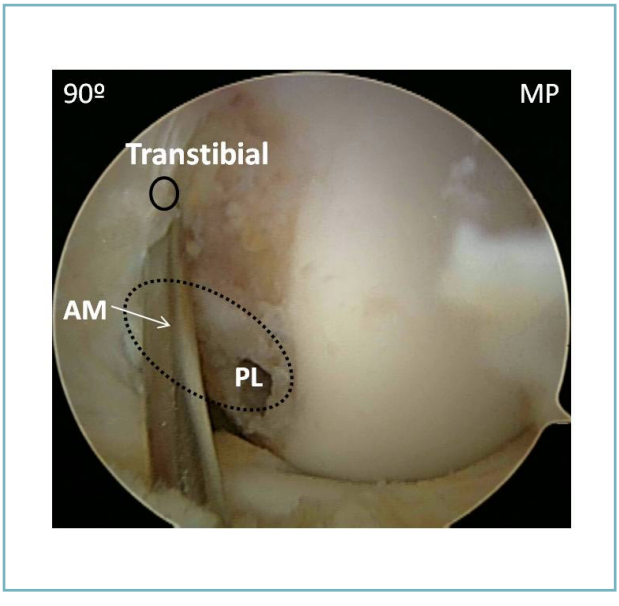


FIGURE 10

Arthroscopic image of left knee at approximately 90° flexion illustrating an isometric position high and deep in the intercondylar notch via a transtibial approach. The subsequent bone tunnel will be located outside the native ACL insertion site. Also shown are AM and PL bone tunnels placed within the native insertion site (dotted line) achieved via transportal drilling. (Image courtesy of the University of Pittsburgh Medical Center).

6.8.7 Anatomic single- and double-bundle ACL reconstruction

A concept that many regard as having revolutionised ACL reconstruction was the emergence of the DB reconstruction technique during the early 2000's. This was not, however, a novel concept. Aware of the separate yet synergistic tension patterns and anatomy of the AM and PL bundles, Ludloff *et al*. as early as 1927, highlighted the need for the reconstructed ACL to consist of two separate bundles [108] as did Ivar Palmer in the 1930's.[109]

In 1997, Sakane *et al*. examined the in-situ force distribution between the AM and PL bundles of the ligament in response to applied anterior tibial loads. Their results showed that the magnitude of forces in the PL bundle was significantly affected by the flexion angle, whereas the magnitude of in-situ forces in the AM bundle remained relatively constant. [110] This study highlighted the fact that, in order for an ACL graft to reproduce the in-situ forces of the native ACL, a reconstruction technique would have to take account of the role of both AM and PL bundles. This idea gained support and popularity following the application of the concept of DB reconstruction to clinical practice. [111-114] The theoretical advantage of the procedure is that the two bundles can be tensioned separately, thereby mimicking more of the native tension patterns of the ACL bundles. As a result, in addition to restoring AP laxity by reconstructing the AM-bundle, it has been believed that DB ACL reconstruction more effectively restores rotational laxity to which the PL bundle makes the primary contribution.[115] Recent biomechanical and clinical trials have shown superior results in support of this technique, suggesting that a DB anatomic ACL reconstruction can result in the more effective restoration of rotational stability in vitro than SB reconstruction.[116-118] However, a number of studies with a short to mid-term follow-up have also shown few potential benefits of DB reconstruction compared with SB reconstruction in terms of laxity restoration or subjective PROMSs.[119-121] It must be stressed again that DB ACL reconstruction is not synonymous with anatomic ACL reconstruction. It is merely a step closer to replicating the native ACL anatomy; it can still be performed non-anatomically.

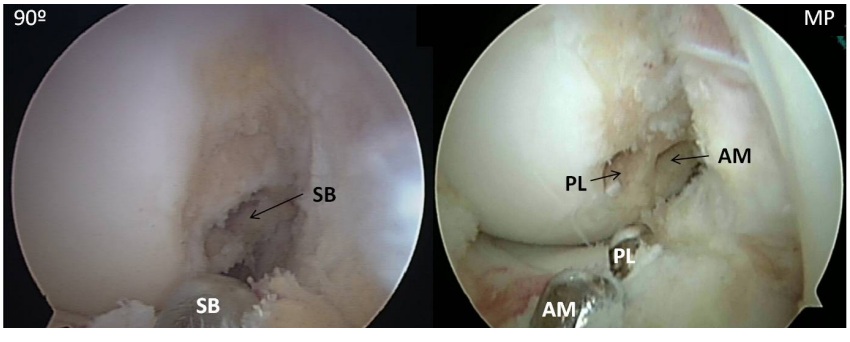


FIGURE 11

Arthroscopic image of right knee at approximately 90° flexion, with anatomic bone tunnels established for SB and DB reconstruction. (Image courtesy of the University of Pittsburgh Medical Center).

6.9 FAILURE

There are many definitions of what is regarded as a failed ACL reconstruction. Aside from a manifest traumatic or non-traumatic graft re-rupture, different objective and subjective variables can be used to determine whether there was a failure in successfully achieving the predefined indications and goals of the reconstruction itself and what ultimately constitutes a failed reconstruction. The exact aetiology and pathophysiology of the failure is multifactorial and sometimes not immediately apparent. Possible contributory factors (often in combination) include pain, decreased range of motion, recurrent episodes of instability, subsequent reduced level of athletic activity postoperatively, persistent AP and/or rotatory laxity postoperatively, infection and/or manifest graft re-rupture.

Functional stability is a commonly utilised end-point when determining the success of an ACL reconstruction and success can, for example, be gauged using various PROM's as well as objective functional tests. On the other hand, however, characterising and distinguishing the subtle nuances of successful, unsuccessful and failed results after an ACL reconstruction has proved more difficult. In addition, the degree of laxity that defines graft failure is not universally accepted, with cut-off values for residual side-to-side differences in AP laxity ranging from 3-5 mm.[122-125] It is noteworthy that objective laxity or MRI-verified graft failure do not always correlate with subjective symptoms of instability.[38]

Factors associated with graft failure are also multifactorial and include recurrent trauma most often during sports,[126] patient age,[127-130] graft choice,[129, 131-133] small graft size,[134], technical errors during index surgery,[91], biological failure [135] and persistent postoperative knee laxity.[73]

The true incidence of graft failure is challenging to ascertain and is not known at present. The incidence of graft failure reported in the literature is between 2-11% during the first 10 years following the index ACL reconstruction, depending on the time during the postoperative follow-up at which the observation is made.[136-139] Several recent systematic reviews have reported failure rates of between 3.6% and 5%.[140-142] Looking at the revision rate, similar numbers can be found with reports of 2-3% within the first two years [126, 143] and up to 8-10% at seven to 10 years. [136, 138] The KPACLRR reports overall revision rates of 1.7% [144] and 4.1% five years postoperatively was reported by the Danish ACL Reconstruction Register. [145] The Swedish National Knee Ligament Register reports 2.9% revision rates within the first three years after primary ACL reconstruction, and overall revision rates (2005-2014) of 3.9%.[48]

It is crucial to use a combination of validated objective and subjective end points when defining 'failure' in reports on long-term results after ACL reconstruction. Registries provide a unique source of data often with well-defined concrete end points such as revision surgery. Although the true incidence of graft failure may be underestimated, revision surgery possibly better reflects the proportion of patients with clinically significant symptoms and disability as a result of their reconstruction failure. In addition, high-quality RCTs, with long-term follow-up and with well-defined end points would provide an optimal complement to registry studies.

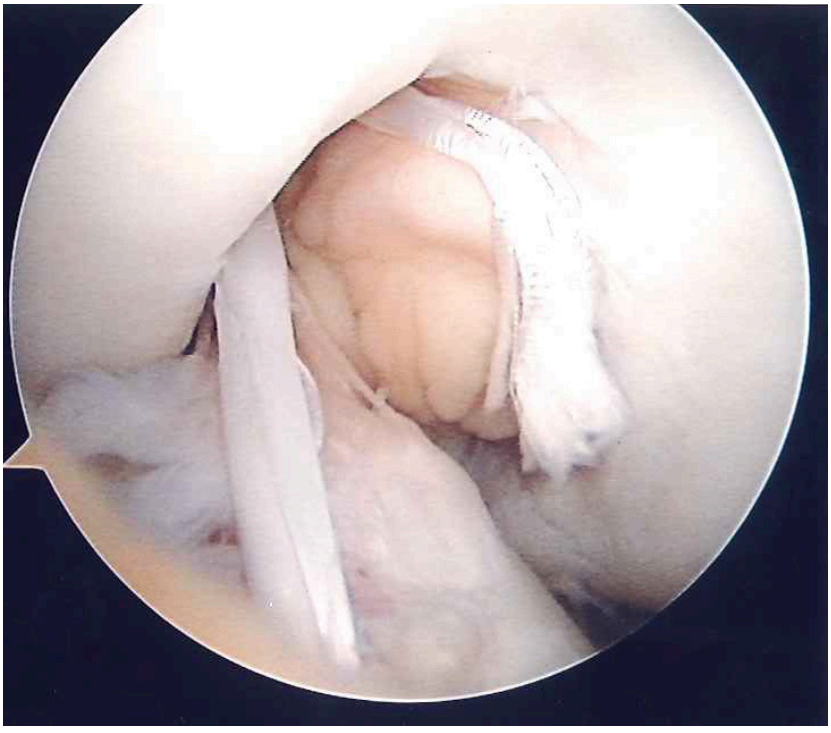


FIGURE 12

Arthroscopic image of the right knee showing a graft rupture following a knee injury 2 years after anatomic SB reconstruction using HT graft.

07 Aims

Study I

To determine through a meta-analysis of the current literature whether anatomic DB reconstruction compared with anatomic SB reconstruction more effectively restores AP laxity, rotatory laxity and leads to fewer graft failures

Study II

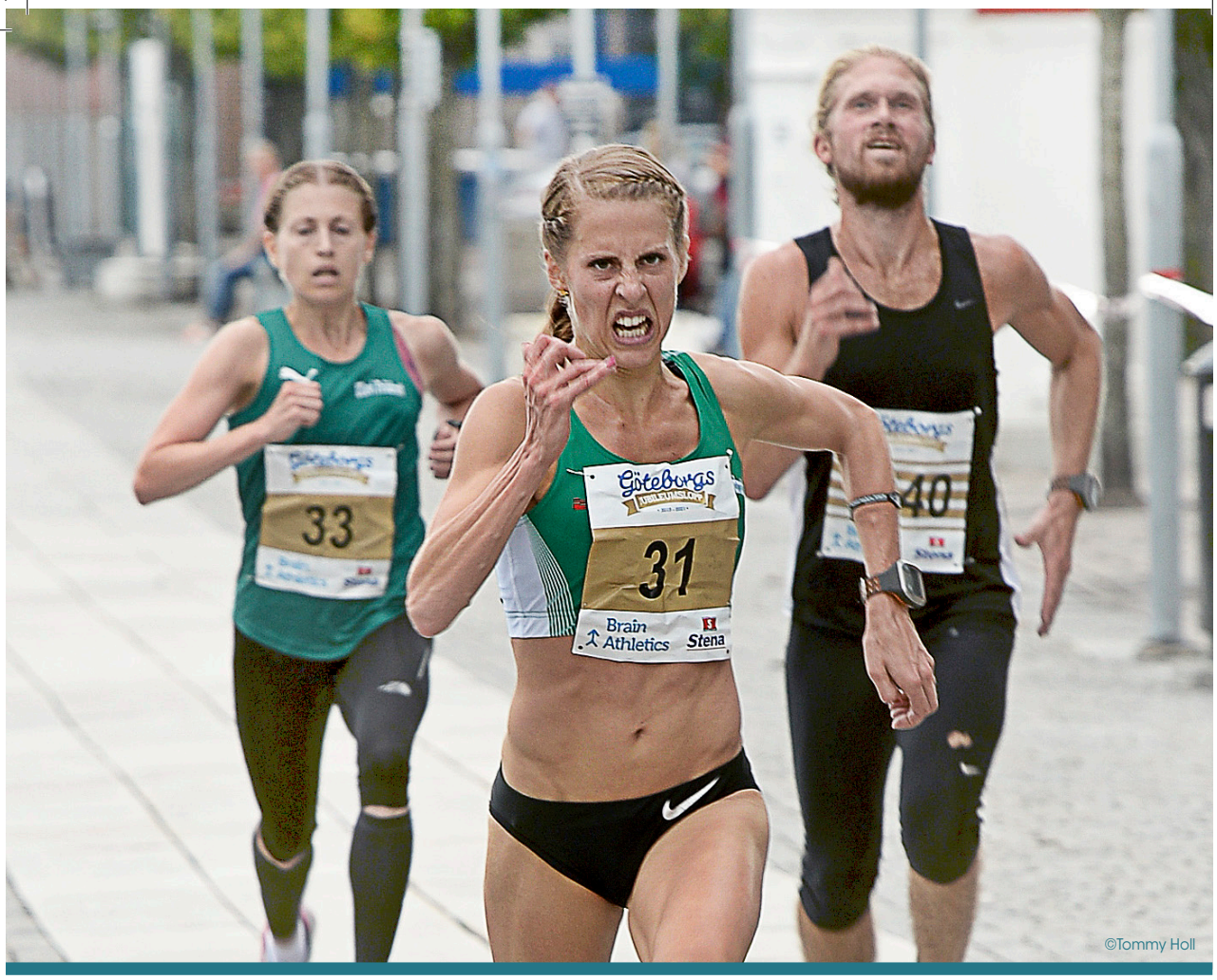
To apply the AARSC to current studies comparing SB and DB reconstruction in order to evaluate the reporting of surgical details and the degree to which these clinical studies fulfil the criteria for anatomic ACL reconstruction

Study III

To investigate whether anatomic DB reconstruction leads to a better clinical outcome at a five-year follow-up compared with anatomic SB reconstruction

Study IV

To apply the AARSC to the Swedish National Knee Ligament Register and on a large cohort of patients in order to describe the current preferences in terms of surgical techniques used by ACL surgeons in Sweden and evaluate whether these techniques are associated with a risk of revision ACL surgery



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08 Patients

Study I

Studies of adults with isolated total ACL rupture were eligible for inclusion. Studies of patients with open physes and cadavers were not included. The 15 studies included for meta-analysis yielded a total of 970 patients, of whom 426 underwent SB reconstruction and 544 DB reconstruction. No further demographic analysis of the included patients was undertaken within the scope of this meta-analysis.

Study II

Studies of adults with isolated total ACL rupture were eligible for inclusion. Studies of patients with open physes and cadavers were not included. No demographic data relating to the included patients were extracted, as the focus of the study was primarily the reporting of items on the AARSC.

Study III

This is a mid-term follow-up of a previously reported cohort.[146] Participants were recruited from two hospitals (n=31 and n=74 respectively). Only patients over the age of 18 years with unilateral ACL injury were eligible for inclusion. The exclusion criteria were a concomitant posterior cruciate ligament (PCL) injury, medial or lateral collateral ligament laxity greater than 1+, previous major knee surgery, or a contralateral ACL injury. Patients who met the inclusion criteria were consecutively enrolled in the study and were randomised to undergo either anatomic SB reconstruction (n=52) or anatomic DB (n=53) reconstruction using closed envelopes administered by the study coordinator. Two patients did not receive the allocated intervention, one patient discontinued the intervention because of a contralateral femoral fracture and fifteen patients were lost to follow-up. The five-year follow-up examinations were performed on 87 patients (83%), (SB: n=41; DB: n=46) (**Figure 13**).

The demographics of the study groups are presented in **Table 1**. The pre-injury Tegner activity level was significantly lower in the DB group (SB: median, 8; range: 3-9; DB: median, 8; range: 0-9, p=0.02). Preoperatively, there were no significant differences between the study groups in terms of the preoperative Tegner activity level, the Lysholm knee score, the one-leg-hop test, the extension or flexion deficit of the knee, the KOOS, the side-to-side laxity tests and the pivot-shift test.

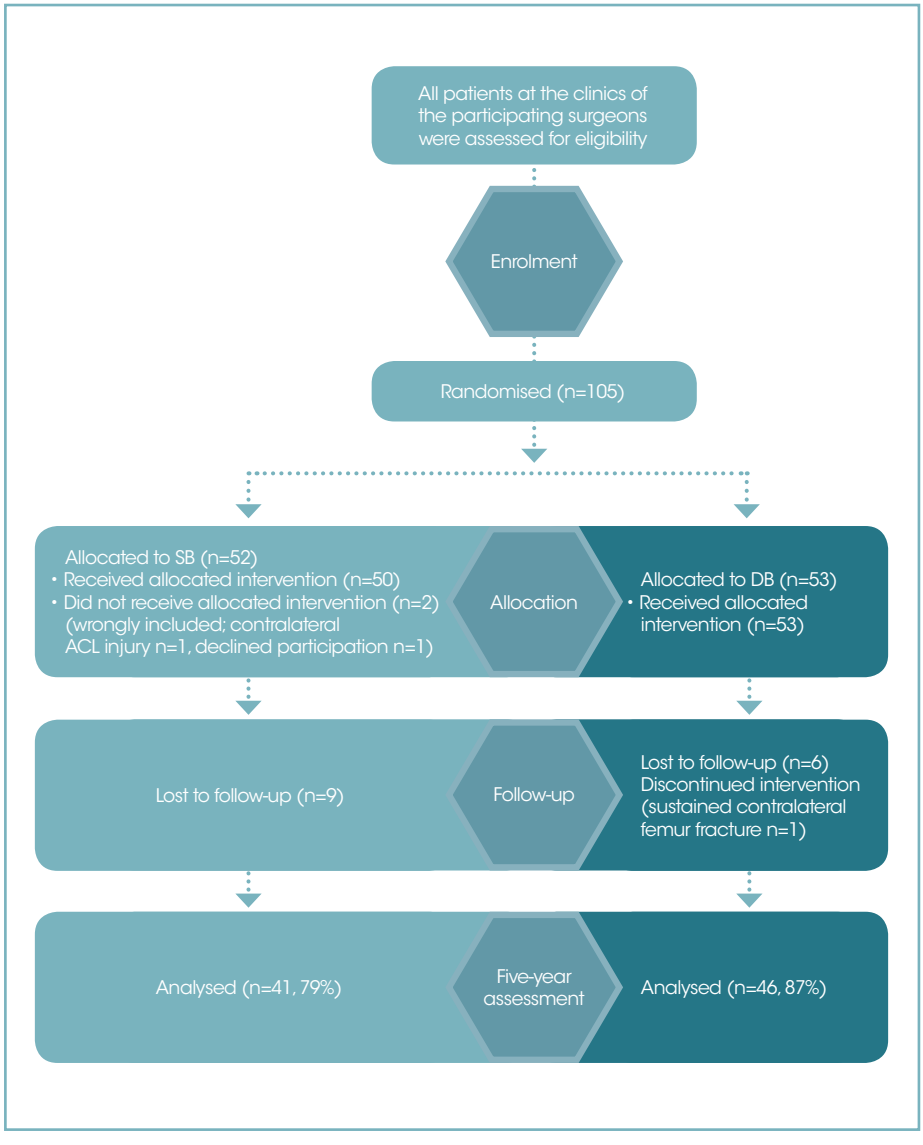


FIGURE 13
Flowchart of patients included in Study III.

		SB (n=50)	DB w(n=53)	P-value
Age (years) **Median (range)** **Mean (SD)**		25 (18-52) 28 (8	29 (18-52) 30 (9.2	n.s.
Patient sex (male:female)		35:15	35:18	n.s.
Injured side (right:left)		28:22	32:21	n.s.
Pre-injury Tegner activity level **Median (range)** **Missing values**		8 (3-9)	8 (0-9) 1	**p=0.02**
Time between the injury and index operation (months) **Mean (SD)**		23 (37)	24 (42)	n.s.
Follow-up period (months) **Mean (SD)** **Missing values**		65 (3.8) 9	63 (4.3) 7	n.s.
Associated injuries (meniscal and/or chondral lesions) **Yes:no (%)**		38 (76):12 (24)	35 (66):18 (34)	n.s.
Cause of additional surgery until the five-year follow-up (n=87)		**SB (n=41)**	**DB (n=46)**	n.s.
	Meniscal	4	1	
	Meniscal and chondral	1	-	
	Chondral	-	2	
	Notchplasty	2	1	
	Loose bodies	1	-	
	Tibial interference screw removal	1	-	
BMI preop (n=103)		**SB (n=50)**	**DB (n=53)**	n.s.
Median (range) **Mean (SD)** **Missing values**		24.9 (20.7 – 37.2) 25.5 (3.6) 14	25.1 (19.9 – 33.8) 24.9 (2.5) 11	

n.s., unable to show significant differences; SD, standard deviation

TABLE 1

Demographics of patients in Study III.

Study IV

A total of 17,682 patients were included in the study (n=10,013 males [56.6%] and 7,669 females [43.4%]), representing the number of unique patients between the ages of 13-49 years, who underwent index ACL reconstruction using hamstring grafts between 1 Jan 2005 and 31 Dec 2014, with surgical details of their index ACL reconstruction available through our survey and after exclusion criteria were applied (**Figure 14**). Follow-up began on the date of primary ACL reconstruction and ended with ACL revision surgery, or on 31 December 2014, whichever occurred first. No minimum follow-up time was pre-specified; instead, patients with a possible follow-up shorter than the earliest documented event (revision ACL surgery) in the specific cohort were censored from analysis. Patients were excluded if exact dates for ACL reconstruction or revision surgery or if exact details of the surgeon who performed the surgery were missing. The median age at index surgery was 24 years (range 13-49 years). A total of 552

(3.1%) patients underwent subsequent ipsilateral ACL revision surgery (n=296 males [53.6%] and 256 females [46.4%]). (**Table 2**)

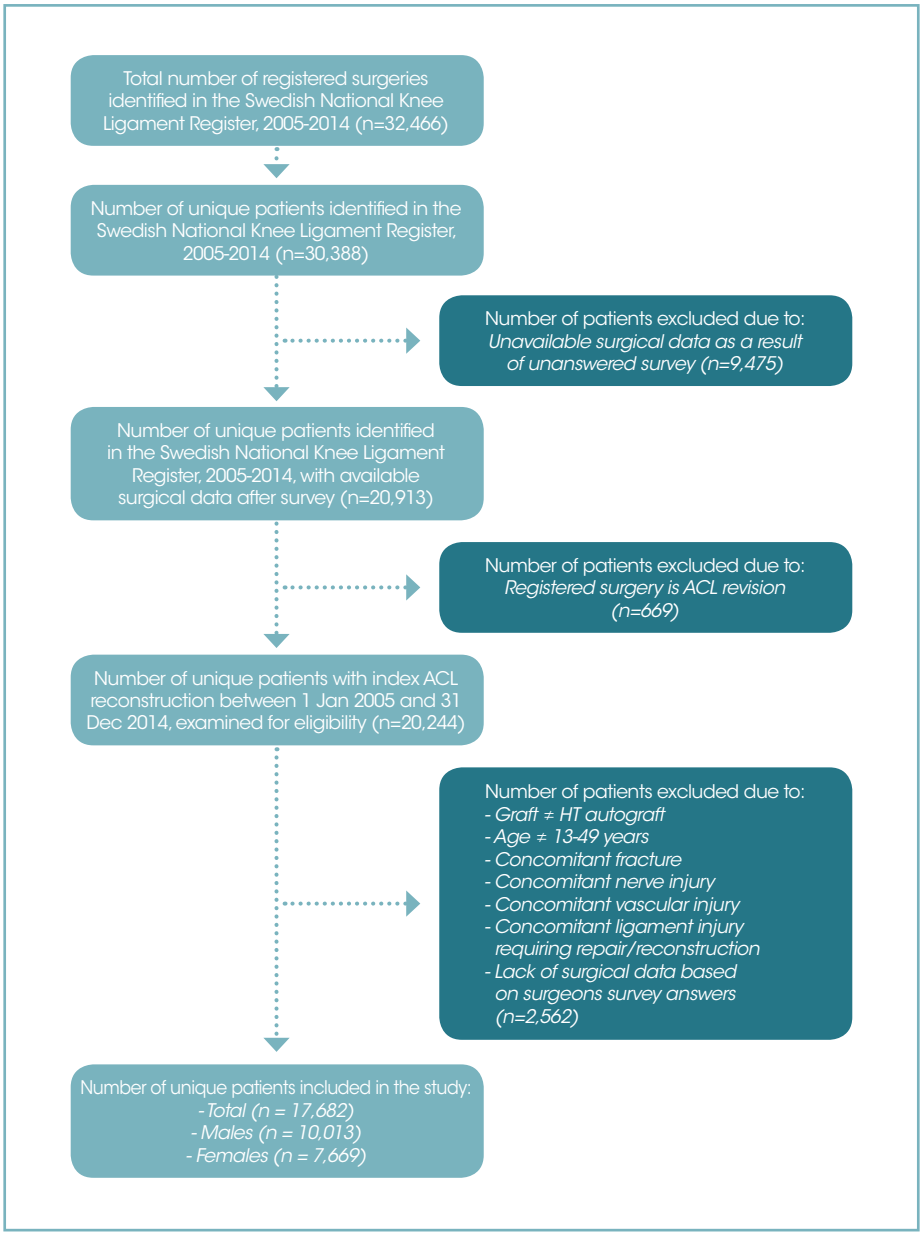


FIGURE 14

Flowchart of inclusion and exclusion criteria.

			Cohort (n=17,682)
		%	Number
Patient sex	Male	56.6	10,013
	Female	43.4	7,669
Age at index ACL reconstruction	13-15 years	7.4	1,300
	16-20 years	28.7	5,057
	21-25 years	20.7	3,667
	26-30 years	14.2	2,513
	31-35 years	10.0	1,777
	36-49 years	18.9	3,350
Concomitant MCL injury at index surgery	Yes	2.4	425
	No	97.6	17,257
Concomitant LCL injury at index surgery	Yes	0.6	100
	No	99.4	17,582
Meniscus injury present (medial and/or lateral) at index surgery	Yes	43.8	7,743
	No	56.2	9,939
Cartilage injury present at index surgery	Yes	26.0	4,598
	No	74.0	13,084
Meniscus and/or cartilage injury at index surgery	Yes	54.8	9,685
	No	45.2	7,997

TABLE 2
Description of baseline cohort in Study IV.

09 Methods

9.1 DATA SOURCES

PubMed

PubMed is a free digital resource developed and maintained by the National Centre for Biotechnology Information (NCIB), a division of the National Library of Medicine (NLM). PubMed provides free access to the Medical Literature Analysis and Retrieval System Online (MEDLINE), currently a database for more than 22 million indexed citations and abstracts from more than 5,600 scholarly journals, pertaining to health sciences and biomedicine dating back to 1946, as well as additional life science journals not included in MEDLINE. Between 2,000-4,000 completed references are added each day and are indexed

using Medical Subject Headings (MeSH). MeSH terms are generated by the NLM's controlled vocabulary thesaurus to assign specific terms to descriptors of the submitted citation in an hierarchical fashion to enable searching the citations.[147, 148]

Cochrane

The Cochrane Collaboration is a non-profit, non-governmental organisation comprising a group of more than 37,000 volunteers in more than 130 countries. Their endeavour is to generate reliable, up-to-date evidence relevant to the prevention, treatment and rehabilitation of particular health problems or groups of problems. This is achieved though the production and dissemination of Cochrane Reviews, contained in the Cochrane Database of Systematic Reviews, one of several databases in the Cochrane Library. Cochrane Reviews are prepared with strict adherence to a pre-defined and meticulously explicit methodology. In addition to Cochrane Reviews, the Cochrane Library contains a number of additional databases, including the Database of Abstracts of Reviews of Effects (DARE) and the Cochrane Central Register of Controlled Trials (CENTRAL). The main objective of CENTRAL is to Provide a comprehensive collection of randomised and quasi-randomised controlled trials. These trials are predominantly retrieved from PubMed and the EMBASE, irrespective of language or publication date, but also by manually searching published journals and reference lists, as well as unpublished material, such as conference proceedings. [149]

EMBASE

The Excerpta Medica database (EMBASE) is a biomedical database, with specific emphasis on pharmacology, containing more than 29 million records from over 8,500 published peer-reviewed journals with coverage dating back to 1947. The EMBASE encompasses all MEDLINE titles and an additional 2,800 journals not included in MEDLINE. Searching is facilitated through the Elsevier Life Science Thesaurus known as "Emtree", although MeSH terms are also compatible. The EMBASE is a service provided though the academic publishing company Elsevier. [150]

The Swedish National Knee Ligament Register

The Swedish National Knee Ligament Register is a clinical nationwide database that utilises a web-based protocol for data registration. The registry is used by more than 90% of all orthopaedic clinics in Sweden and is supported and financed by the Swedish authorities. The coverage (proportion of participating units in relation to all eligible units) and completeness (proportion of target population in the registry) are 93% and over 90% respectively [151] with a 50-70% response rate on questionnaires. Initially, it was a surgical registry, but attempts are now being made to register all the patients with ACL injury, regardless of surgical or non-surgical treatment. The registry protocol consists of two parts: one surgeon-reported section and one patient-reported section. The surgeon enters information about the activity at the time of injury, time from injury to reconstruction, graft selection and fixation techniques. The data on previous surgery on the reconstructed knee, the contralateral knee and all concomitant injuries are also registered. All surgical procedures performed on the injured knee, including meniscal surgery (resection or repair) and treatment for chondral lesions, are reported. Revisions and repeated surgery for other reasons are registered as separate entries.

The patient section is a web-based protocol and includes several drop-down menus,

including the KOOS [152], Lysholm knee scoring scale [153] and EQ-5D.[154] If any answer is left out, the protocol warns that an answer is missing before final registration is possible. Patients register general demographic information, including height, weight and smoking habits. The self-reported outcome scores are registered preoperatively and at one, two, five and 10 years postoperatively.

9.2 STUDY DESIGN

9.2.1 Systematic review & meta-analysis (Studies I & II)

A systematic review can be regarded as a presentation of data attempting to answer a pre-defined research question. Systematic reviews typically involve a detailed systematic plan and search strategy to identify, appraise and synthesise all relevant empirical evidence that fits pre-defined eligibility criteria for a particular topic of interest. The intended result is to provide an assessment of the validity of the findings of the included studies comprising the review, achieved through an objective assessment of methodological quality and risk-of-bias assessment. The need for rigour in the production of systematic reviews has led to the development of a formal scientific process for their conduct. The Cochrane Handbook for Systematic Reviews of Interventions[155] or the PRISMA statement[156] provide detailed guidelines for this conduct and reporting of data.

A meta-analysis is a statistical technique used to combine the findings from the independent studies included in the systematic review. It is important to remember that the validity of the meta-analysis is dependent on the quality of the systematic review on which it is based. A flawed or unsystematic review process will simply provide a precise quantitative estimate that is incorrect. The precision with which the size of any treatment/intervention effect can be estimated depends largely on the number of patients included in the specific study. This limitation can be overcome in part by a meta-analysis, by combining the results of many trials, with the resultant potential power to detect small yet clinically significant effects. One widely quoted definition of a meta-analysis is "a statistical analysis which combines or integrates the results of several independent clinical trials considered by the analyst to be 'combinable'".[157] This illustrates the need only to include studies that match the specific research question, address the homogeneity of participants, interventions, comparisons, outcomes and settings, in order to obtain a precise answer to a specific question.

Sound information retrieval is an underlying cornerstone in the undertaking of a systematic review or meta-analysis. The process of discovering and selecting studies to review, i.e. the quality of the literature search, is often a balance between "recall" and "precision". In the context of systematic reviews, "recall" expresses the ratio of relevant articles retrieved to all those in a collection that should be retrieved. A literature search with 100% recall would thus retrieve all available relevant articles in the searched databases pertaining to the research question. Despite being an optimistic ambition, in reality this is not feasible. "Precision" expresses the ratio of articles retrieved and deemed to be relevant to all those actually retrieved; in other words, how many irrelevant articles

one must go through in order to find the relevant ones.

Maximising recall to ensure that no relevant articles are missed, without overwhelming the resources of the review team, is one of the inherent challenges when undertaking systematic reviews and meta-analyses.

9.2.2 Randomised controlled trials (Study III)

Randomised controlled trials are thought to represent the highest quality of evidence. The key methodological components of an RCT are use of a control group to which the experimental intervention is compared, and the random, preferably blinded, assignment of participants to the intervention in question. The purpose of randomly allocating participants is to ensure that the baseline characteristics of the participants are homogenous between the groups at the start of the study/comparison. In addition, it reduces the risk of an imbalance in potential known and unknown influential factors (confounders) that could influence the clinical course of the participants. This is a benefit unique to RCTs. This study design should allow for its results to be attributed to differences between the intervention and control, since random assignment, at least in theory, equalises the groups on all other variables. There are, however, potential limitations due to difficulties regarding allocation concealment, blinded assessment of outcome, adherence to protocol and drop-out rates, which have to be evaluated in each individual study.

Low expectations of compliance and/or high drop-out rates, as well as ethical considerations, may limit the feasibility of successfully undertaking an RCT. It is also important to understand that RCTs are often time consuming and demanding to undertake from both an economical and logistical standpoint.

However, RCTs are not immune to bias; one example is the often-employed "intention-to-treat" approach, in which people are considered to have adhered to the assigned treatment, regardless of actual compliance. This can potentially minimise an actual difference between study groups, by including the experience of people who adhered to the exposure along with those who did not. An RCT can also be too small to detect important clinical differences i.e. it is underpowered.[158] The main determinant of the sample size necessary to detect an actual difference between two groups in an RCT is the size of the expected differences related to the effect of the intervention compared with the control. Prior to the start of the study, both sample size and desired power need to be considered. A power analysis is then undertaken to establish what sample size is required for the study to detect a difference between the groups when one actually exists, and correctly reject a null hypothesis. If the expected difference in outcome is small, a relatively larger sample size is needed in order to be able to draw any clear conclusions. If the sample size does not meet this requirement, the study is underpowered posing a risk of type-II error and failure to correctly reject a false null-hypothesis. In addition, RCTs often consist of a relatively homogeneous pool of patients from which significant numbers of patients are intentionally excluded at the expense of external validity. As a result, generalisability to the target population decreases.[159]

9.2.3 Registry studies (Study IV)

A patient register is defined as "an organised system that uses observational study methods to collect uniform data (clinical and other) to evaluate specified outcomes for a population defined by a particular disease, condition or exposure and that serves one or more predetermined scientific, clinical, or policy purposes".[160] They can be used to evaluate clinical or comparative effectiveness, monitor the safety/tolerability of a given treatment and evaluate risk-benefit, measure quality of care and care patterns and provide an insight into the natural history of a given disease, exposure or intervention. National population-based registers of high quality provide a unique source of information, as they comprise a large cross-sectional sample size, often representative of the national population, allowing for the generalisation of the results based on the data (high external validity). Register studies are a good alternative in situations where clinical trials are not feasible, for example, when evaluating rare adverse events, or when the results of clinical trials are not applicable due to the participants being highly selected. Much like cohort studies, register studies generally follow patients over time, but they are generally more flexible, as the focus can be adjusted over time to address additional requirements. It must be remembered, however, that registers are prone to bias. Striving to achieve the highest possible completeness and coverage of a register helps to minimise bias, such as systematic differences in the compared groups (selection bias), the care provided, or exposure to other factors apart from the intervention of interest (performance bias), withdrawals or exclusions of people entered into the study (attrition bias) or how outcomes are assessed (detection bias).

9.3 BIAS ASSESSMENT (STUDY I)

Bias in science is defined as any tendency that limits or prevents an impartial or unprejudiced view of a question. In the field of research, it refers to the introduction of *systematic error* (as opposed to *random error*) into the research methodology, which in turn incorrectly strengthens one outcome over another. It can occur at various phases of the research process, including study design, data collection and analysis and even publication. Unlike random error, which results from sampling variability and often decreases as sample size increases, bias is independent of both sample size and statistical significance. Bias can cause estimates of association to be either larger or smaller than the true association. Reviewers of scientific literature must be aware of the fact that some degree of bias is almost always present and must therefore consider how this may affect the conclusion and credibility of a study. Assessing the risk of bias addresses this question. To aid in this appraisal process, we utilised the Cochrane Collaboration's tool for assessing risk of bias developed by the Cochrane Bias Methods Group, separately addressing five primary domains of bias: selection bias, performance bias, detection bias, attrition bias and reporting bias.[155]

9.4 THE ANATOMIC ANTERIOR CRUCIATE LIGAMENT RECONSTRUCTION SCORING CHECKLIST (STUDIES II & IV)

The development of the AARSC has been described by van Eck *et al.*[161] The first step involved generating the items to be included in the checklist. Three senior orthopaedic surgeons with extensive experience in the field of ACL reconstruction composed a list of 27 items describing possible indicators of both anatomic and non-anatomic ACL reconstruction. Next, 27 experts aided in the process of reducing the list of 27 items and evaluating the face validity of the importance of each item (1=not important, 2=somewhat important, 3=very important, 4=extremely important). In addition, the experts were asked to rate the same items with regard to how often they performed/utilised each item during ACL reconstruction surgery (1=never, 2=sometimes, 3=more often than not and 4=always). The items were then evaluated and included for the revised item list if they received an importance score of 3 or 4 from at least 75% of the experts, or if the median score was 3 or higher. This yielded 17 items. Item validity was evaluated by disseminating these 17 items to a total of 959 peer reviewers qualified to review manuscripts on ACL reconstruction and the aforementioned process was repeated with the same item inclusion criteria. A total of 329 orthopaedic surgeons responded.

Finally, the internal consistency, reliability and validity of the checklist were calculated. Twenty method sections varying in their description of the surgical procedure were selected from a previous systematic review.[162] The senior authors rated the degree of "anatomicness" of the surgical methods described (1=non-anatomic, 2=somewhat anatomic, 3=almost anatomic and 4=completely anatomic).

Eight experienced ACL surgeons, independent of the development process of the checklist, were asked individually to score five of the twenty selected papers using the AARSC. Inter-tester reliability, construct validity and internal consistency could then be calculated.

The final AARSC comprised 17 items pertaining to surgical technique and one item relating to the documentation of bone tunnel placement. The checklist allows for the calculation of an "anatomic score" with a total of 19 points. The senior authors of the AARSC have proposed a minimum required score of 10 points for anatomic ACL reconstruction. This cut-off was established based on the senior authors unanimous agreement upon those items regarded as mandatory when performing an anatomic ACL reconstruction.

The AARSC was adapted for use in **Study IV**. The items were translated into Swedish by a professional language editor and distributed as an online questionnaire to all orthopaedic surgeons registered in the Swedish National Knee Ligament Register.

(See Appendix: AARSC)

9.5 SURGICAL TECHNIQUE (STUDY III)

Four senior surgeons performed all the reconstructions. Standard anterolateral and anteromedial portals were established.

Associated intra-articular injuries, such as meniscal ruptures and chondral lesions, were addressed at the time of the index operation. Femoral and tibial ACL insertion sites were identified, in addition to the lateral intercondylar and bifurcate ridges. ACL remnants were resected. The semitendinosus and gracilis tendons were harvested with an open tendon stripper. Femoral drilling was performed through the AM portal. The tibial tunnels were drilled using a tibial elbow aimer and a fluted reamer. Metal interference screws were used for femoral graft fixation (RCI, Smith & Nephew, Andover, Massachusetts) and bioabsorbable screws for tibial graft fixation (Matryx, ConMed Linvatec, Largo, Florida). In both techniques, all tunnels were placed "anatomically" in accordance with the knowledge of anatomic ACL reconstruction available in 2008-2009 when the surgeries were performed.

Anatomic double-bundle technique

Both the femoral and tibial remnants of AM and PL bundles were identified with the knee in 90 degrees of flexion. The femoral tunnels were addressed first. The femoral insertion sites of the AM and PL bundles were marked with an awl. The AM tunnel was drilled first just behind the bifurcate ridge, followed by the PL tunnel just in front of this, in 39 patients using a free-hand technique and in 14 patients using a DB femoral guide (Acufex anatomic ACL guide system, Smith & Nephew). The tibial tunnels were drilled in the centre of the insertion site of the AM and PL bundles respectively, with AM tunnel placement in front of the anterior horn of the lateral meniscus and the PL tunnel in front of the PCL. The AM graft consisted of a doubled semitendinosus tendon. The PL graft consisted of a doubled or tripled gracilis tendon. Tibial fixation was performed in 5° to 10° of knee flexion for the PL bundle and in 40° to 60° of knee flexion for the AM bundle.[146]

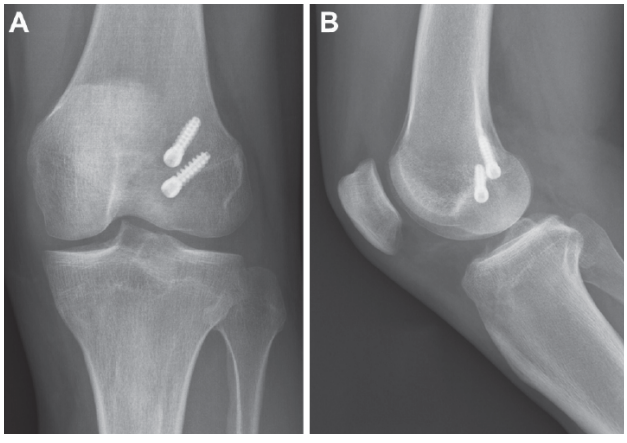


FIGURE 15

A Anteroposterior and **B** lateral radiographs of the right knee in the early postoperative period of a male patient in the DB group demonstrating the tunnel positions in the femur and tibia. (Reprinted with the kind permission of The American Journal of Sports Medicine).

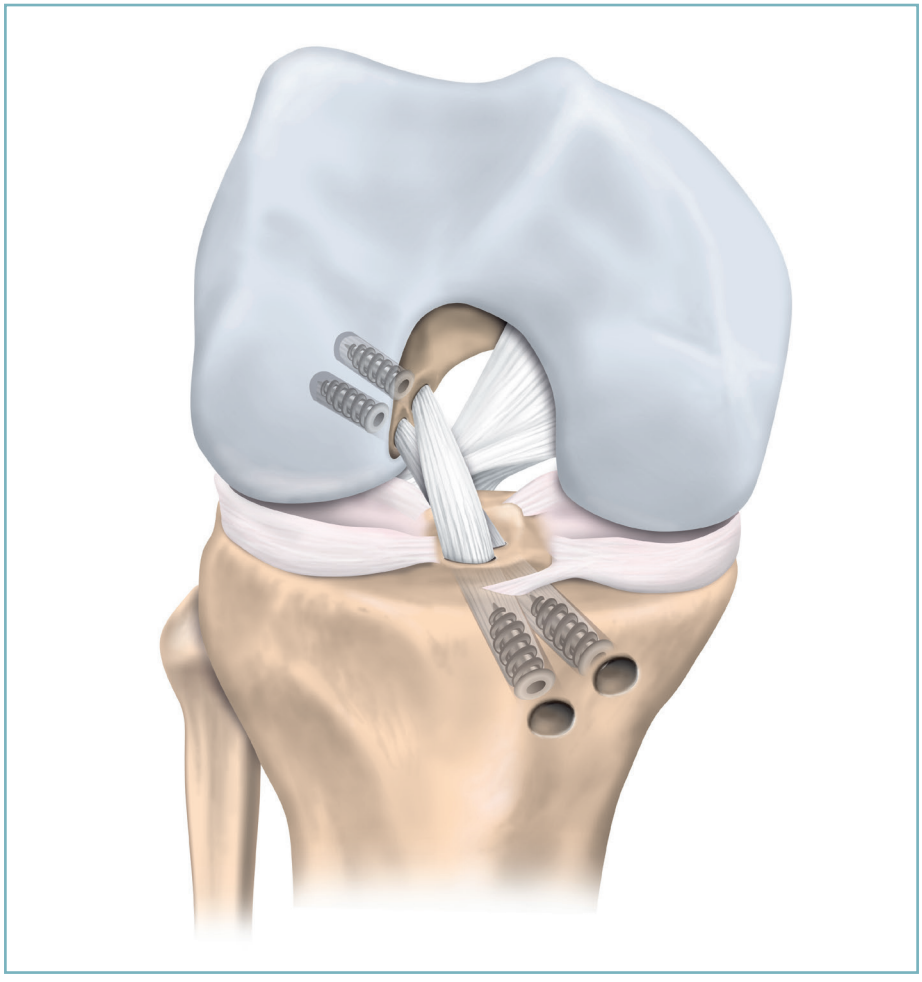


FIGURE 16
Anatomic DB ACL reconstruction using HT graft.

Anatomic single-bundle technique

The femoral tunnel was addressed first. The femoral ACL insertion site was marked with an awl in the shallow aspect of the AM bundle insertion site, aimed at the centre of the ACL insertion site in order to place the centre of the tunnel just behind the bifurcate ridge about 8-10 mm from the posterior cartilage with the knee in 90 degrees of flexion. The femoral tunnel was predrilled using a 4.0-mm sharp non-cannulated drill or a guide wire, before the final tunnel determined by the size of the graft was drilled. On the tibial side, the centre of the tunnel was placed in alignment with the anterior horn of the lateral meniscus. The ACL graft consisted of four- or five-stranded semitendinosus and gracilis tendons. Tibial fixation was performed in 10˚ to 20˚ of knee flexion.[146]

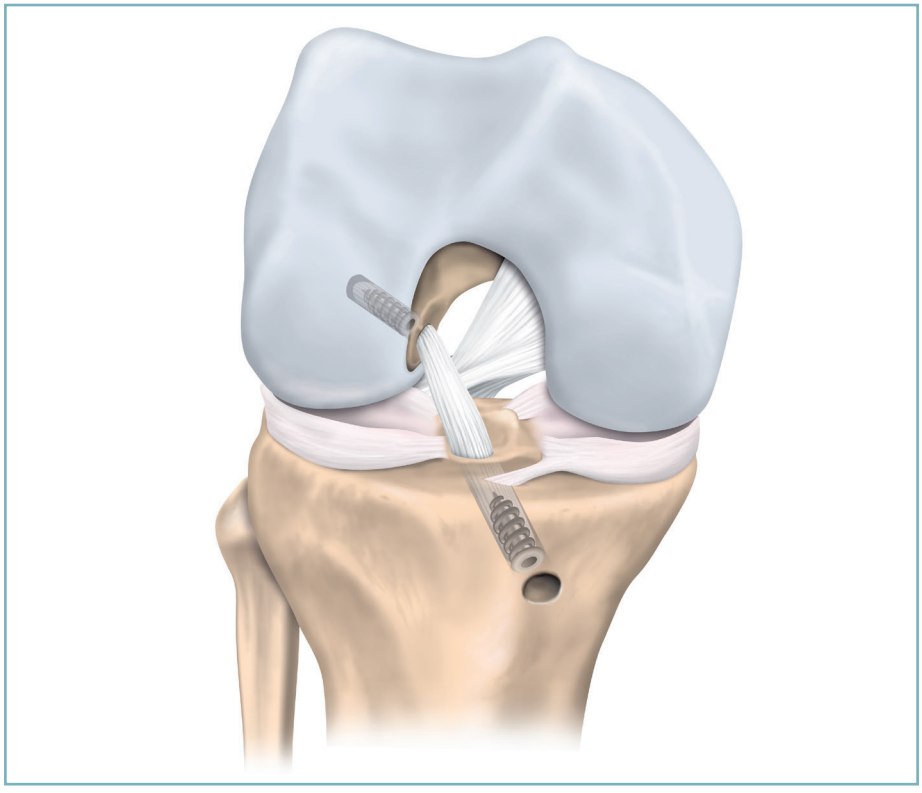


FIGURE 17
Anatomic SB ACL reconstruction using HT graft.

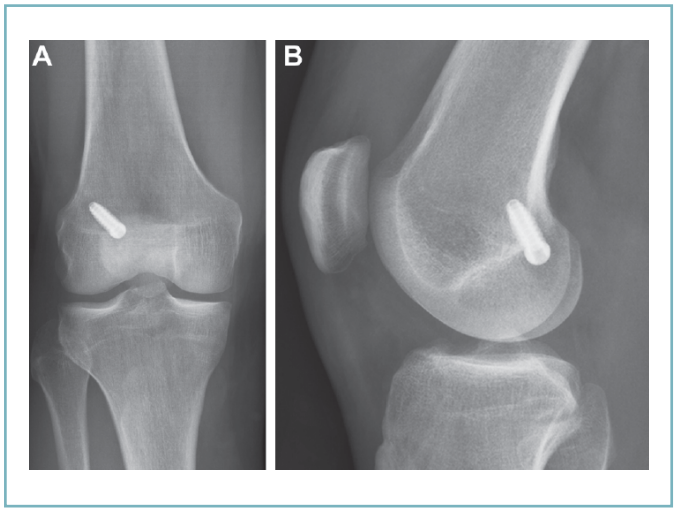


FIGURE 18
A Anteroposterior and **B** lateral radiographs of the right knee in the early postoperative period of a male patient in the SB group demonstrating the tunnel positions in the femur and tibia. (Reprinted with kind permission of The American Journal of Sports Medicine).

9.6 REHABILITATION (STUDY III)

All patients underwent rehabilitation in accordance with the same guidelines under the supervision of their local physiotherapists, permitting immediate full weight bearing, full range of motion (ROM) including full hyperextension and without the use of a brace. Closed kinetic chain exercises were started immediately postoperatively. Running was permitted at three months and contact sports six months postoperatively at the earliest, provided that the patient had regained full functional stability in terms of strength, co-ordination and balance as compared with the contralateral leg.[146]

9.7 CLINICAL EXAMINATIONS

Blinded examiners (STUDY III)

One independent physiotherapist performed all pre- and postoperative follow-up examinations. The physiotherapist was blinded to the surgical technique to which the patient had been randomised to but not to the aim of the study at the time of the examination.

Lachman (Studies I & III)

The manual Lachman test was estimated by the examiner as the amount of anterior drawer movement with the knee in 15° to 20° of flexion. It was graded as 0, + (<5 mm), ++ (5-10 mm), or +++ (>10 mm), compared with the uninjured contralateral knee.[163]

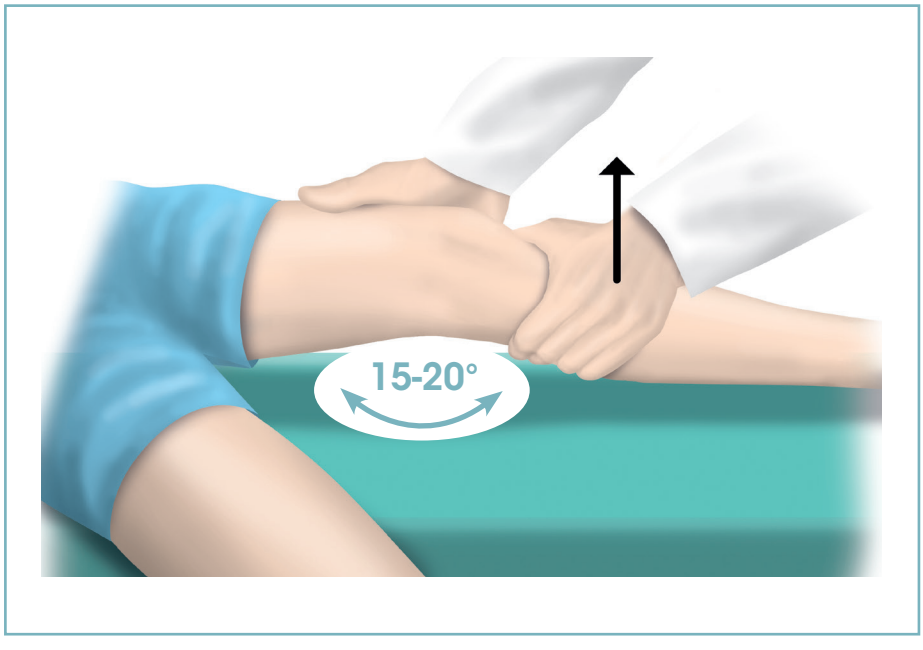


FIGURE 19
The manual Lachman test.

KT-1000 (Studies I & III)

Both knees were examined with the patient in the supine position, the knees in 30° of flexion and in a neutral position. [164, 165] This position was kept constant during the examination and in all patients by utilising a thigh support, thigh straps and footrest. The instrumented KT-1000 arthrometer (MEDmetric Corp, San Diego, California) was used to test the anterior displacement of the tibia in relation to the femur and was registered at 134 N of displacement force and as the maximum manual test (MMT).[166] A minimum of three measurements of each knee were made, and the average value was registered. The uninjured knee was always examined first. All KT-1000 measurements were performed by the same examiner/physiotherapist, as per the recommendation of Sernert *et al*.[167]

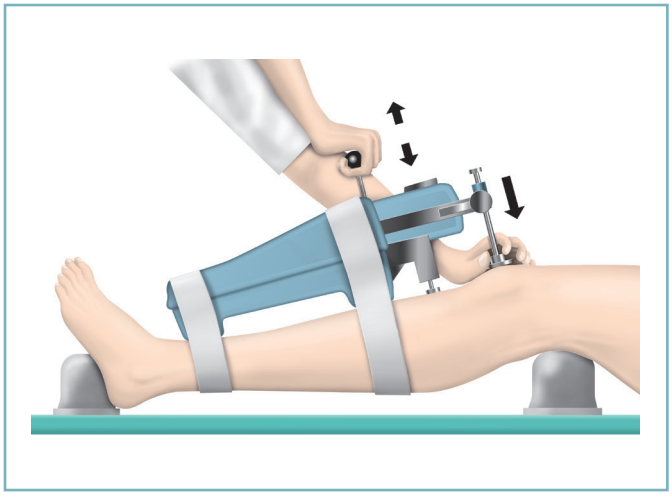


FIGURE 20

KT-1000 arthrometer is used to measure anterior displacement of tibia with a 134N anterior force applied through the handle.

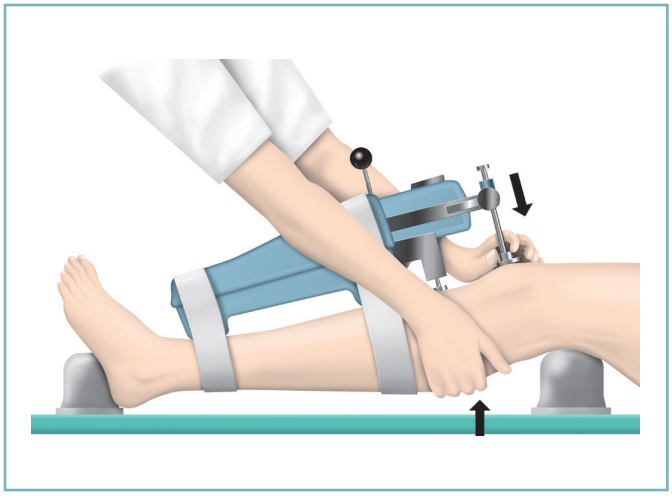


FIGURE 21

The maximum manual test (MMT). KT-1000 arthrometer is used to measure maximum anterior of the tibia with the force being manually applied through the proximal calf rather than the handle.

Anterior drawer (Study I)

The patient is supine with 45° of hip flexion, 90° of knee flexion and the feet planted flat on the surface. An anteriorly directed load is applied to the tibia by the examiner and an increased anterior tibial translation or lack of a "firm" end-point is noted. The test is graded as +1 (<5 mm), +2 (5-10 mm) or +3 (>10 mm), compared with the uninjured contralateral knee.

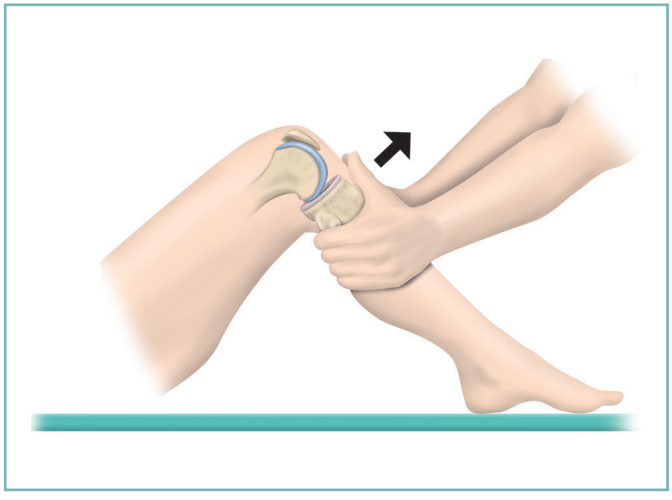
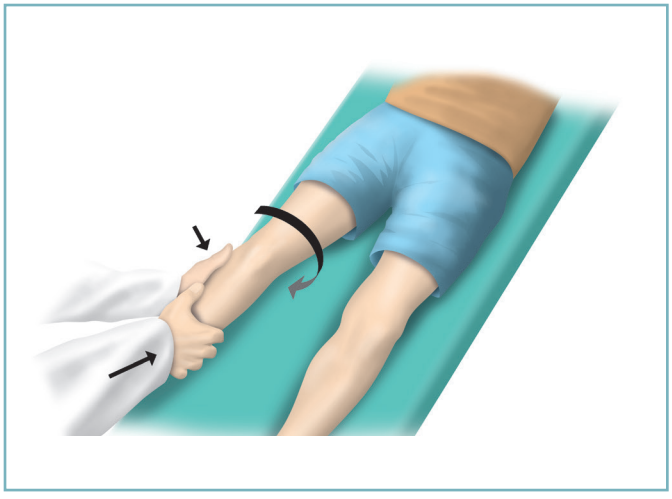


FIGURE 22

The anterior drawer test.

Pivot-shift test (Studies I & III)

The pivot-shift test is the most specific test for ACL injury.[36] The test is performed with the patient in a supine position, the hip in 30° of flexion and the knee in full extension. The examiner then applies a valgus stress to the knee and an axial load while internally rotating the tibia. The knee is moved into flexion from the fully extended position. A positive test is indicated by the subluxation of the tibia while the femur rotates externally followed by a reduction of the tibia at around 30-40 degrees of flexion. This reduction can often be felt and graded accordingly. The pivot-shift test was clinically graded using grades 0 to III according to International Knee Documentation Committee (IKDC) guidelines.[63]



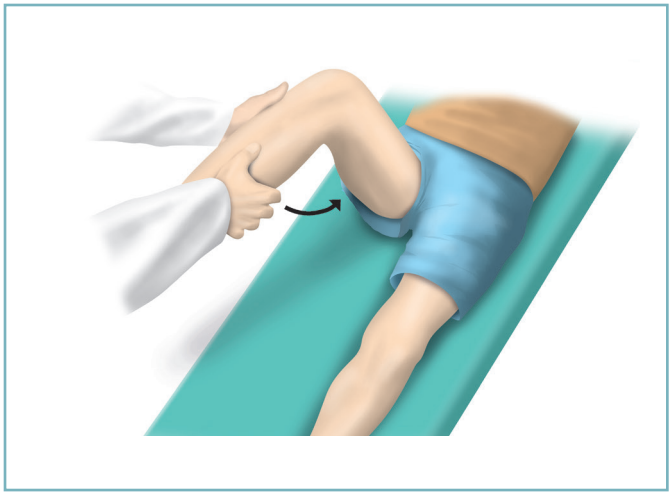


FIGURE 23-24

The pivot shift test starts with examiner applying a valgus stress and an axial load to the knee while internally rotating the tibia. The knee is moved into flexion from the fully extended position.

Range of motion (Study III)

The patient was examined in a supine position using a hand-held goniometer and a visual measurement was made along the 0-180° scale on the goniometer to the nearest degree.[168, 169] The uninjured leg was evaluated first. Maximum range of active extension followed by maximum range of active flexion was measured. Cases of hyperextension were also noted. Side-to-side differences were calculated and an extension/flexion deficit was regarded as being present in cases with a side-to-side difference of ≥ 5°. Extension/flexion deficit was dichotomised to YES/NO.

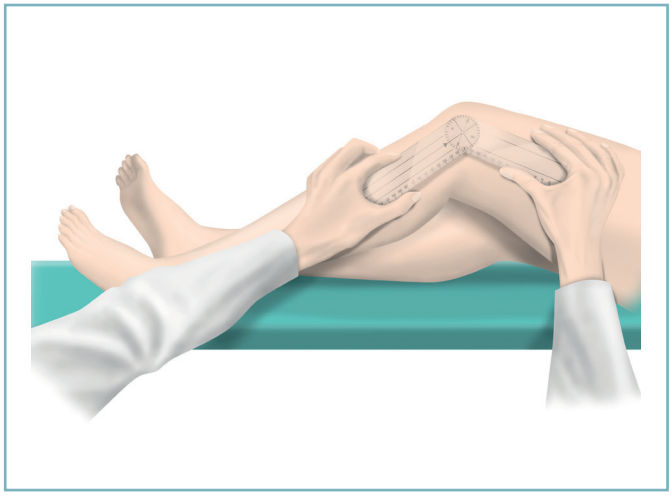


FIGURE 25
Range of flexion and extension measured using a goniometer.

Quantified antero-posterior laxity using intraoperative navigation (Study I)

Two studies included for meta-analysis in Study I used the OrthoPilot (B. Braun Aesculap, Tuttlingen, Germany) navigation system to evaluate AP laxity intraoperatively.[170, 171] In addition to aiding in bone tunnel placement, the system allows for AP as well as rotatory laxity measurements via transmitters fastened to K-wires placed on pre-defined landmarks on the knee. In one study, the Praxim ACL Surgetics navigation system (Praxim La Tronche, France) was used to measure AP laxity.[172] This system works by computing the accurate morphology of the patient's knee from a deformable statistical model, without using CT, radiography or fluoroscopy. Several hundred scattered points are acquired quickly by the surgeon, by "painting" the cartilage and bone surface with a probe. These points are registered and a 3D model is created. This model can then aid in bone tunnel placement as well as registering laxity measurements.

Quantified rotatory laxity using intraoperative navigation (Study I)

Three studies included for meta-analysis in Study I used the previously described OrthoPilot (B. Braun Aesculap, Tuttlingen, Germany) navigation system to evaluate rotatory laxity intraoperatively. [170, 171, 173]. In one study, the Praxim ACL Surgetics navigation system (Praxim La Tronche, France) was used to measure rotatory laxity.[172] Hemmerich et al. utilised a technique of taking low-resolution MRI while simultaneously applying internal and external torsional loads to the knee in full extension and at 30° of flexion.[174]

One-leg-hop test (Study III)

The one-leg-hop-test was performed by jumping and landing on the same foot holding the hands behind the back. The non-injured leg was always tested first. Three attempts were allowed for each leg and the longest hop was registered for each leg separately. A quotient (%) between the index and non-injured leg was calculated.[175]

Square-hop test (Study III)

The square-hop test was performed by standing on the leg to be tested, outside a 40 x 40 cm square marked with tape on the floor. For the right leg, the patients were instructed to jump clockwise in and out of the square as many times as possible during a period of 30 seconds. For the left leg, the patient performed the test in a counter-clockwise direction. The test was video recorded and both the total number of jumps and the number of successful jumps, without touching the taped square, were counted. A quotient (%) between the index and non-injured leg was calculated. This test was modified from the one previously described by Ostenberg *et al.*[176]

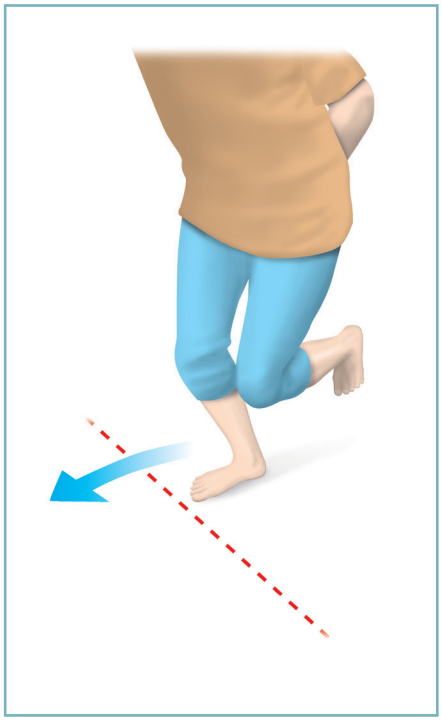


FIGURE 26
One-leg hop test.

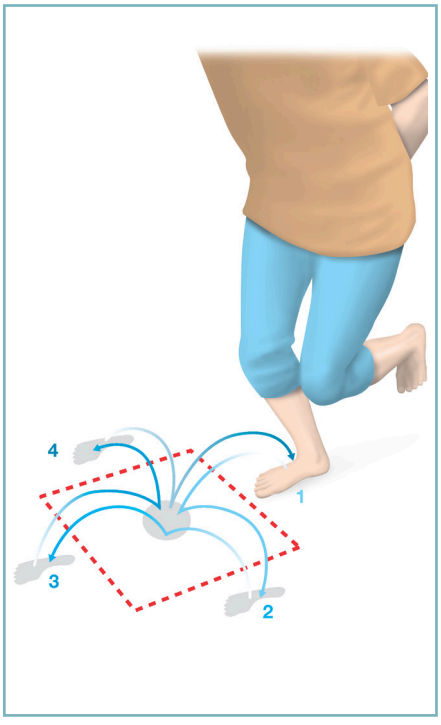


FIGURE 27
Square-hop test.

9.9 FUNCTIONAL SCORES

KOOS (Study III)

The Knee injury and Osteoarthritis Outcome Score (KOOS) is a self-administered instrument measuring outcome after knee injury. It has been validated for use in both short- and long-term outcome measurements after knee arthroplasty, ACL reconstruction, meniscectomies and post-traumatic OA.[152, 177-179] It was originally developed as an extension of the Western Ontario and McMaster Universities (WOMAC) Osteoarthritis Index [180] which primarily assesses pain, stiffness and function in patients with any type of knee injury who run an increased risk of developing OA. This in turn provides the KOOS with content validity for both young and old patients with manifest or a risk of OA. The KOOS comprises 42 questions distributed within five separately scored subscales: Pain (9 questions), Symptoms (7 questions), Function in Daily Living (ADL) (17 questions), Function in Sport and Recreation (Sport/Rec) (5 questions) and Knee-related Quality of Life (QoL) (4 questions). For each subscale, the score is normalised to a 0-100 scale. Higher scores indicate better status.

Lysholm score (Study III)

Initially the Lysholm score was designed as a physician-administered tool to measure outcomes after knee ligament surgery.[181] It has since been modified and is now a patient-administered instrument and is validated for use in the long-term follow-up of ACL injury, as well as injury to menisci and cartilage and patellar dislocations. [182] In Study III, the modified Lysholm score was patient administered with the scores of the answer alternatives blinded to the patient.[183] The Lysholm score consists of eight items; Limp (5 points), Support (5 points), Locking (15 points), Instability (25 points), Pain (25 points), Swelling (10 points), Stair Climbing (10 points) and Squatting (5 points).[153]

Tegner activity scale (Study III)

The Tegner activity scale was developed to complement the Lysholm score. This new scale graded activity based on work and sports activities. The Tegner Activity Scale yields a grade between 0-10. It covers activities of daily life, represented by activity levels between 0-4, and recreational or competitive sports, represented by activity levels 5-10.[153]

9.10 RADIOGRAPHY (STUDY III)

At an early postoperative stage (at approximately six weeks) and in conjunction with the five-year follow-up, the patients enrolled in **Study IV** underwent unilateral standard radiographs of the index knee, with weight-bearing AP and lateral views with 20˚ to 30˚ of flexion of the knee. An independent musculoskeletal radiologist interpreted the radiographs and assessed them according to the Fairbank classification system.[60] The Fairbank system dichotomously rates the presence of flattening, narrowing and ridging of the joint in the medial and lateral compartment of the knee. The cumulative number of positive findings, from 0 to 6, was calculated for each patient, as previously described by Lidén *et al*.[66] Patello-femoral OA was classified as "none", "minor", "moderate" or "severe" and the presence of patello-femoral osteophytes as "none", "minute", "moderate" and "large". In addition to the

Fairbank system, each patient was also evaluated using the grading systems of Ahlbäck[62] and Kellgren-Lawrence[61]

Ahlbäck		Kellgren & Lawrence	
Grade	**Radiographic findings**	**Grade**	**Radiographic findings**
Grade I	Joint space narrowing (joint space < 3 mm)	Grade 0	No radiographic features of OA
Grade II	Joint space obliteration	Grade 1	Doubtful joint space narrowing and possible osteophytic lipping
Grade III	Minor bone attrition (0–5 mm)	Grade 2	Possible joint space narrowing and definite osteophyte formation
Grade IV	Moderate bone attrition (5–10 mm)	Grade 3	Definite joint space narrowing, multiple osteophytes,sclerosis and possible bone deformity
Grade V	Severe bone attrition (>10 mm)	Grade 4	Marked joint space narrowing, large ostephytes,severe sclerosis and definite bone deformity

TABLE 3

The Ahlbäck classification and Kellgren and Lawrence grading system of radiographic knee OA of the tibiofemoral joint.

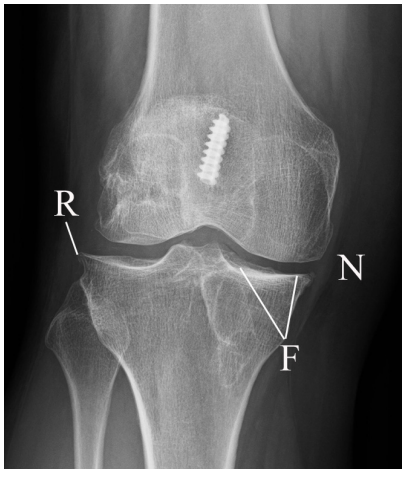


FIGURE 28

Plain radiograph of the right knee with OA changes described according to the Fairbank classification, showing the presence of flattening (F), narrowing (N) and ridging (R) of the joint in the medial and lateral compartment of the knee. (Image courtesy of Jüri Kartus).

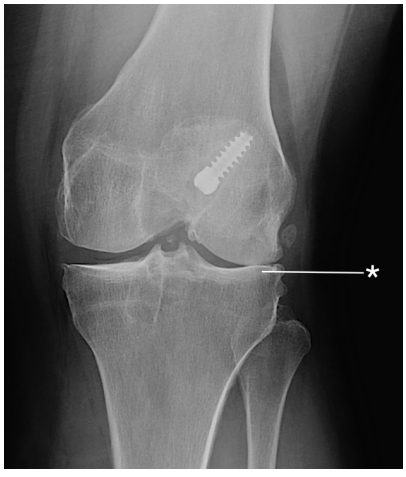


FIGURE 29

Plain radiograph of the left knee showing OA changes predominantly in the lateral compartment (*), classified as Ahlbäck III. In addition, marked joint space narrowing, osteophyte formation, subchondral sclerosis and bone deformity is also evident (Kellgren-Lawrence grade 4). (Image courtesy of Lars Rostgard-Christensen).

9.11 STATISTICAL METHODS

Study I

A statistical meta-analysis of the data was performed using the metan command version sbe24_3 for Stata (Version 12.1, StataCorp LP, Texas, USA). In some studies, zero events were reported. Following the Cochrane recommendation, 0.5 was added to cases and non-cases in both study groups (http://handbook.cochrane.org). In the cases where the standard error could not be obtained from the studies or after requesting them from the authors, standard errors were instead calculated based on the values reported in the studies within the same group with regard to that particular variable. The results were expressed as the OR with 95% CI for dichotomous outcomes and SMD with 95% CI for continuous outcomes. A random-effect meta-analysis was used to account for heterogeneity. The I^2 is provided to show the level of heterogeneity. The I^2 index can be interpreted as the percentage of the total variability in a set of effect sizes that is attributable to genuine heterogeneity between the groups. Statistical significance was set at a P-value of < 0.05.

Study II

A statistical analysis of the data was performed using the IBM SPSS Statistics (version 21, IBM Corporation, USA). Descriptive statistics were used to summarise all the recorded data. A comparison of the AARSC score depending on the level of evidence and year of publication for the SB and DB groups was performed using one-way ANOVA. Statistical significance was set at a P-value of < 0.05

Study III

The primary variable in the study was the pivot-shift test. The study was powered to reveal a difference of 1 grade on the pivot-shift test between the study groups, with a power of more than 80%.It was assumed that a difference of 1 grade in the pivot test was clinically important; the standard deviation of the pivot-shift test was estimated to be 1.5 grades. To achieve a power of 80%, 36 patients were thus needed in each group. To increase the power of the study and to allow for loss to follow-up, 105 patients were initially randomised. Mean (± standard deviation) and median (range) values are presented when applicable. For comparisons of dichotomous variables between the groups, the $\chi 2$ test was used. When comparisons of both continuous and non-continuous variables were required, the Mann-Whitney U test was used. The Wilcoxon signed-rank test was used for comparisons of the preoperative and postoperative data and comparisons between six-week and five-year radiographic assessments within the study groups. The Spearman test was used for correlation analysis between the cumulative Fairbank score and BMI. Statistical significance was set at a P-value of < 0.05.

Study IV

A statistician assigned to the Swedish National Knee Ligament Register performed all the statistical analyses. A statistical analysis was performed in IBM SPSS Statistics (Version 23.0, IBM Corp, Armonk, NY, USA). A Kaplan-Meier survival analysis was used to assess the cumulative graft survival rates. Statistical significance was defined as a 95% CI for hazard ratios not including 1.0 and a P-value of < 0.05. A multivariate analysis adjusted for possible confounding factors (age, patient gender, concomitant injury to menisci or cartilage) was analysed using a Cox regression model and expressed as hazard ratios and 95% CI. The assumption of proportional hazards was assessed by using log-log plots.

9.12 ETHICS

Studies I and **II** are literature studies (meta-analysis and systematic review respectively) and are by definition a collection of data from studies for which ethical approval has already been granted. Ethical approval for Studies I and II was therefore not necessary. **Study III** was approved by the Regional Ethics Review Board in Gothenburg (ref. ID: 157-08). **Study IV** was approved by the Regional Ethics Review Board in Gothenburg (ref. ID: 760-14).

10 Summary of papers

10.1 STUDY I

Anatomic single- versus double-bundle ACL reconstruction: a meta-analysis

Aim

To determine through a meta-analysis of current literature whether anatomic DB reconstruction compared with anatomic SB reconstruction more effectively restores AP and rotatory laxity and leads to fewer graft failures

Study design

Meta-analysis

Study protocol

The study was conducted following the

preferred reporting items for systematic reviews and meta-analyses (PRISMA) guidelines. [156]

Patients and methods

A systematic electronic search was performed in the PubMed (MEDLINE), EMBASE and Cochrane Library databases. (See Appendix: Search string) Publication dates set for inclusion were from January 1995 to August 2011. An additional updated search was performed in July 2012 in only the PubMed (MEDLINE) database and relevant publications between August 2011 and July 2012 were included. All records were screened based on title and abstract by the first author and independently validated by a co-author, as well as the senior author. Study selection was based on pre-defined inclusion and exclusion criteria. The investigated variables were the surgical treatment of ACL injury using anatomic SB or anatomic DB reconstruction techniques. A synthesis of results was performed using meta-analysis.

Outcome measurements/data items

The data extracted from the included studies were as follows: author, year, title, journal, volume, issue, pages, ISSN, DOI, abstract, author address, database provider, category, study type, level of evidence and country. Where stated, sample size and follow-up time were noted. Surgical details regarding the technique used in each case were also obtained and included drilling technique, placement of tibial and femoral tunnels and tension patterns of the grafts used. Data regarding kinematic tests were extracted and included the pivot-shift test, Lachman test, anterior drawer test, KT-1000 measurements, AP laxity measurements using navigation and total internal-external (IRER) laxity measured using intraoperative navigation systems. No predefined concept of what constitutes a graft failure was created. The number of graft failures was extracted from the included studies if the authors explicitly used the terms “graft failure” or “graft rupture”.

Results

A total of 7,154 studies were identified of which 15 papers met the eligibility criteria and were included for meta-analysis. **(Figure 30**) Of the 15 studies included (n=970 patients), eight were randomised controlled trials (n=513 patients) and seven were prospective comparative studies (n=457 patients). The included studies were published between 2007 and 2012. Follow-up times varied, with mean follow-up times ranging from five months to five years. Ten studies reported values for the pivot-shift test. In terms of side-to-side differences in AP laxity, 10 reported values were measured using the KT-1000 arthrometer and one using the Rolimeter. Three studies reported AP laxity measured by navigation. Rotational laxity was reported in five studies using perioperative navigation. Graft failures were reported in six studies; however, only one study performed a statistical analysis of these data.

Anatomic DB reconstruction demonstrated less postoperative AP laxity measured with the KT-1000 arthrometer and with intraoperative navigation systems, compared with anatomic SB reconstruction (SMD 0.36 [95% CI, 0.21–0.51]; $p<0.001$ and SMD 0.29 [95% CI, 0.01–0.57]; $p=0.042$ respectively). Anatomic DB ACL reconstruction did not lead to significant improvements in the pivot-shift test, Lachman test, anterior drawer test, total IRER or graft failure rates compared with anatomic SB ACL reconstruction. (**Table 4**)

Conclusion

Anatomic DB reconstruction is superior to anatomic SB reconstruction in terms of

the restoration of primarily AP laxity. Anatomic DB ACL reconstruction does not appear to lead to significant improvements in terms of the pivot-shift test, Lachman test, anterior drawer test, total IRER or graft failure rates compared with anatomic SB ACL reconstruction based on a meta-analysis of current literature.

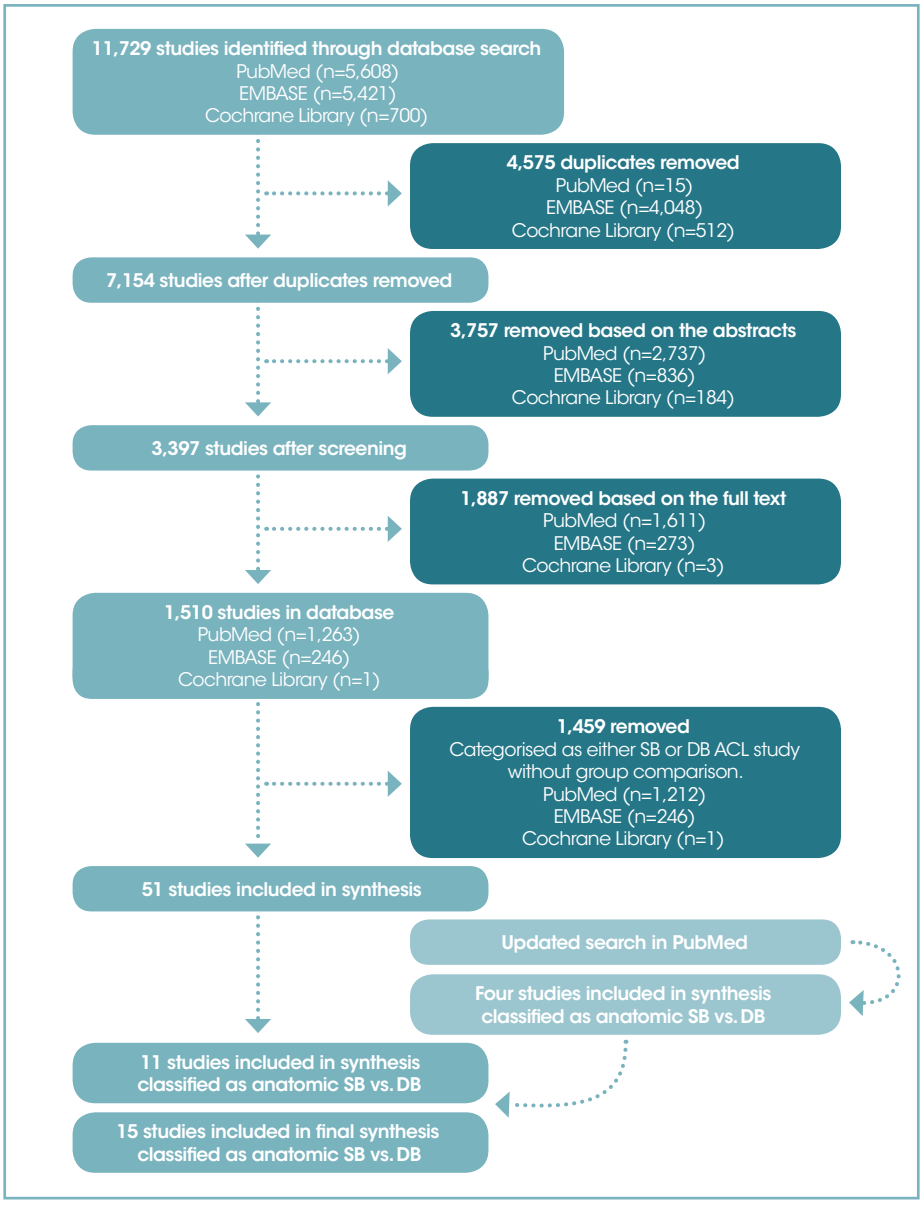


FIGURE 30

Flow chart of the selection of studies for the systematic review (Study I)

Variable	Pooled OR/SMD	95% CI	P-value	I^2 (%)
Pivot-shift	1.96	0.99-3.87	n.s.	48.9
Lachman	1.99	0.72-5.45	n.s.	0
Anterior drawer	2.05	0.41-10.24	n.s.	-
KT-1000	0.36	0.21-0.51	**(P<0.001)**	0
Total Internal-external rotation	0.27	-0.51-1.05	n.s.	89.9
Anterio-posterior –laxity	0.29	0.01-0.57	**(P=0.042)**	0
Graft failure	2.96	0.96-9.18	n.s.	0
n.s., not significant.				

TABLE 4
Results of meta-analysis.

10.2 STUDY II

A systematic review of single- versus double-bundle ACL reconstruction using the anatomic anterior cruciate ligament reconstruction scoring checklist

Aim

To apply the AARSC to current studies comparing SB and DB reconstruction in order to evaluate the reporting of surgical details and the degree to which these clinical studies fulfil the criteria for anatomic ACL reconstruction.

Study design

Systematic review

Study protocol

The study was conducted following the PRISMA guidelines.[156]

Patients and methods

A systematic electronic search was performed in the PubMed (MEDLINE), EMBASE and Cochrane Library databases. (See Appendix: Search string) The publication dates set for inclusion were from January 1995 to August 2014. An additional updated search was performed in January 2014 in only the PubMed (MEDLINE) database and relevant publications between August 2011 and July 2012 were included. All records were screened based on title and abstract by the first author and independently validated by a co-author, as well as the senior author. Study selection was based on pre-defined inclusion and exclusion criteria [184]. The investigated variables were the surgical treatment of ACL injury using SB or DB reconstruction techniques. Only studies comparing SB with DB reconstruction were included in this systematic review, regardless of graft type or fixation method. Descriptive statistics were used to summarise all the recorded data. The comparison of AARSC score depending on the level of evidence and year of publication for the SB and DB groups was performed using one-way ANOVA.

Outcome measures/data items:

the data that were obtained from the included papers were the following: author, year, title, journal, volume, issue, pages, ISSN, DOI, abstract, author address,

database provider, category, study type, level of evidence and country. In addition, the items from the AARSC were extracted for both SB and DB groups.

Results

Eight thousand nine hundred and ninety-four studies were analysed; 77 were included. (**Figure 31**) The time span of the included studies stretches from 2004 to 2014. An analysis of the study types revealed that randomised clinical trials (29; 38%) and prospective comparative studies (29; 38%) were the most frequent study type and that most studies were published in 2011 (19; 25%). The most commonly reported items for both SB and DB groups combined were; graft type (152; 99%), femoral- and tibial fixation method (149; 97% respectively), knee flexion angle during graft tensioning (124; 81%) and placement of the tibial tunnel at the tibial ACL insertion site (101; 66%). (**Table 5**)

A subgroup analysis revealed that six studies (8%) in the SB group and eight (10%) in the DB group reported placement in the femoral ACL insertion site but did not report visualisation of the insertion site itself. Twenty-two studies (29%) in the SB group and 34 (44%) in the DB group reported both the placement and visualisation of the femoral ACL insertion site.

Twenty-two studies (29%) in the SB group and 23 (30%) in the DB group reported the placement of bone tunnels within the tibial insertion site but did not document the visualisation of the insertion site. Twenty-two studies (29%) in the SB group and 34 (44%) in the DB group reported both the visualisation of the tibial ACL insertion site and the subsequent placement of the tibial bone tunnels within it.

Seventeen studies (22%) in the SB group and 24 (31%) in the DB group reported the placement of the femoral bone tunnel within the femoral ACL insertion site using TP drilling. Eleven studies (14%) in the SB group and 18 (23%) in the DB group reported the placement of the femoral bone tunnel within the femoral ACL insertion site without documenting the use of TP drilling. (**Table 6**)

Measurements of the femoral and tibial ACL insertion sites, visualisation of bony landmarks on the femur and individualisation of the ACL reconstruction were poorly reported. The highest level of documentation used for ACL tunnel position for both groups was most often one dimensional, e.g. drawing, surgical notes or o'clock reference. The DB reconstruction was generally more thoroughly reported. The means for the AARSC were 6.9 ± 2.8 for the SB group and 8.3 ± 2.8 for the DB group. Both means were below a proposed minimum score of 10 for anatomic ACL reconstruction as defined in the original publication. There were no significant differences in the AARSC score for either the SB or DB group depending on the level of evidence of the study or the year of publication.

Conclusion

A substantial underreporting of surgical data was observed in the current studies comparing SB and DB reconstruction. The mean AARSC scores were below the proposed minimum score of 10 for anatomic ACL reconstruction. This underreporting creates difficulties when comparing and pooling the results of previous studies and warrants improvements in the reporting of surgical data in future studies of ACL reconstruction. The AARSC can be used as a tool in facilitating this, as well as improving surgical techniques for anatomic ACL reconstruction.

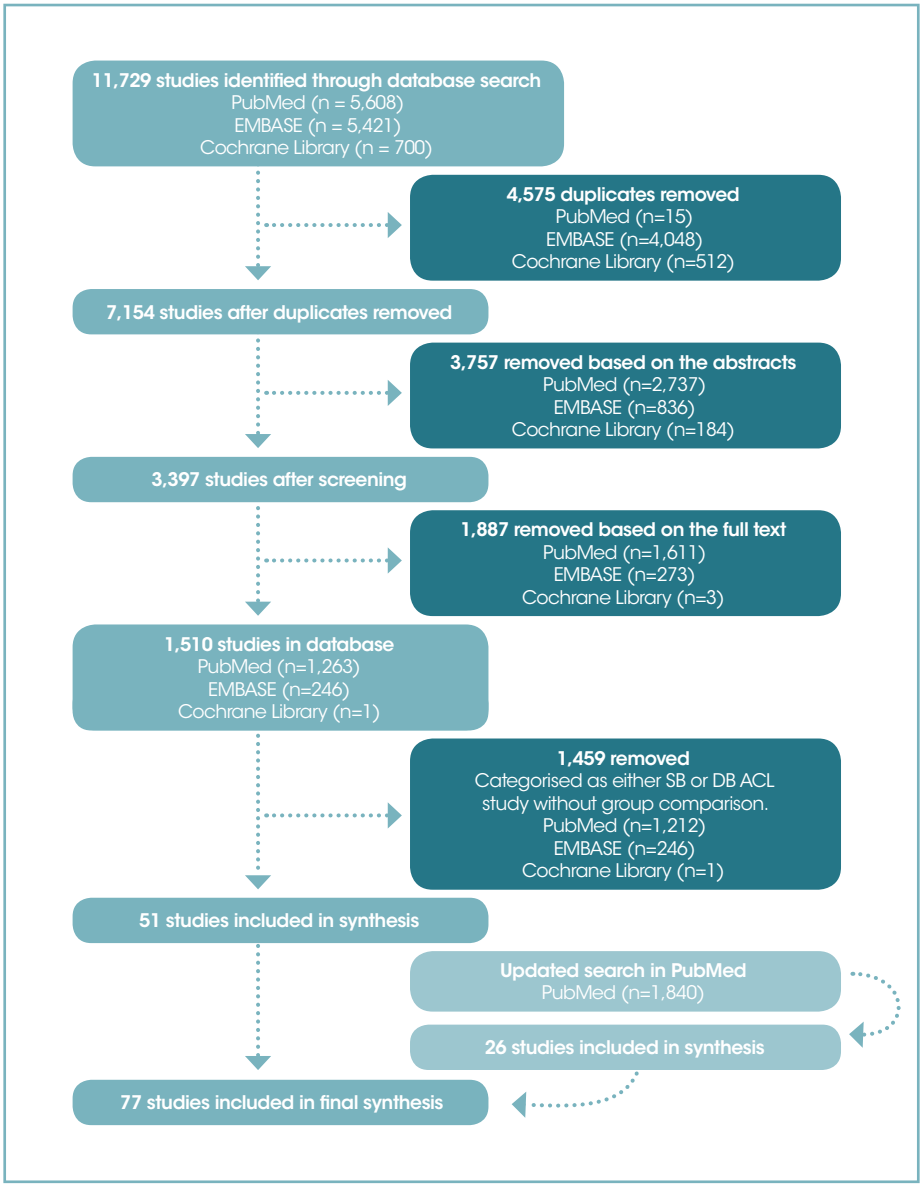


FIGURE 31

Flow diagram of the selection of studies for the systematic review (Study II).

Anatomic ACL score Items	§	Single-bundle		Double-bundle		Total	
		n	(%)	n	(%)	n	(%)
Individualisation of the surgery for each patient	1	6	8	6	8	12	8
Use of a 30-degree arthroscope	1	3	4	4	5	7	5
Use of an accessory medial portal	1	9	12	25	32	34	22
Direct visualisation of the femoral ACL insertion site	1	30	39	41	53	71	46
Measuring the femoral ACL insertion site dimensions	1	1	1	1	1	2	1
Visualising the lateral intercondylar ridge	1	6	8	10	13	16	10
Visualising the lateral bifurcate ridge	1	4	5	5	6	9	6
Placing the femoral tunnel(s) in the femoral ACL insertion site	1	28	36	42	55	70	45
Transportal drilling of the femoral ACL tunnel(s)	1	27	35	32	42	59	38
Direct visualisation of the tibial ACL insertion site	1	29	38	39	51	68	44
Measuring the tibial ACL insertion site dimensions	1	1	1	1	1	2	1
Placing the tibial tunnel(s) in the tibial ACL insertion site	1	44	57	57	74	101	66
Documenting femoral fixation method	1	74	96	75	97	149	97
Documenting tibial fixation method	1	74	96	75	97	149	97
Documenting knee flexion angle during femoral tunnel drilling	1	19	25	34	44	53	34
Documenting graft type	1	76	99	76	99	152	99
Documenting knee flexion angle during graft tensioning	1	58	75	66	86	124	81
Highest level of documentation used for ACL tunnel position *	0	45	58	39	51	84	55
Highest level of documentation used for ACL tunnel position #	1	19	25	25	32	44	29
Highest level of documentation used for ACL tunnel position ¤	2	13	17	13	17	26	17

§ = Points for each item.
* = Drawing, diagram, surgical note, dictation, or clock-face reference.
# = Arthroscopic pictures, radiographs, 2D MRI, or 2D CT.
¤ = 3D MRI, 3D CT, or navigation

TABLE 5

Items from the anatomic ACL scoring system and the frequency of the reported data.

		Placing the tunnel(s) in the ACL insertion site															
		Single-bundle								Double-bundle							
		Tibia				Femur				Tibia				Femur			
		No		Yes		No		Yes		No		Yes		No		Yes	
		n	(%)	n	(%)	n	(%)	n	(%)	n	(%)	n	(%)	n	(%)	n	(%)
Direct visualisation of the tibial ACL insertion site	No	26	34	22	29	41	53	7	9	15	19	23	30	24	31	14	18
	Yes	7	9	22	29	8	10	21	27	5	6	34	44	11	14	28	36
Direct visualisation of the femoral ACL insertion site	No	25	32	22	29	41	53	6	8	16	21	20	26	28	36	8	10
	Yes	8	10	22	29	8	10	22	29	4	5	37	48	7	9	34	44
Transportal drilling of the femoral ACL tunnel(s)	No	25	32	25	32	39	51	11	14	17	22	28	36	27	35	18	23
	Yes	8	10	19	25	10	13	17	22	3	4	29	38	8	10	24	31
Use of an accessory medial portal	No	29	38	39	51	46	60	22	29	15	19	37	48	26	34	26	34
	Yes	4	5	5	6	3	4	6	8	5	6	20	26	9	12	16	21

TABLE 6

Cross-table with frequencies calculated for placement of tunnels in insertion sites and certain surgical techniques.

10.3 STUDY III

A comparison of anatomic double- and single-bundle techniques for anterior cruciate ligament reconstruction using hamstring tendon autografts: a prospective randomised study with a five-year clinical and radiographic follow-up

Aim

To investigate whether anatomic DB reconstruction leads to a better clinical outcome at five-year follow-up compared with the anatomic SB reconstruction

Study design

Randomised controlled trial

Patients and methods:

105 patients (33 women, 72 men; median age, 27 years; range, 18-52 years) were randomised and underwent ACL reconstruction (DB group; n=53 and SB group; n=52). All reconstructions were performed anatomically, with the visualisation and placement of bone tunnels within the femoral and tibial ACL insertion sites, using the anteromedial portal for the femoral tunnel drilling and utilising interference screws for tibial and femoral fixation. One blinded observer examined the patients both preoperatively and at follow-up (median, 64 months) with multiple subjective and objective clinical evaluation tests. Radiographic assessments of OA were performed using the Ahlbäck, Kellgren-Lawrence and Fairbank grading systems at the six-week and final follow-up evaluations.

Outcome measures

The outcome measurements were PROMs (Tegner, Lysholm, KOOS), an objective evaluation of knee function (range of motion, one-leg-hop test, square-hop test), an objective evaluation of AP laxity (manual Lachman test and KT-1000) and rotational knee laxity (pivot-shift test), graft failure and radiological evidence of OA.

Results

Eighty-seven patients (83%) were available for examination at the five-year follow-up. There were no significant differences between the anatomic DB and anatomic SB reconstruction groups at five-year follow-up in terms of the pivot-shift test. Moreover, 32 patients (89%) in the SB group and 38 (84%) in the DB group had a negative (grade 0) pivot-shift test at the final follow-up (n.s.) No significant differences between the groups could be shown at the final follow-up in terms of the KT-1000 anterior MMT, KT-1000 anterior 134N or the manual Lachman test. (**Table 7**)

Significant differences could not be shown between the groups in terms of the Tegner activity level, the Lysholm knee score or KOOS at final the follow-up. Tegner activtity level at five-year follow up was significantly lower compared to pre-injury Tegner within both the SB ($p<0.001$) and DB group ($p<0.001$). Thirty-four patients (83%) in the SB group and 35 (76%) in the DB group did not reach the same or higher pre-injury Tegner activity level (n.s.). In terms of the one-leg-hop test and square-hop test, there were no significant differences between the groups at the final follow-up. (**Tables 8 & 9)**

Both groups improved significantly between the preoperative and the five-year follow-up assessments in terms of all variables, except for the range of extension (extension deficit) in the SB group (n.s.) and the range of flexion (flexion deficit) in the DB group (n.s.). Moreover, the range of flexion (flexion deficit) was significantly poorer at follow-up than preoperatively within the SB group ($p=0.03$). (**Table 9**)

The SB group showed increased OA in the lateral knee compartment according to the Ahlbäck classification six weeks postoperatively compared with the DB group ($p=0.01$). No other differences in OA were seen between the groups at six weeks or at final follow-up. Within the DB group, there was a significant increase in the development of OA between the six-week and the five-year postoperative radiographic assessments according to the Ahlbäck classification in terms of the lateral compartment, the cumulative Fairbank and the Kellgren-Lawrence classification. Correspondingly, in the SB group, a significant increase in the presence of patellofemoral osteophytes was seen. In addition, the cumulative Fairbank score at the five-year follow-up differed between the patients with and without concomitant injuries in the whole cohort, irrespective of surgical technique ($p=0.01$), and in the SB group ($p=0.046$) but not in DB group. No correlation was found between cumulative Fairbank score at five-year follow-up and BMI in either group. (**Table 10**)

During the follow-up period, no patient developed septic arthritis or underwent revision ACL reconstruction. Thirteen patients, nine in the SB group and four in the DB group, underwent second-look arthroscopic surgery (n.s). Six patients, five in the SB group (median=24, range: 18-29) and one (21 years old) in the DB group sustained a contralateral ACL injury (n.s).

Conclusion

The five-year follow-up comparing ana-

tomic DB and SB ACL reconstruction was unable to reveal significant differences in terms of AP or rotational laxity, functional and patient-reported outcomes, or radiographic evidence of OA.

		Preoperative (n=103)		Five-year follow-up (n=81)		Pre-operative SB vs DB	5-Year Follow-up SB vs DB
		SB n=50	DB n=53	SB n=36	DB n=45		
KT-1000 anterior MMT side-to-side difference (mm) **Median (range)** **Mean (SD)** **Missing values**		6.0 (0-11) 5.6 (2.7)	6.0 (-2-12) 5.4 (3.0) 1	2 (-4-8)*** 2.3 (2.7)	2 (-7-8.5)*** 2.2 (2.7)	n.s.	n.s.
KT-1000 anterior 134N side-to-side difference (mm) **Median (range)** **Mean (SD)** **Missing values**		5.0 (-1-11) 5.2 (2.4)	5.3 (-4-15) 5.2 (3.2) 1	2.3 (-4-11)*** 2.8 (3.1)	2.5 (-3-10)*** 2.6 (3.0)	n.s.	n.s.
Manual Lachman test, n (%)	**0**			18 (50%)	20 (44%)	n.s.	n.s.
	+1	1 (2%)		18 (50%)***	25 (56%)***		
	+2	44 (88%)	47 (89%)				
	+3	5 (10%)	6 (11%)				
Pivot-shift test, n (%)	**0**			32 (89%)	38 (84%)	n.s.	n.s.
	+1	1 (2%)	1 (2%)	4 (11%)***	7 (16%)***		
	+2	46 (92%)	50 (94%)				
	+3	3 (6%)	2 (4%)				

***Significant difference between preoperative and follow-up values within the group (p<0.001)

† Side-to-side difference; SB; n=36 and DB; n=45. Patients with a contralateral reconstructed/injured ACL were excluded when the side-to-side difference was analysed at the five-year follow-up.

TABLE 7

Knee laxity assessments according to the KT-1000 arthrometer, manual Lachman and pivot-shift tests preoperatively and at the five-year follow-up.†

	Preoperative (n=103)		Five-year follow-up (n=87)		Preoperative SB vs DB	5-year follow-up SB vs DB
	SB n=50	DB n=53	SB n=41	DB n=46		
KOOS pain **Median (range)** **Mean (SD)** **Missing values**	75 (14-100) 73 (16)	76 (28-100) 72 (16) 1	94 (28-100)*** 87 (19)	97 (58-100)*** 94 (9) 1	n.s.	n.s.
KOOS symptoms **Median (range)** **Mean (SD)** **Missing values**	64 (32-100) 66 (17)	64 (29-100) 64 (18) 1	90 (11-100)*** 83 (22)	93 (61-100)*** 88 (12) 1	n.s.	n.s.
KOOS ADL **Median (range)** **Mean (SD)** **Missing values**	88 (21-100) 83 (16)	89 (38-100) 81 (18) 1	100 (26-100)*** 93 (18)	100 (75-100)*** 97 (6) 1	n.s.	n.s.
KOOS sports/rec **Median (range)** **Mean (SD)** **Missing values**	40 (0-80) 40 (24)	35 (0-100) 38 (25) 1	90 (0-100)*** 75 (33)	90 (20-100)*** 83 (19) 1	n.s.	n.s.
KOOS QoL **Median (range)** **Mean (SD)** **Missing values**	25 (0-56) 28 (13)	31 (0-75) 34 (18) 1	75 (13-100)*** 69 (25)	81 (19-100)*** 79 (19) 1	n.s.	n.s.

No Significant differences could be shown between the DB and SB groups.

*** Significant difference between preoperative and follow-up values within the group ($p<0.001$).

TABLE 8

KOOS preoperatively and at the five-year follow-up.

	Preoperative (n=103)		Five-year follow-up (n=87)		Preoperative SB vs DB	5-year follow-up SB vs DB
	SB n=50	DB n=53	SB n=41	DB n=46		
Tegner activity level § **Median (range)** **Missing values**	4 (1-7)	4 (0-6) 1	6 (2-9)***	6 (3-8)***	n.s.	n.s.
Lysholm knee score (points) **Median (range)** **Missing values**	62 (9-85)	64 (19-100) 3	90 (8-100)***	91 (64-100)*** 2	n.s.	n.s.
Square-hop test total (%)† **Median (range)** **Missing values**			94 (42-143) 3	98 (72-130) 8		n.s.
Square-hop test correct (%)† **Median (range)** **Missing values**			91 (29-142) 8	97 (61-179) 14		n.s.
One-leg-hop test (%)† **Median (range)** **Missing values**	79 (0-120)	73 (0-116) 1	96 (0-134)**	90 (0-120)**	n.s.	n.s.
Extension† **Extension deficit, yes:no (% yes)** **Median (range) degrees** **Mean (SD) degrees** **Missing values**	29:20 (59%) 5 (-5 - 15) 3 (4) 1	33:19 (64%) 5 (-5 - 20) 5 (5) 1	14:22 (39%) 0 (-5 - 15) 2 (4)	18:25 (42%)* 0 (-5 - 10) 2 (4	n.s.	n.s.
Flexion† **Flexion deficit, yes:no (% yes)** **Median (range) degrees** **Mean (SD) degrees** **Missing values**	22:27 (45%) 0 (-10 - 15) 4 (6) 1	32:20 (62%) 5 (-5 - 45) 7 (10) 1	24:12 (67%)* 5 (-5 - 20) 5 (6)	28:15 (65%) 5 (-15 - 20) 5 (6) 2	n.s.	n.s.

Significant difference between preoperative and follow-up values within the group (*p<0.05, ** p<0.01, *** p<0.001).

§ Tegner activtity level at five-year follow up was significantly lower compared to the pre-injury Tegner activity level within the SB (p<0.001) and DB group (p<0.001).

† Side-to-side difference; SB; n=36 and DB; n=45. Patients with a contralateral reconstructed/injured ACL were excluded when variables involving the side-to-side difference were analysed in the five-year postoperative follow-up.

TABLE 9

The functional, objective and subjective results preoperatively and at the five-year follow-up.

		Six-week follow-up (n=103)		Five-year follow-up (n=87)		Six-week follow-up	Five-year follow-up	SB n=41	DB n=46
		SB n=50	DB n=53	SB n=41	DB n=46	SB vs DB	SB vs DB	Six-week vs Five-year	Six-week vs Five-year
Ahlbäck classification medial (grade)	0	37 (90%)	41 (87%)	35 (88%)	39 (85%)	n.s.	n.s.	n.s.	n.s.
	I	4 (10%)	6 (13%)	4 (10%)	5 (11%)				
	II			1 (3%)	2 (4%)				
	III								
	IV								
	V								
	m.v.	9	6	1					
Ahlbäck classification lateral (grade)	0	36 (88%)	47 (100%)	34 (85%)	39 (85%)	P=0.01	n.s.	n.s.	P<0.01
	I	4 (10%)		3 (8%)	7 (15%)				
	II	1 (2%)		1 (3%)					
	III			2 (5%)					
	IV								
	V								
	m.v.	9	6	1					
Cumulative Fairbank changes	0	32 (78%)	40 (85%)	25 (63%)	25 (54%)	n.s.	n.s.	n.s.	P=0.001
	1	2 (5%)	1 (2%)	3 (8%)	7 (15%)				
	2	4 (10%)	4 (9%)	5 (13%)	5 (11%)				
	3	1 (2%)	1 (2%)	3 (8%)	6 (13%)				
	4	1 (2%)	1 (2%)	1 (3%)	2 (4%)				
	5	1 (2%)		2 (5%)	1 (2%)				
	6			1 (3%)					
	m.v.	9	6	1					
Kjellgren-Lawrence classification	0	31 (78%)	41 (87%)	23 (61%)	24 (53%)	n.s.	n.s.	n.s.	P<0.001
	1	3 (8%)	1 (2%)	7 (18%)	10 (22%)				
	2	5 (13%)	5 (11%)	5 (13%)	10 (22%)				
	3			1 (3%)	1 (2%)				
	4	1 (3%)		2 (5%)					
	m.v.	10	6	3	1				
Patello-femoral osteo-phytes	None	38 (93%)	44 (96%)	30 (75%)	39 (87%)	n.s.	n.s.	P=0.01	n.s.
	Minor	3 (7%)	2 (4%)	9 (23%)	4 (9%)				
	Moderate			1 (3%)	2 (4%)				
	Large								
	m.v.	9	7	1	1				
Patello-femoral OA	None	41 (100%)	46 (100%)	40 (100%)	44 (98%)	n.s.	n.s.	n.s.	n.s.
	Minor								
	Moderate				1 (2%)				
	Severe								
	m.v.	9	7	1	1				

m.v., missing values
n.s., unable to show significant differences

TABLE 10

Radiographic evaluation of OA in the early postoperative period (6 weeks) and at the five-year follow-up.

Revision surgery in anterior cruciate ligament reconstruction - A cohort study of 17,682 patients using the Anatomic Anterior Cruciate Ligament Reconstruction Scoring Checklist applied to the Swedish National Knee Ligament Register

Aim

To apply the AARSC to the Swedish National Knee Ligament Register and on a large cohort of patients in order to describe the current preferences in terms of surgical technique used by ACL surgeons in Sweden, and evaluate whether these techniques were associated with a risk of revision ACL surgery.

Study design

Cohort study;

Patients and methods

Data were extracted from the Swedish National Knee Ligament Register between 1 January 2005 and 31 December 2014. Patients who underwent primary ACL reconstruction with a hamstring tendon were included. The follow-up started on the date of primary ACL reconstruction and ended with ACL revision surgery or on 31 December 2014, whichever occurred first. A total of 17,682 patients were included (n=10,013 males [56.6%] and 7,669 females [43.4%]). The analysed variables were patient age, patient gender and concomitant intra-articular injuries. Surgical variables were collected using an on-line questionnaire. (see Appendix: Survey) Groups were created based on the specific surgical technique used (**Table 11**). The primary study end-point was revision surgery, defined as the replacement of a primary ACL reconstruction. Survival analysis was used to assess the cumulative graft survival rates expressed as HR and 95% CI and adjusted for confounding factors using multivariate statistics.

Outcome measurements:

The primary study end-point was ACL revision surgery, defined as the replacement of a primary ACL reconstruction.

Results

A total of 108 (61.7%) surgeons completed the questionnaire. The current adoption of the individual items on the AARSC is illustrated in **Figure 32**. In terms of the highest level of documentation of graft placement, 71.3% of the respondents reported using drawings, surgical notes, dictation or clock-face reference, which yields zero points to the total score. The remaining 28.7% reported using arthroscopic pictures, plain radiographs, 2D magnetic resonance imaging (MRI) or 2D computed tomography (CT) to document this, yielding one point. None of the respondents reported using the highest level of documentation according to the AARSC (yielding two points) namely 3D MRI, 3D CT, or navigation. The mean nationwide AARSC score based on the questionnaire answers was 13.84 points (**Figure 33**). The overall crude revision rate was 3.1%. Patient sex was not associated with a risk of revision (HR 1.128 [95% CI, 0.954-1.333]; P=0.159). Younger age was associated with an increased risk of revision, and this risk decreased with increasing age. The youngest age group (13-15 years) showed the largest increase in risk of revision compared with the reference age group (36-49 years) (HR 5.259 ([95% CI, 3.532-7.833]; P<0.001). When comparing patients 13-25 years of age (n=10,042) with those 26-49 years of age (n=7,640), the

younger age group showed a 3.19-fold significantly increased risk of revision compared with the older age group (HR 3.190 [95% CI, 2.587-3.934]; P<0.001). (**Figure 34**). Cartilage injury present at index surgery was associated with a decreased risk of revision (HR 0.720 [95% CI, 0.587-0.883]; P=0.002). (**Table 12**)

Patients in the TT-non-anatomic group had the lowest risk of revision surgery compared with the TP-reference group (HR=0.694 [95% CI, 0.490-0.984]; P=0.041). In contrast, the TP-anatomic group had a higher risk of revision surgery compared with the TP-reference group (HR=1.310 [95% CI, 1.047-1.640]; P=0.018). There were no significant differences in the risk of revision surgery between the TT-anatomic and TT-partial anatomic groups compared with the TP-reference group (**Figure 35**). Visualising all landmarks was not associated with the risk of revision surgery. Transportal femoral bone tunnel drilling was associated with an increased risk of revision surgery compared with TT femoral bone tunnel drilling (HR=1.399 [95% CI, 1.163-1.682]; P<0.001) (**Table 13**) (**Figure 36**).

Conclusion

Anatomic ACL surgery, characterised by the use of several essential AARSC items, was associated with a lower risk of revision surgery compared with anatomic bone tunnel placement via TP drilling. Non-anatomic bone tunnel placement via TT drilling resulted in the lowest risk of revision surgery after ACL reconstruction.

Group	Use of an accessory medial portal	Visualisation of the femoral ACL insertion site	Visualisation of the tibial ACL insertion site	Lateral intercondylar ridge identified	Bifurcate ridge identified	Placing the femoral tunnel(s) in the femoral ACL insertion site	Placing the tibial tunnel(s) in the tibial ACL insertion site	Transportal drilling of the femoral ACL tunnel(s)
TP reference	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
TP anatomic						Yes	Yes	Yes
TT anatomic						Yes	Yes	No
TT partial-anatomic						No	Yes	No
TT non-anatomic						No	No	No
All landmarks		Yes	Yes	Yes	Yes			
No landmarks		No	No	No	No			
TP drilling								Yes
TT drilling								No

† Empty spaces are not assigned to a mandatory answer requirement. Surgeons can thus answer 'Yes' or 'No' to these items.

TABLE 11

Answer requirements characterising defined groups †.

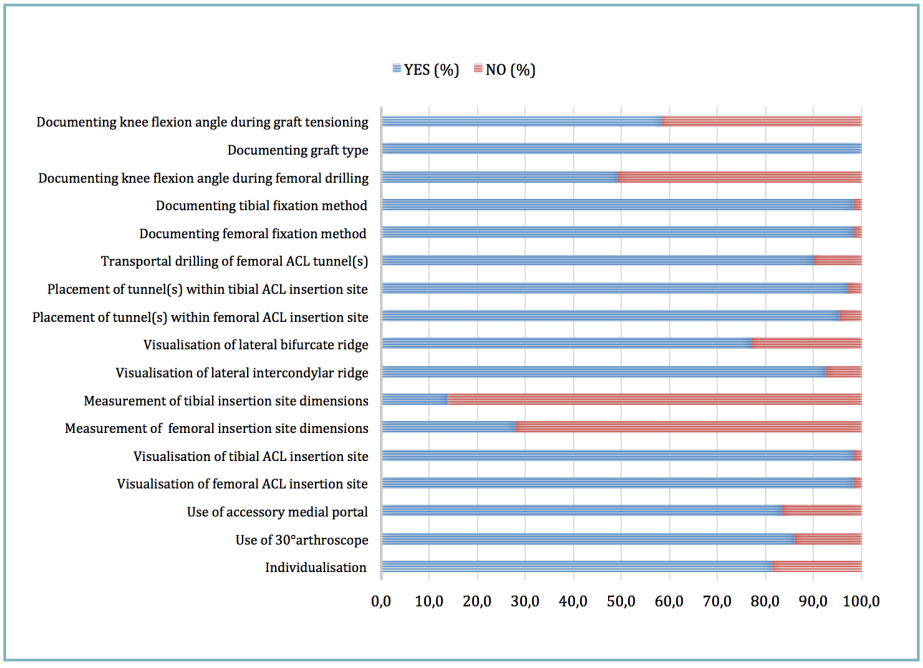


FIGURE 32

Graph showing current adoption of the individual items of the AARSC.

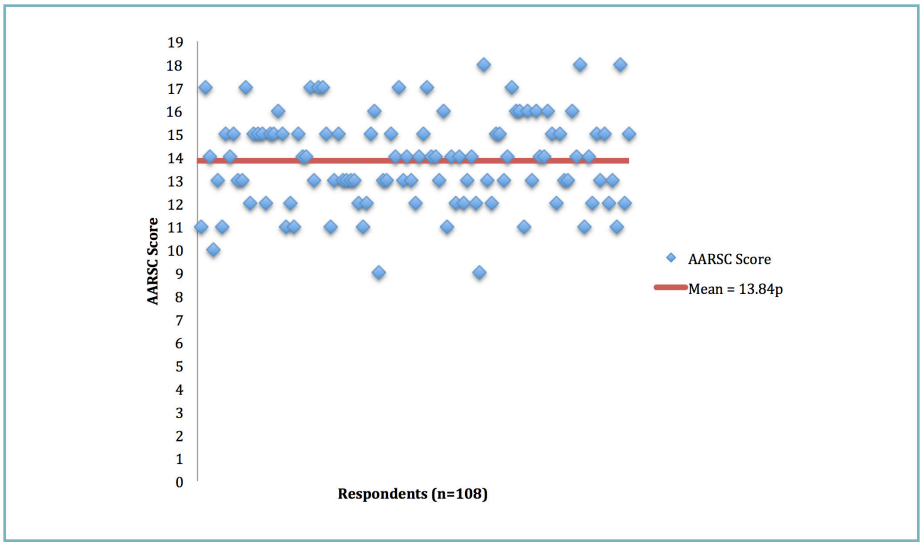


FIGURE 33

Mean AARSC score based on respondents questionnaire answers.

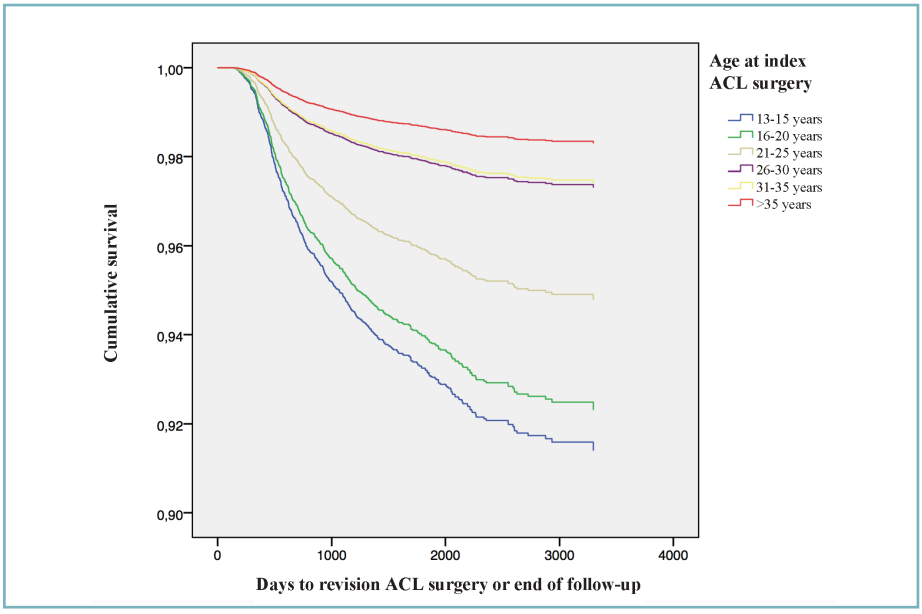


FIGURE 34

Kaplan-meier survival function of age at index surgery and revision ACL surgery.

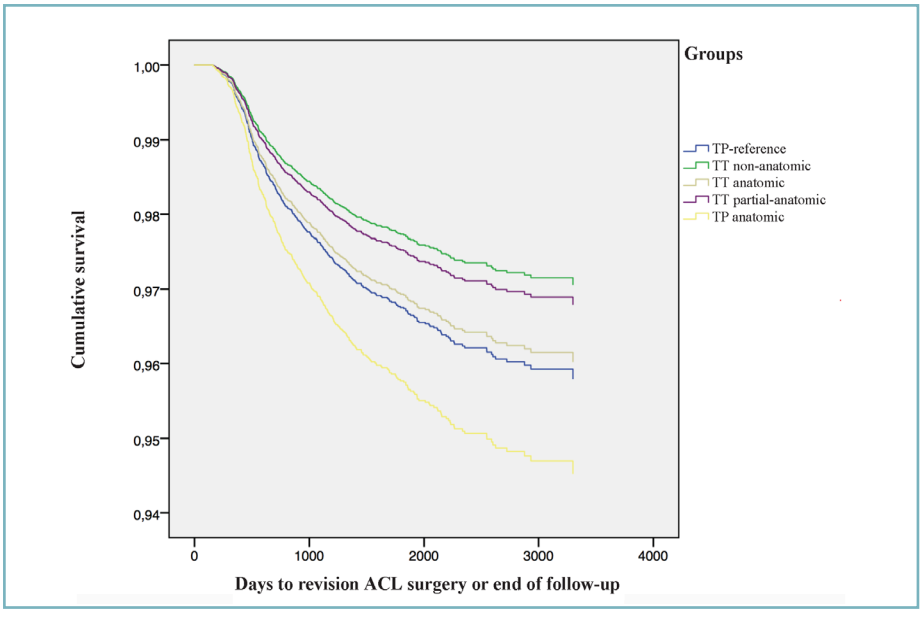


FIGURE 35

Kaplan-meier survival function of surgical technique and revision ACL surgery.

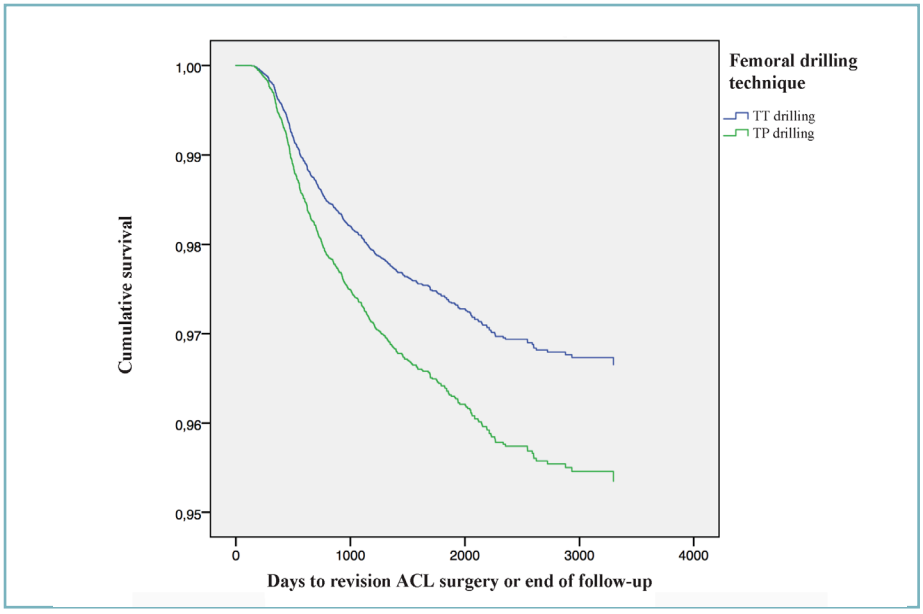


FIGURE 36

Kaplan-meier survival function of femoral drilling technique and revision ACL surgery.

		Revision cohort (n=552)				
		N	%	Hazard rate	95% CI	P-value
Patient sex	**Male §**	296	53.6	1.128	0.954-1.333	n.s
	Female	256	46.4			
Age at index ACL reconstruction	**13-15 years**	74	13.4	5.259	3.532-7.833	**<0.001**
	16-20 years	252	45.7	4.675	3.297-6.628	**<0.001**
	21-25 years	117	21.2	3.131	2.155-4.548	**<0.001**
	26-30 years	43	7.8	1.590	1.021-2.476	**0.040**
	31-35 years	30	5.4	1.527	0.941-2.479	n.s
	36-49 years §	36	6.5	-	-	-
Meniscus injury present (medial and/or lateral) at index surgery	**Yes**	238	43.1	0.994	0.840-1.176	n.s
	No §	314	56.9			
Cartilage injury present at index surgery	**Yes**	117	21.2	0.720	0.587-0.883	**0.002**
	No §	435	78.8			

§ Reference group.

TABLE 12

Patient sex, age and concomitant injury and risk of revision ACL surgery.

Group				HR			ADJUSTED HR §		
				HR	95% CI	P-value	HR	95% CI	P value
Comparison group	N of events †	Reference group	N of events †						
TT non-anatomic (n=1,296)	n=40	TP-reference (n=6,685)	n=162	0.704	0.497-0.998	**0.049**	0.694	0.490-0.984	**0.041**
TT anatomic (n=2,159)	n=77			0.942	0.717-1.239	0.671	0.944	0.718-1.241	0.679
TT partial anatomic (n=1,516)	n=48			0.723	0.522-1.001	0.050	0.759	0.548-1.051	0.097
TP anatomic (n=4,036)	n=146			1.285	1.027-1.607	**0.028**	1.310	1.047-1.640	**0.018**
All land-marks (n=9,398)	n=252	No land-marks (n=831)	n=27	1.387	0.928-2.072	0.110	1.392	0.931-2.081	0.107
TP drilling (n=12,440)	n=380	TT-Drilling (n = 5,110)	n=167	1.390	1.157-1.670	**< 0.001**	1.399	1.163-1.682	**< 0.001**

§ Multivariate Cox regression analysis adjusted for patient sex, patient age and meniscal or chondral injury.
† Event = revision ACL surgery.

TABLE 13

Surgical technique and risk of revision ACL surgery.

11 Discussion

11.1 ANATOMIC ACL RECONSTRUCTION

The last decade has seen an evolution in the surgical technique involved in ACL reconstruction from one in which the objectives were "isometric" tunnel placement and the avoidance of intercondylar notch roof impingement, towards a more anatomically correct reconstructive technique referred to more commonly today as "anatomic" ACL reconstruction. It is important to remember that anatomic ACL reconstruction is a concept as opposed to a specific surgical procedure. Interestingly, early open techniques achieved this to some extent by emphasising the importance of visualising the ACL insertion sites and the subsequent placement of tunnels therein.[185, 186]

The emergence (or re-emergence) of the concept of anatomic ACL reconstruction has shed light on the scope of heterogeneity in the studies that make up much of what we regard as being the foundation of our current understanding of ACL surgery and its techniques. There has been much interest in graft selection, fixation methods and rehabilitation protocols, to some extent overlooking the possible influence of the non-anatomic surgical technique adopted when comparing these studies and/or pooling their results.

11.1.1 Anatomic Anterior Cruciate Ligament Reconstruction Scoring Checklist

Many researchers have claimed that they have adopted anatomic ACL reconstruction techniques. However, two previous systematic reviews indicated that, when outlining the specifics of their anatomic ACL reconstruction, the authors often provided only limited information. Moreover, variations in anatomic techniques were found.[162, 187] To further evaluate the possible benefit of performing anatomic reconstruction and to be better equipped when comparing studies, it is important to use standardised, thoroughly evaluated criteria for what constitutes anatomic ACL reconstruction. The development and validation of the AARSC provides a list of these criteria and it is a tool that can not only be used in the preoperative planning phase but which also allows for the grading of ACL reconstruction procedures in individual patients, for reviews of the documentation of surgical techniques in published studies claiming anatomic ACL reconstructions, and for peer reviews of scientific manuscripts.[161]

11.1.2 Reporting of surgical data

In **Study II** we applied the AARSC to the results of a systematic review of the literature on clinical studies comparing SB and DB ACL reconstructions. The results were in line with the aforementioned systematic reviews in that there was a substantial underreporting of pertinent surgical data with AARSC means for both groups; well below the proposed minimum score of 10 points. As tunnel placement within the native ACL insertion sites on the tibia and femur is a central principle of the anatomic reconstruction, it was of particular interest to note the reporting of this specific detail. The majority of authors in both the SB group and the DB group reported placement of the tibial tunnel(s) at the insertion site for the native ACL. However, far fewer of them claimed visualisation of the insertion site. Only 29% in the SB group and 44% in the DB group reported both visualisation and anatomical placement on the tibial and femoral insertion site. Similarly, pertinent bony landmarks like the lateral intercondylar ridge and the lateral bifurcate ridge were reported to have been visualised in only 6-10% of studies. These landmarks are present in both sub-acute and chronic cases. Moreover, the lateral bifurcate ridge marks the border between the AM and PL bundles. Therefore, the latter can be therefore regarded as a vital aid in the placement of the tunnels in DB reconstruction.

Interestingly, 29% of authors in the SB group and 30% of authors in the DB group

claim placement in the tibial insertion site without documenting the visualisation of the insertion site. Correspondingly on the femoral side, 8% in the SB and 10% in the DB group claim placement within the insertion site without documenting the fact that they visualised the insertion site. This clearly illustrates the discrepancy between claimed anatomic tunnel placements and insertion site visualisation in the current literature. The question of whether anatomic placement of the femoral bone tunnel(s) is possible using TT drilling has been disputed.[80, 81, 188-190] Only 22% in the SB group and 31% in the DB group claim placement of femoral bone tunnel within the femoral ACL insertion site using TP drilling. Eleven studies (14%) in the SB group and 18 (23%) in the DB group claim placement of femoral bone tunnels within the femoral ACL insertion site without documenting the use of TP drilling. These findings raise certain questions as to the feasibility of in fact placing the bone tunnels within the femoral insertion site and warrants caution when reading these studies and drawing conclusions from their results.

It is noteworthy that the absent reporting of an item of the AARSC may not necessarily be synonymous with the absent implementation of that particular item. Nonetheless, this discrepancy raises certain questions when interpreting the results of these individual studies. With apparent gaps in important information on surgical detail, are we guaranteed that a sound surgical technique was utilised, in accordance with the principles of anatomic reconstruction? Can we be sure of the surgeons' tunnel placement despite inadequate visualisation? Moreover, with such (possible) heterogeneity between these studies, are their results comparable and can we reproduce or extrapolate these results to form the basis for future guidelines? Clearly, there is a need to recognise these obvious limitations when interpreting and pooling their results. Moreover, it is of interest to see that the mean AARSC scores for SB and DB groups were 6.9 and 8.3 respectively. Considering that the proposed minimum score in order to regard the reconstruction as being *anatomic* is 10 points, both groups clearly fall short of this. Of the 77 studies included in the review upon which the AARSC was implemented, 18 in the SB group and 28 in the DB group had scores of 10 points or greater. This illustrates that data are more thoroughly reported when describing the DB procedure, possibly a consequence of increased interest and focus on anatomic landmarks, insertions sites and technical details of the surgical procedure that have come hand in hand with the emergence of the relatively novel DB technique. It is difficult to say whether these mean AARSC values in fact reflect a more anatomic reconstruction in the DB group as they primarily refer to reported data in studies. It does, however, point to a promising trend where we hope in the future to see the development and establishment of standardised anatomic ACL reconstruction techniques, as well as standardised and applicable tools that can be used to compare studies on this subject. As a future application, the AARSC can prove to be a valuable instrument in this respect.

11.1.3 The AARSC and the Swedish National Knee Ligament Register

In **Study IV**, the AARSC was introduced for the first time into a clinical setting and was implemented at a national level in the form of an on-line questionnaire. The items

of the checklist were translated into Swedish and distributed to all surgeons registered in the Swedish National Knee Ligament Register in part to gauge the level of current adoption of anatomic techniques among ACL surgeons. A mean AARSC score of 13.84 points was obtained. Only two of the 108 respondents to the questionnaire had a mean AARSC score of < 10 points. Considering the proposed minimum of 10 points, this result points to a promising adoption of more anatomic techniques by Swedish ACL surgeons. The two least utilised items of the checklist were measurement of the tibial and femoral ACL insertion sites. Interestingly, when comparing these findings with those in **Study II**, we found that these same two items were the two least reported items in the current literature comparing SB and DB reconstruction. In addition, the results from **Study IV** showed that more than 98% of respondents claimed that they visualised the tibial insertion site and as many claimed that they visualised the femoral insertion site as part of their current ACL reconstruction technique. This is considerably more than that what was reported in the current literature summarised in **Study II** (44% and 46% for respectively). Similarly, 95.4% of the respondents to the questionnaire in **Study IV** claimed that they placed their tunnels within the tibial insertion site and 97.2% within the femoral insertion site. This too, is considerably higher than the corresponding values reported in **Study II** (66% and 45% for SB and DB respectively). It must be mentioned, however, that the time span of the studies included in **Study II** stretched from 2004-2014, with almost half the studies being published prior to 2011. The differences we have observed between the studies could possibly be explained by the fact that anatomic ACL reconstruction is currently a more established concept in the field of ACL reconstruction and that in fact, at least in Sweden, surgeons are adopting more anatomic techniques.

11.2 ANATOMIC SINGLE- VS. DOUBLE-BUNDLE ACL RECONSTRUCTION

There is support in the literature for the claim that anatomic graft placement within the native ACL insertion sites compared with non-anatomic ACL graft placement is more effective at controlling anterior tibial translation and rotational laxity, and more closely reproduces normal knee kinematics. [79, 95-101] There is also evidence supporting the fact that anatomic bone tunnel placement is more effectively facilitated using independent drilling as opposed to TT drilling.[80, 81, 188-190] In keeping with the concept of anatomic ACL reconstruction, it may seem appealing to reconstruct the ACL with two bundles instead of only one. The DB procedure is, however, more technically challenging, entails a considerable learning curve, places increased demands on the surgeon's technical ability and results in potentially more invasive revision procedures as well as higher costs. There are a number of studies comparing the two techniques, with conflicting results in terms of objective and subjective outcomes, as well as the development of osteoarthritis. This calls into question whether the potential long-term benefits outweigh the increased surgical complexity of the procedure.

It is, however, noteworthy that the comparability of many of the studies comparing the SB and DB techniques can be questioned as they display large-scale heterogeneity in

both their reporting and implementation of surgical technique with regard to drilling techniques and adoption of non-anatomic/anatomic tunnel placements for example. In other words, it is hardly possible simply to compare SB and DB reconstructions, as this yields a heterogeneous sample upon which to draw conclusions.

11.2.1 AP laxity

The restoration of AP laxity is one of the primary goals of ACL reconstruction. The manual Lachman test has historically been the most commonly utilised manual test for suspected ACL injury as well as post-operative laxity, mainly due to its ease of use, reproducibility and high sensitivity. The subjective nature of the test limits it somewhat however, and this has led to an increase in the use of instrumented tests of AP laxity, using the KT-1000 arthrometer, for example, providing a standardised non-invasive test, easily applicable to the clinical setting. In **Study I**, we performed an extensive review of the literature, and subsequent meta-analysis of gathered data, paying specific attention to the inclusion of studies specifically comparing *anatomic* SB and *anatomic* DB ACL reconstructions. This yielded 15 studies. The meta-analysis revealed that anatomic DB reconstruction was superior to anatomic SB when it came to the restoration of anterior translation as measured by instrumented laxity tests namely the KT-1000 and navigation. Load distribution across two separate grafts in a larger portion of the knees range of motion of the knee, instead of only one, in addition to increased insertion site coverage, could potentially be advantageous in terms of graft incorporation, maturation, possibly explaining our findings of anatomic DB superiority over SB in terms of restoration of anterior laxity. It is also plausible that these results represent a graft elongation in the SB reconstructions, as a result of non-anatomic load distribution across the graft, that is not present in the DB reconstructed grafts, reflected in the DB superiority over SB in terms of restoration of anterior laxity. The observed difference in anterior laxity between SB and DB ACL reconstructions in the included studies ranged from 0.1 to 1.3 mm. This may be of questionable clinical relevance, as such small improvements may not immediately influence the short-term results. However, it is noteworthy that the KT-1000 is a static laxity measurement that does not account for AP translation possibly in combination with rotatory loads, during true functional loading. As a result, even small changes such as these may impact overall knee homeostasis and kinematics and influence outcome in the long-term perspective, with subsequent deleterious effects on cartilage and menisci, and should thus not be neglected.[191]. In their *in vitro* study, Yagi *et al.* showed that DB grafts displayed significantly higher *in situ* forces compared with SB grafts under 134N anterior tibial loading, more closely resembling native ACL *in situ* forces under the same conditions, possible further explaining our results.[192] A number of recent systematic reviews and meta-analyses reveal results similar to ours, with superior KT-1000 arthrometry data for DB as compared with SB ACL reconstruction.[120, 121, 193-196] Only one study, however, drew a distinction between anatomic and non-anatomic techniques when including their studies for analysis.[197] In **Study III**, we were unable to demonstrate significant differences between the DB and SB groups in terms of manual or instrumented

laxity tests for anterior laxity (Lachman and KT-1000 respectively), but significant improvements were observed within the groups when comparing pre-operative values with those at the final follow-up. Similar results have been found in previous studies comparing anatomic SB with anatomic DB reconstruction.[119, 173, 198-203] There is a possibility that these results reflect the importance of utilising anatomic techniques and anatomic bone tunnel placement, as opposed to the number of bundles used.[204, 205]

11.2.2 Rotatory laxity

The recent development and implementation of the concept of anatomic ACL reconstruction and the DB technique has also led to an increased interest in evaluating rotatory laxity as an outcome measurement following ACL reconstruction. The pivot-shift test has been the method of choice for evaluating rotatory laxity in a clinical setting. The ultimate goal of anatomic ACL reconstruction in terms of rotatory laxity is to eliminate the pivot-shift phenomenon. In **Study I**, no statistically significant differences after meta-analysis of 15 studies comparing anatomic SB with DB were seen in terms of instrumented or manual tests of rotational laxity. Ten studies reported values for the pivot-shift test, two of which found a significant difference between the groups in favour of DB. In terms of absolute values when pooling pivot-shift results from the 10 studies for SB (n=284) and DB (n=374), a total of 325 (87%) patients in the DB group had a negative pivot-shift test as opposed to 210 (74%) in the SB group. It is, however, difficult to draw conclusions from this. One possible influential factor is the notion of a learning curve in anatomic ACL reconstruction, and more importantly, DB reconstruction. If such a difference in learning curves exists between SB and DB, the included studies may not have "captured" a possible true difference in outcome between the anatomic SB and DB techniques, if such differences do in fact exist. In addition, it is important to remember that the pivot-shift test exhibits moderate levels of inter- and intra-observer reliability, as a result of its subjective interpretation compounded by heterogeneity in execution, making it a somewhat blunt test of rotational laxity.[43] Only two of the six included studies that used navigation to measure rotatory laxity reported significant differences between the SB and DB groups, both in favour of the DB group. Meredick *et al.* reported findings similar to ours in their meta-analysis, finding no significant difference in pivot-shift testing between SB and DB groups.[120] One limitation to their findings is, however, that they drew no distinction between anatomic and non-anatomic reconstruction techniques.

Five recent meta-analyses have found that DB reconstruction has superior pivot-shift results compared with SB reconstruction.[121, 193-195, 206] Again, no clear distinction was made between anatomic and non-anatomic techniques.

A meta-analysis performed by van Eck *et al.*[197] analysed seven studies they classified as anatomic SB versus anatomic DB reconstruction (there was, however, a discrepancy with regard to four studies classified as anatomic by van Eck *et al.* that we chose to classify as non-anatomic). Their sub-group analysis comparing these

anatomic groups revealed significant differences in favour of DB reconstruction in the restoration of both rotational laxity using the pivot-shift test and anterior laxity measured with KT-1000 arthrometry. The discrepancy in our results regarding rotatory laxity may be explained by our stringent inclusion criteria, which entailed only including anatomic reconstructions in our analysis. In addition, van Eck *et al*. performed a sub-group analysis on non-anatomic SB and DB reconstructions that revealed no significant differences in laxity measurements between the two groups. This raises the question of whether it is the adherence to the concepts of anatomic reconstruction that is the key, rather than the number of bundles used.

In **Study III**, patients randomised to either anatomic SB or anatomic DB ACL reconstruction were evaluated five years postoperatively. Eighty-nine percent of patients in the SB group and 84% in the DB group had a negative (grade 0) pivot-shift test at follow-up (n.s). These findings are corroborated by previous studies.[119, 173, 198-203, 207] Hussein *et al*. compared anatomic DB reconstruction with anatomic SB and conventional TT SB and found that anatomic DB was significantly superior to all other groups in terms of the restoration of rotatory laxity as measured by the pivot-shift test. They also reported that anatomic SB was superior to conventional transtibial SB in this same respect.[117] Again, this illustrates a possibility that these results reflect the importance of the anatomic ACL reconstruction performed as opposed to the number of bundles used *per se*.

There is conflicting evidence in the current literature regarding the possible benefit of DB reconstruction in the restoration of rotatory laxity measured by the pivot-shift test. The results from Studies **I and III** were unable to confirm this benefit. Having said that, there are few high-quality randomised studies specifically comparing anatomic SB with anatomic DB reconstructions and even fewer with long-term follow-up. In addition, it must, however, be remembered that a dynamic rotational laxity test such as the pivot-shift test represents joint behaviour in the extremes of knee rotation, outside the knee envelope of laxity, and may not be fully representative of the rotational laxity experienced, even in the injured or reconstructed knee during dynamic motion. In addition, as previously mentioned, morphology, generalised ligamentous laxity and injury patterns/ partial ligament injury influence the value of most, if not all, rotatory knee laxity tests and this must be taken into consideration.

11.2.3 Osteoarthritis

In **Study III**, the SB group showed increased OA in the lateral knee compartment according to the Ahlbäck classification six weeks postoperatively compared with the DB group (p=0.01). The clinical significance of these findings, however, is questionable. These findings probably represent osteoarthritic changes present prior to the ACL reconstruction, possibly even from injuries sustained prior to the ACL injury itself. Whether the patients in the SB group had more chondral and/or meniscal injuries specifically in the lateral compartment at index surgery, compared with the DB group, is not known. In addition, no significant differences were observed between the groups six weeks postoperatively using the Fairbank or Kellgren-Lawrence

classifications, or at the five-year follow-up using the Ahlbäck classification, further calling into question the relevance of this finding.

A subgroup analysis of patients in **Study III** exhibiting concomitant injuries to cartilage and/or menisci (i.e. SB and DB pooled), revealed that the cumulative Fairbank score was significantly worse at the five-year follow-up compared with early-postoperatively both when pooling SB and DB patients (P = 0.01) and in the SB group alone (P = 0.046). Interestingly, however, no significant increase in the Fairbank score was seen for the DB group with concomitant injuries at the five-year follow-up (n.s). This raises the interesting questions in terms of the protective effects, seen as early as five years postoperatively, of anatomic DB reconstruction on the progression of OA in knees following ACL reconstruction in the setting of all too common concomitant injuries. Care must be taken in drawing conclusions from these findings, however, as logistical and technical difficulties resulted in a number of missing values in the interpretation of the plain radiographs both at the six-week and five-year follow-up. In addition, the Fairbank classification has been criticised for overestimating the presence of knee OA.[208] A significant increase in the presence of patellofemoral osteophytes in the SB group at follow-up was found. In line with this, *in vitro* studies examining tibiofemoral and patellofemoral contact areas and contact pressure have shown that anatomic DB reconstruction more closely re-establishes these to the normal state resembling a native uninjured ACL than did SB ACL reconstruction does.[209, 210] Despite the inherent limitations of *in vitro* studies, these findings shed light on an intriguing thought that DB reconstruction may in fact, in the long term at least, protect the knee from subtle residual kinematic and biomechanical changes that ACL injury and subsequent reconstruction entail and possibly more effectively hinder the development of OA.

11.2.4 Subjective and functional outcomes

In **Study III**, significant differences could not be demonstrated between the groups in terms of Tegner activity level, Lysholm knee score, or KOOS. The current evidence relating to subjective outcomes after ACL reconstruction is conflicting. One recent systematic review of nine overlapping meta-analyses comparing SB and DB ACL reconstruction found higher IKDC subjective scores favouring DB as compared with SB ACL reconstruction reported in one meta-analysis, whereas four meta-analyses found no difference between SB and DB groups. None of the nine included meta-analyses found significant differences in the Tegner or Lysholm scores between the DB and SB groups. The results of the present study indicate, despite significant improvements within each group at follow-up, that there was generally a low return to pre-injury Tegner scores; however, the study was not able to demonstrate significant differences between groups at follow-up.[211]

Focusing on the KOOS, despite being validated for ACL injuries [178], there are potential limitations to its use in the short and mid-term follow-up after ACL reconstruction. These limitations may originate from the very manner in which the KOOS was devised, namely that it was modelled upon the WOMAC, primarily an instrument used to capture symptoms

of OA. Recent studies have suggested that the KOOS subscales, "Function in Sports and Recreation" (Sport/Rec) and "Knee-Related Quality of Life" (QoL), are perhaps more relevant to subjective outcome after ACL reconstruction [212], as the other three KOOS sub-scales may be more sensitive to symptoms of OA, the subjective symptoms of which may not be immediately apparent to the patient in the short or mid-term. There is now an adapted version of the KOOS called the $KOOS_4$ in which the ADL subscale is eliminated and an average score for the remaining four KOOS subscales is calculated. This is done to avoid potential ceiling effects, as many patients undergoing ACL reconstruction are relatively young and may not experience difficulties pertaining to ADL. Tanner *et al*. found, when comparing the IKDC to the KOOS, that the IKDC contained more items that patients regarded as important and relevant in capturing their symptoms after ACL injury.[213] Interestingly, despite not revealing any significant differences in the KOOS at the five-year follow-up between the SB and DB groups in **Study III**, the largest improvements in the mean KOOS score compared with preoperative values were seen in the KOOS subscales of "Function in Sports and Recreation" (Sport/Rec) and "Knee-Related Quality of Life" (QoL) in both groups. This further illustrates the potential value of these two subscales in particular in gauging mid-term subjective outcomes following ACL reconstruction. In addition, it highlights the need for the long-term follow-up of these two groups.

Using PROM's such as the KOOS to determine the "success" of ACL reconstruction is challenging and the results vary in the current literature. Frobell *et al*. define treatment failure after ACL reconstruction as a KOOS (QoL) subscale value of < 44 points.[214] Barenius *et al*.[215] define the rates of functional recovery as KOOS scores ranging from 81 to 91, corresponding to the lower threshold of the 95% CI of the Swedish reference population for the score,[216] and treatment failure as a KOOS of < 44 points. In a recent consensus report, Lynch *et al*. [217] propose PROM threshold scores between 85 and 90 (scale 0-100) as a successful outcome after ACL reconstruction. In addition, a recently published report from the Norwegian Knee Ligament Register showed that the risk of later revision was 3.7 times (95% CI 2.2–6.0) higher in patients with a two-year postoperative KOOS QoL of < 44 compared with patients with a KOOS QoL of > 44.[218] Other ACL reconstruction registers have reported mean scores of 60 to 69 for QoL one to two years after ACL reconstruction,[219] and the MOON cohort reported median scores of 75 for QoL two and six years after ACL reconstruction.[220] These values are somewhat lower than the previously proposed cut-off points for "successful" ACL suggested by Lynch *et al* and Barenius *et al*. Caution is warranted when using success as a term and assigning a KOOS score accordingly. It must be remembered that all PROM's are subjective, hence it may be better to observe relative improvements rather than absolute values.

Seven patients in the SB group (17%) and 11 (24%) in the DB group, (n.s), returned to the same or a higher Tegner activity level compared with their pre-injury level at the five-year follow-up. The relatively low return to pre-injury activity level is not immediately apparent. The long time interval between injury and reconstruction in both may have played a role in this, possibly a consequence of the national health-care routines at the time, where a period of physiotherapy and non-surgical treatment

was considered first, prior to a decision to perform ACL reconstruction being made. An increased period between injury and reconstruction has been seen to correlate to increased findings of concomitant injuries to menisci and cartilage [221-224], as well as lower activity levels,[225] possibly also explaining both the concomitant meniscal and cartilage injuries seen in both groups in the present study and the generally low return to activity. Relatively high pre-injury Tegner levels were seen with median values of 8 in both groups and 6 in both groups at five-year follow-up, which could also explain the low postoperative return to those same levels. It is, however, difficult however to draw conclusions about the effect the specific surgical technique *per se* had on postoperatively achieved activity levels. A previous literature review reported that 56% of patients who underwent ACL reconstruction returned to their pre-injury level of sports activity. This was despite a larger proportion of the patients achieving satisfactory clinical functional test outcomes (single-leg hop, isokinetic muscle strength for example), illustrating the impact of concomitant psychological factors on ACL reconstruction outcome.[226, 227] In a recent systematic review and meta-analysis of 48 studies which evaluated return to sport after ACL reconstruction, 82% of the 5,770 patients returned to same level of sports participation: 63% returned to their pre-injury level of participation and 44% returned to competitive sport at follow-up. Interestingly, the same review revealed that studies published after 2000 were found to have a significantly higher rate of return to competitive sport (56%) when compared with studies published prior to 2000 (44%) possibly explained by advances in surgical technique and rehabilitation protocols.[228] It is equally important to note that the reasons for reduced activity level postoperatively may be unrelated to knee function and that both objective- and subjective factors are undoubtedly involved. Individual patient expectations and motivation to participate in rehabilitation and compliance, in addition to the surgical technique used, are all factors that can affect the subjective postoperative results. [229, 230]

No significant differences were found between the SB and DB groups in **Study III** in terms of the hop tests or in knee ROM. A residual ROM deficit was, however, seen in both the SB (extension deficit) and DB (flexion deficit) groups at follow-up. The current evidence on ROM, expressed as an extension or flexion deficit after SB or DB ACL reconstruction, is conflicting. Araki *et al.* reported no significant differences in manual knee extension with heel height difference, knee flexion and extension muscle peak torque at 60° between anatomic SB and DB ACL reconstructions. [198] Li *et al.* reported results in support of the findings in **Study III** in their comprehensive meta-analysis where extension deficits were less common in the DB groups.[196] In contrast, Tiamklang *et al.*, as well as van Eck *et al.*, reported no differences between groups in terms of ROM. [121, 197] However, the loss of motion in both groups in the present study was small and, despite being statistically significant, was perhaps clinically not important. This suggests that there is usually good post-operative range of motion in the knee joint, but occasionally, there may be a deficit in terminal range of motion in both flexion and extension.

Current concerns about the DB procedure include the technical demands of the procedure itself in creating more than two tunnels, the potential for tunnel expansion and blow-out between them, the potential for increased difficulty in DB

revision cases and whether the studies demonstrating "significantly" improved restoration of rotational laxity are in fact mirrored by improved clinical outcomes in the long term. Naturally, these concerns are not unfounded and must be addressed when individualising the procedure to each patient. As previously mentioned, much of the available literature comparing SB and DB ACL reconstructions, specifically anatomic techniques, consists of short and, at best, mid-term follow-up, illustrating the need for further high-quality studies with long-term follow-up.

11.3 GRAFT FAILURE AND REVISION

11.3.1 Graft-failure

Failed ACL reconstruction and subsequent revision for whatever reason can often entail a considerable investment of time, effort, rehabilitation and emotional distress for the patient, in addition to the complexity and inherent costs of multiple surgeries for the healthcare system. Moreover, there is support in the literature to indicate that the postoperative results after revision ACL reconstruction are inferior to those of primary ACL reconstruction.[231-233] It is important to note, however, that the definition of failure in the literature varies, ranging from manifest, often traumatic graft re-rupture, biological failure relating to graft incorporation and residual postoperative laxity with poor PROMs to septic complications resulting in revision, to name a few. Another important aspect to consider is where the distinction lies between a graft failure and simply classifying it as a "re-injury". Naturally, this is dependent on several factors, such as postoperative time span, achieved Tegner level, and, again, how one defines "failure". Much of the current literature on modes of failure after ACL reconstruction predates the recent shift in interest in performing anatomic ACL reconstruction. For this reason it is worth considering the failure of anatomic ACL reconstruction as a separate entity.

11.3.2 Single- and double-bundle ACL reconstruction

In **Study I**, a total of six studies reported on graft failure when comparing anatomic SB (n=171 patients) with anatomic DB (n=207 patients) reconstructions. A total of 13 failures were reported in the SB group, while there were four in the DB group (OR 2.96 [95% CI, 0.96-9.18] p = 0.06). Follow-up ranged from 13-60 months. In the study with the longest follow-up of five years, a total of seven failures in the SB group (33%) and one in the DB group (5%) were reported (P=0.043).[201] The graft ruptures in the SB groups were all caused by a "minor accident", while the single rupture in the DB group was due to a major trauma with bone fractures. All these failures occurred during the early years of the study, which began in 2003. The authors reported appropriate bone tunnel placement seen at revision surgery, without the need to replace them. These details make the interpretation of these results in relation to the surgical technique and comparisons between the SB and DG groups challenging. It is possible that the trauma the patients experienced would have led to a graft fail-

ure, regardless of whether the patients had a SB or DB reconstruction. Remembering that these surgeries were performed during a period when the concept of both "anatomic" and DB ACL reconstruction was novel, it is also possible that an inherent learning curve was involved and that even SB techniques improved as interest in, and the implementation of, DB techniques increased. It must be remembered that the acceptance of new procedures is based on their believed value relative to previously accepted ones, and, that this process can be influenced by the individuals undertaking the study, reporting the results and by their selection of patients for treatment. With the introduction of "new" treatments and techniques, there is therefore always the inherent risk of (positive outcome) publication bias.

Naturally, the significant difference in observed failure rates between the groups could reflect the fact that the DB reconstructions were able more effectively to withstand potentially deleterious loads compared with the SB reconstructions, resulting in fewer failures. The relatively high failure rate in these patients may have been caused by the early return to pivoting sports at six months. In the other five studies reporting on graft failure, values of 11%, 8.6% and 3% failures were reported in the SB groups and 2.8%, 2.8% and 1.4% for DB groups.[119, 199, 207, 234, 235] The crude failure rates observed between these groups indicate lower failure rates with anatomic DB reconstruction, but without demonstrable statistical significance. The current evidence indicates comparable graft-failure rates for SB and DB reconstruction.[121, 193, 194, 211, 236-239]. The stringent inclusion criteria implemented in the meta-analysis yielded relatively few studies comparing the anatomic SB and DB techniques, limiting current data upon which to perform a meta-analysis. This could in part explain the lack of a statistically significant difference in failure rates. In addition, the potential under-powering of the included studies, and a subsequent risk of type-II errors, must be considered in all these studies.

In **Study III**, no patients required revision ACL reconstruction during the five-year follow-up. This could be explained by the implementation of anatomic ACL reconstruction techniques with adequate restoration of the ACL and its properties as a ligamentous restraint. Seven patients in the SB group (17%) and 11 (24%) in the DB group ($p=0.43$), returned to the same or a higher Tegner activity level compared with to their pre-injury level at the five-year follow-up. These values are somewhat low for both groups and could also possibly explain the low failure rate, as a reduced activity level may act as a graft-protective measure in these patients. Graft integrity in the patients in **Study III** was, however, only verified by objective clinical tests and not MRI, which would have been desirable but was alas not possible within the scope of the study. There is therefore a possibility that cases of graft failure went un-diagnosed as a result of this, possibly explaining the low failure rate.

Although there was no statistically significant difference between the SB and DB groups in **Studies I and III** in terms of graft failure, the question arises of whether these are still clinically relevant findings, highlighting the need to analyse larger samples of anatomic reconstructions ensuring adequate power, as well as the need for long-term follow-up.

11.3.3 Revision

Establishing the true rate of graft failure is challenging and it must be assumed that the true rate of failed grafts is higher than the revision rates reported in the literature. The possible reasons for this include the fact that some graft failures may go undiagnosed and some surgeons may not regard certain patients as candidates for revision surgery, despite clinically significantly poor outcomes after their index procedure. Moreover, not all patients with graft failure opt for surgical revision but accept a reduction in activity level and chronic knee instability and there are patients undergoing revision without being included in a study, register, or other data collections. In addition, there appears to be a lack of agreement as to the definition of graft failure in the current literature, making it difficult to compare studies using graft failure as their end-point. Using ACL revision makes this easier, as it is a firm end-point and probably represents the proportion of patients with graft failure who have a clinically significant disability. Having said that, however, revision surgery as a failure outcome is not without its limitations, as it probably represents a conservative gauge of clinical failure after ACL reconstruction, as previously mentioned.

In **Study IV**, the crude overall revision rate was low (3.1%) comparable to that reported in current registry studies.[132, 133, 145]. Younger age was associated with an increased risk of revision, reiterating current evidence.[127, 132, 134, 144, 240-242] It seems plausible that this may be a result of younger patients having a higher activity level than older patients both pre-injury and subsequently post-operatively, thereby exposing the graft to deleterious strain. It may also be a consequence of a lack of compliance with postoperative rehabilitation regimens and restrictions, resulting from an over-eagerness to return to activity. It is also possible that younger patients impose higher demands and expectations on the reconstruction and opt for revision surgery to a greater extent than older patients. Activity levels are unfortunately not reported in the Swedish National Knee Ligament Register, making adjustment for this potential confounder difficult. One interesting finding in **Study IV** was that non-anatomic bone tunnel placement via TT drilling resulted in the lowest risk of revision surgery. This may seem surprising, but it might have a logical explanation. Since these grafts are placed non-anatomically, the forces applied to the grafts may be lower, potentially protecting the grafts from deleterious loading.[96, 106, 107] This may also in part explain the results from the Danish Knee Ligament Reconstruction Register showing an increased risk of revision ACL reconstruction when the antero-medial portal drilling technique was compared with the TT technique [RR 2.04 (95% CI: 1.39-2.99)].[105]

Moreover, the incorrect placement of a graft will probably result in some residual rotational laxity of the knee thus creating persisting instability.[79, 95] This instability may cause the patients to adapt their behaviour and activity level, thereby reducing the risk of sustaining a re-rupture of the ACL graft. In addition to this, the residual laxity may lead to increased osteoarthritic changes that, in turn, with time, stabilise the knee, reducing the need for revision surgery. Furthermore, the residual laxity may also be regarded by some as constituting a failed reconstruction, as the aim of the reconstructive procedure itself is to restore native knee kinematics as closely as possible. This creates an unfair

comparison between the "successful" anatomic reconstruction and "unsuccessful" non-anatomic reconstruction, warranting caution when comparing groups of patients distinguished solely by the drilling techniques used. Patients in the anatomic reference group, comprising eight essential AARSC items, with the visualisation of both insertion sites, identification of the ridges and anatomic tunnel placement via TP drilling utilising an accessory medial portal, showed a reduced risk of revision compared with TP drilling and anatomic tunnel placement on the femur and tibia. This could perhaps further illustrate that a learning curve is involved in anatomic ACL reconstruction. Surgeons performing reconstructions according to the TP-reference group may be more experienced, performing larger volumes of reconstructions a year, possibly explaining the difference in the risk of revision surgery. **Study IV** shows that simply grouping patients into only TT and TP drilling techniques, without considering other further surgical data such as placement and visualisation, is not enough and clearly creates a confounding effect that is not adjusted for. The interpretation of studies only assessing drilling technique should therefore be made with great caution.

A cross-sectional multi-centre study of 460 revision cases by the MARS group revealed that in at least 50% of the revision cases, technical error was either a predominant or contributory factor. Of these technical errors, malpositioning of the femoral (80%) and/or tibial (37%) tunnels were the leading causes. Leys *et al.* reported a 17% SB HT graft-failure rate after a 15-years follow-up with a "non-ideal tunnel placement" cited as a contributory factor.[243] In their 20-year follow-up of 90 patients reconstructed with PT graft Thompson *et al.* report that a coronal graft angle of < 17° (i.e. a more vertically oriented graft) was associated with an increased risk of failure compared with an angle of > 17° (77% vs. 96% survival respectively) by a factor of 8.5, further illustrating the potential benefits of anatomic bone-tunnel and graft placement.[244] It is noteworthy, however, that these reconstructions are not strictly anatomic SB reconstructions and a number of them were probably performed with a TT technique during a period in which the anatomic reconstructive technique surgeons strive to implement today was still a novel concept. This could explain in part why these values are considerably higher than those of anatomic reconstructions and anatomic DB reconstructions in particular, in addition to the fact that they are based on longer follow-up data, which are not yet available for anatomic SB or DB reconstructions. These values may still, however, provide some reference for researchers attempting to appreciate the long-term viability of anatomic SB and DB reconstructions compared with the more traditional non-anatomic ones over time and with sufficient follow-up.

Consequently, could the failure-rates in studies comparing anatomic SB- and DB reconstructions reported in the current literature simply be a result of that we have not followed them long enough to reveal the true differences? Could anatomic SB reconstructions to some extent in fact also be prone to repetitive microtrauma, elongation and risk of failure in the long term, more than anatomic DB reconstructions? It is to be hoped that the answers to these questions lie in continued long-term follow-up studies specifically comparing anatomic SB and DB reconstructions.

12 Limitations

Studies I and II

Although an extensive literature search was undertaken with the assistance of two experts in electronic search methods at the Sahlgrenska University Hospital Library, the search was restricted to three databases, PubMed (MEDLINE), EMBASE and the Cochrane Library. In addition to this, the search was further limited to publications in English and with pre-defined years of publication (1995-2012). In addition to the risk of not achieving 100% recall, there is also the potential of publication bias. Authors were contacted for unpublished data, but unfortunately not all of them replied. Study inclusion was not limited to only Level I studies, which in part lowers the overall level of evidence of both **Studies I and II**. The extensiveness of the search yielded a large number of

studies to categorise, and there is a chance that some relevant studies were overlooked in both **Studies I and II**. To assess bias in **Study I**, the Cochrane Collaboration tool for bias assessment was used.[245] This is a tool intended for application to RCTs, but it was applied to both RCTs and prospective comparative studies. In addition, the bias summary assessment of each study was not presented. Meta-analysis should preferably only have been undertaken on those studies with the lowest risk of bias, or meta-analysis stratified according to the risk of bias. This was not done and thus poses the risk that bias was downplayed in the discussion and conclusions. In **Study I**, an analysis of the heterogeneity (I^2) of the included studies was made, but no pre-defined cut-off value was specified. Most of the analyses showed, however, no/low heterogeneity, apart from the analysis of internal-external (IRER) laxity (I^2=*89.9*). In spite of this, we still chose to pool these outcomes and this should therefore be taken into account when interpreting the results of this analysis.

Study III

One primary end-point was a negative pivot-shift test, a subjective test prone to limitations due to its subjective interpretation and variability in execution. There is a possibility that the study was underpowered. No power analysis was conducted with regard to outcome variables other than pivot-shift. We stated that contralateral injuries were the grounds for exclusion at randomisation/start of the study, but the contralateral injuries that occurred during the five-year follow-up period were still included for the analysis of PROMs at the five-year follow-up, for example. These were only excluded when side-to-side comparisons were made, e.g. KT-1000. So, how do we know if the KOOS values given represent the index injury, or the contralateral one? This is due to a certain extent to practical limitations, as patients fill in the PROM form in the Swedish National Knee Ligament Register and no distinction is made there, as to the injury for which the PROM is being documented. There is also the potential influence of multiplicity inference when using PROM instruments such as these and repeating measurements with them during the follow-up. This poses a risk of a type-I error. Adjustment for this can be made using a Bonferroni correction, for example, but none was undertaken. Due to technical problems, there were a total of 15 patients with missing radiographs in the early postoperative period. The loss of baseline radiographic images due to technical/logistical difficulties unfortunately creates a limitation for the comparison of OA development early postoperatively and at follow-up. Randomising the patients eliminates the opportunity to individualise the surgical procedure for each patient, thereby making one of the cornerstones of anatomic ACL reconstruction impossible. The length of the follow-up of five years is also a potential limiting factor, as effects on OA, for example, may not be evident at five years.

Study IV

One important limitation is that the primary end-point was revision surgery, which fails to identify all graft failures, as not all failures opt to undergo revision surgery. Data on graft failure are lacking in the Swedish National Knee Ligament Register. The true rate of graft failure is therefore probably underestimated. In this study, a retrospective analysis was performed through an on-line questionnaire on surgical data, which can in turn entail an element of recall bias. Assuming honest answers, the surgeon can still erroneously recall dates on which a certain technique

was adopted. To minimise recall bias, responders were asked only to answer the question if they were sure of the date they adopted or abandoned the surgical technique in question. In addition, responders were asked only to specify years and not months in an attempt to further minimise recall errors. Moreover, all patients that were operated on during time periods when the surgeon was "in between" surgical techniques were not included. A response rate higher than the achieved 61.7% would have been preferable. No verification of the surgical techniques utilized by the non-responders to the questionnaire was undertaken, creating an element of selection bias. The results of this study are only applicable to ACL reconstructions using HT autografts. When dealing with data from large sample sizes, such as those in register studies, it is possible to achieve statistical significance from data analysis that may not be of clinical significance. It is therefore paramount that these results are scrutinised for their relevance in the clinical setting. One shortcoming of the Swedish National Knee Ligament Register is the absence of data on activity level (Tegner), making statistical adjustment for this potential confounding factor impossible. It is not possible to prove causality based on the results of register studies such as this one, largely due to the inherent performance and selection bias the study type entails. This is in fact a limitation common to all register studies.

13 Conclusions

Study I

Anatomic DB reconstruction is superior to anatomic SB reconstruction in terms of the restoration of AP laxity measured using the KT-1000 and intra-operative navigation. Anatomic DB reconstruction is not superior to anatomic SB reconstruction in terms of the restoration of rotational laxity as measured by the pivot-shift test or intra-operative navigation. Anatomic DB reconstruction does not lead to fewer graft failures compared with anatomic SB reconstruction.

Study II

A substantial underreporting of surgical data was found in the current literature relating to both SB and DB reconstructions The calculated means of AARSC were, for both SB and DB reconstructions,

below the proposed minimum score of 10 points for anatomic ACL reconstruction. This underreporting creates difficulties when comparing and pooling the results of studies.

Study III

A mid-term follow-up comparing anatomic DB and SB ACL reconstruction did not demonstrate significant differences in terms of AP or rotational laxity, functional and patient-reported outcomes, or radiographic evidence of OA.

Study IV

The overall crude revision rate was low. Non-anatomic bone tunnel placement via TT drilling was associated with the lowest risk of revision surgery after ACL reconstruction. Anatomic ACL surgery, characterised by the use of several essential AARSC items, was associated with a lower risk of revision surgery compared with anatomic bone tunnel placement via TP drilling.

14 Future perspectives

14.1 INDIVIDUALISATION

Individualising the surgical procedure for each patient is regarded as a cornerstone in the concept of anatomic ACL reconstruction and involves more than simply deciding on SB or DB reconstruction. The concept of individualising the ACL reconstruction to each patient means that the patient's injury mechanism, activity level, occupation, anatomy, postoperative outcome expectation, activity-level ambition and so on are taken into consideration by the surgeon when tailoring the most appropriate treatment option. Tailoring the reconstruction to the patient should start with establishing a clear and comprehensive understanding of the requirements of

the patient, including the patient's preferences and expectations, lifestyle, occupation and activity level. The surgeon must be meticulous and take a detailed history to assess and understand the injury mechanism and perform a physical examination. Multi-ligamentous injuries and other associated injuries must be identified. The pre- or intraoperative mapping of the patients' anatomical characteristics, including the visualisation of ACL remnants, the visualisation and measurement of tibial and femoral insertion site sizes and intercondylar notch dimensions, as well as an appreciation of the individual variability in the size and shape of the ACL insertion sites, are all equally important. However, it is perhaps now equally important that this concept of individualisation also encompasses individualised rehabilitation programs and criteria for returning to sports/activity in the postoperative treatment phase.

14.2 ANATOMY

There has recently been a rebirth in interest in extra-articular tenodesis as a complement to intra-articular reconstruction, with the specific emphasis on the antero-lateral ligament.[246, 247] The potential contribution of this to anatomic ACL reconstruction in terms of clinical outcome remains to be seen. In addition, recent studies discuss the flat "ribbon-like" form of the ACL and a "C-shaped" tibial insertion, without any clear distinction between the AM and PL bundles. Although potentially challenging technically, an anatomic ACL reconstruction with a "flatter" alignment of the graft and its insertion on the femur and tibia is an intriguing thought and it will hopefully be explored in the near future.[16, 17] To date, traditional thinking has produced ACL trials distinguished by, for example, graft type, graft fixation method, or tunnel position. Further research on variables, such as the bony morphology of the femoral condyles and tibial slope, is undoubtedly of interest.

14.3 AARSC

While multiple surgical techniques, graft options and rehabilitation protocols have been studied with regard to ACL reconstruction, considerable heterogeneity remains in the utilisation and reporting of surgical techniques by ACL surgeons. It is to be hoped that the future use of AARSC will provide a unique tool in promoting anatomic ACL reconstruction techniques, as well as increasing comparability between future studies of the subject.

14.4 QUANTIFICATION OF DYNAMIC LAXITY

One major issue related to the assessment of the pivot-shift test is the executional variability and subjective interpretation of the manoeuvre. In order to evaluate different surgical interventions, the quantification of dynamic knee laxity is an intriguing ambition. The pre- and intra-operative quantification of knee kinematics during the pivot-shift test can be used to create treatment algorithms for complicated cases

of knee instability, perhaps shedding light on preoperative low-grade versus high-grade laxity patterns and their influence on graft kinematics following ACL reconstruction. Exciting research is currently under way with a view to developing tools and applications to allow for this quantification in the in-office setting.[248, 249] Treatment algorithms for dynamic knee laxity using these tools will probably be more widely utilised in the future. In the meantime, the use of a previously presented standardised manoeuvre in order to minimise inter-examiner variation and to facilitate comparisons between studies, is recommended.[250]

14.5 PREVENTION

The identification of athletes who run an increased risk of sustaining a non-contact ACL injury requires continued research efforts. The fact that female athletes in certain sports run a higher risk of sustaining a knee ligament injury than male athletes has been clearly shown, but the reasons for this represent an on-going dilemma that has not yet been answered. Inherent anatomic differences alone do not explain this. Environmental, hormonal and neuromuscular/biomechanical factors play a role. The results of a recent study identified significant gene expression differences in ruptured but otherwise normal ACL tissue between young female and male athletes. The identified genes are involved in the production of major molecules in the ACL extracellular matrix, collagen turnover and production. The authors conclude that this may impact ACL structural integrity, as well as the biomechanical characteristics of the ACL, and may account for the weaker ACLs in female compared with male individuals.[251] The direct implication of these findings remains to be seen, but may provide further insight into how to effectively identify individuals with an increased risk of ACL injury. This in turn could be used to individualise injury preventions programs and implement them at an early stage, as prevention of ACL injury, must be regarded as the ultimate goal.

"It is better to know some of the questions than all of the answers"

James Thurber

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Appendix 16

16.1 SEARCH STRING (STUDIES I AND II)

"Anterior Cruciate Ligament" [Mesh] OR "anterior cruciate ligament" [tiab] OR ACL [tiab]) AND ("Surgical Procedures, Operative" [Mesh] OR surgical [tiab] OR surgery [tiab] OR reconstruction [tiab] OR reconstructive [tiab] OR reconstructed [tiab]) AND (English [lang] AND ("1995" [PDAT]: "3000" [PDAT])

16.2 AARSC

van Eck et al.
Evidence to Support the Interpretation and Use of the Anatomic Anterior Cruciate Ligament Reconstruction Checklist
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ANATOMIC ACL RECONSTRUCTION SCORING SYSTEM

Below you will find the **Anatomic ACL Reconstruction Scoring System.** Anatomic ACL reconstruction is defined as *the functional restoration of the ACL to its native dimensions, collagen orientation, and insertion sites.* This scoring system was developed to determine to what degree ACL reconstruction was performed in an anatomic fashion. This scoring system can be used to grade ACL reconstruction procedures for individual patients as well as for review of the description of surgical methods in studies/ manuscripts on anatomic single- and double-bundle ACL reconstructions. The scoring system uses multiple items that were determined to be reliable and valid primary indicators of the degree of "anatomic" ACL reconstruction.

If the following items were performed the number of point that is assigned to them should be added to the total score. The maximum score is 19 points.

- ☐ Individualization of the surgery for each patient
- ☐ Use of a 30 degrees arthroscope
- ☐ Use of an accessory medial portal, in addition to the a lateral and medial portal
- ☐ Direct visualization of the femoral ACL insertion site
- ☐ Measuring the femoral ACL insertion site dimensions
- ☐ Visualizing the lateral intercondylar ridge
- ☐ Visualizing the lateral bifurcate ridge
- ☐ Placing the femoral tunnel(s) in the femoral ACL insertion site
- ☐ Trans-portal drilling of the femoral ACL tunnels
- ☐ Direct visualization of the tibial ACL insertion site
- ☐ Measuring the tibial ACL insertion site dimensions
- ☐ Placing the tibial tunnel(s) in the tibial ACL insertion site
- ☐ Documenting of femoral fixation method
- ☐ Documenting of tibial fixation method
- ☐ Documenting knee flexion angle during femoral tunnel drilling
- ☐ Documenting graft type
- ☐ Documenting knee flexion angle during graft tensioning

What was the highest level of documentation used for ACL tunnel position in ALL involved subjects?

- ☐ Drawing, diagram, operative note, dictation, or clock face reference
- ☐ Arthroscopic pictures, radiographs, 2D MRI, or 2D CT
- ☐ 3D MRI, 3D CT, or navigation

☐

Enkät avseende operationsmetod vid primär främre korsbandsrekonstruktion

Nedan finner Ni en lista över 17 utvalda moment eller tekniker som kan tillämpas vid primär främre korsbandsrekonstruktion.

För varje punkt, ber vi Er att svara på 3 frågor.

1) Fram till och med vilket årtal genomförde/använde Ni i princip **aldrig** det aktuella momentet/tekniken? Ange årtal.

2) Från och med vilket årtal genomförde/använde Ni i princip **alltid** det aktuella momentet/tekniken? Ange årtal.

3) Genomför/använder Ni momentet/tekniken idag? Ja eller Nej.

Om Ni alltid eller aldrig har genomfört/använt momentet/tekniken i fråga, kryssa då för rutan "Alltid använt" eller "Aldrig använt".

Vänligen ange även Ert namn, Er kliniktillhörighet och Er E-post-adress.

Namn: **Klinik:** **E-post:**

	Alltid använt	Aldrig använt	I princip aldrig utförd fram till och med:	I princip alltid utförd från och med:	Utförs idag:
1. Valet av operationsmetod är individuellt anpassat för varje enskild patient.	☐	☐			
2. Användning av artroskop med 30-gradig optik.	☐	☐			
3. Användning av en accessorisk medial port.	☐	☐			
4. Främre korsbandets "footprint" i femur identifieras.	☐	☐			
5. Främre korsbandets "footprint" i tibia identifieras.	☐	☐			
6. Mätning av det främre korsbandets "footprint" i femur.	☐	☐			
7. Mätning av det främre korsbandets "footprint" i tibia.	☐	☐			
8. Lateral intercondylar ridge identifieras	☐	☐			
9. Lateral bifurcate ridge identifieras.	☐	☐			
10. Bentunneln i femur borras så att den mynnar i det främre korsbandets "footprint" i femur.	☐	☐			
11. Bentunneln i tibia borras så att den mynnar i det främre korsbandets "footprint" i tibia.	☐	☐			
12. Bentunneln i femur borras via en accessorisk port (transportal borrning istället för transtibial).	☐	☐			
13. Metoden för att fixera graftet i femur dokumenteras.	☐	☐			
14. Metoden för att fixera graftet i tibia dokumenteras.	☐	☐			
15. Knäflexion i antal grader, när bentunneln i femur borras, dokumenteras.	☐	☐			
16. Valet av graft dokumenteras.	☐	☐			
17. Knäflexion i antal grader, i samband med att graftet spänns och fixeras, dokumenteras.	☐	☐			

18. Vilken av följande metoder använder Ni för att dokumentera graftets placering?

- ◯ Ritning, operationsberättelse, placering enligt urtavla
- ◯ Artroskopisk fotodokumentation, slätröntgen, tvådimensionell MR, tvådimensionell CT
- ◯ Tredimensionell MR, tredimensionell CT, navigation

Observera att alla frågor är obligatoriska.

Skicka

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18 Papers I-IV

PAPER I

Anatomic single- versus double-bundle ACL reconstruction: a meta analysis

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PAPER II

A systematic review of single- versus double-bundle ACL reconstruction using the anatomic anatomic anterior cruciate ligament reconstruction scoring checklist

Desai N, Alentorn-Geli E, van Eck CF, Musahl V, Fu F Karlsson J, Samuelsson K

Knee Surgery, Sports Traumatology, Arthroscopy. 2016; 24(3): 862-872

E-published 2014 Oct 26

PAPER III

Comparison of anatomic double- and single-bundle techniques for anterior cruciate ligament reconstruction using hamstring tendon autografts: a prospective randomized study with 5-year clinical and radiographic follow-up

Karikis I, Desai N, Sernert N, Rostgard-Christensen L, Kartus J

The American Journal of Sports Medicine

E-published 2016 Mar 6, doi:10.1177/0363546515626543

PAPER IV

Revision surgery in anterior cruciate ligament reconstruction - A cohort study of 17,682 patients using the Anatomic Anterior Cruciate Ligament Reconstruction Scoring Checklist applied to the Swedish National Knee Ligament Register

Desai N, Andernord D, Sundemo D, Alentorn-Geli E, Musahl V, Fu F, Forssblad M, Karlsson J, Samuelsson K

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