Changing paradigms of anterior cruciate ligament surgery

From transtibial to a more anatomic approach

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Scientific environment

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Abbreviations

ACL	Anterior cruciate ligament
GAG	Glucosaminoglucan
MGA	Middle genicular artery
PROMs	Patient reported outcomes
AM	Anteromedial
PL	Posterolateral
IM	Intermediate
MOON	Multicenter Orthopaedic Outcome Network
TT	Transtibial
IKDC	International Knee Documentation Commite
MRI	Magnet resonance imaging
PCL	Posterior cruciate ligament
ITB	Iliotibial band
ESSKA	European society for sports traumatology, knee surgery and arthroscopy
HDS	Haraldsplass Deaconess Hospital
AOSSM	American orthopaedic society for sports medicine
OA	Osteoarthritis
AJ	Amis and Jakob line
CT	Computer tomography
ICC	Intraclass correlation coefficient
CAS	Computer assisted surgery

Abstract

The current thesis consists of four papers evaluating results after anterior cruciate ligament reconstruction using two different surgical techniques. Paper I and II evaluate long-term outcomes after a transtibial technique using a so-called "anti-impingement" guide for tibial tunnel placement. Clinical examination, patient reported outcome measures and radiographic osteoarthritis/tunnel placement evaluation was performed. Paper III and IV utilized postoperative 3D-CT to evaluate graft tunnel placement in a cohort of patients in the midst of a change from the transtibial technique to an AM-portal (or more anatomic) technique. Femoral tunnel placement was measured relative to an empirical anatomic centre (based on an average native femoral insertion from a range of anatomic studies).

Paper I and II found a low revision rate of 4%, good patient reported outcomes (PROMs) – in terms of mean Lysholm score of 89 and mean IKDC subjective score of 83 – and a low prevalence of osteoarthritis. At clinical examination, however, there was a 20% incidence of 2+ pivot shift, indicating a significant failure in restoring native knee kinematics. Further, a 24% incidence of posterior tibial tunnels – defined as 50% or more along the anterior-posterior direction of the tibial plateau – was found to be related to rotatory instability (2+ pivot shift) with associated significant worse outcome in PROMs. Paper III and IV depicted the change in femoral tunnel position from the transtibial technique to the AM-portal technique, with an initial great variation in tunnel positions indicating that ACL remnants and bony landmarks were unreliable for guiding femoral tunnel placement. Further, both the feedback from postoperative CT assessments (Study I) and the use of intraoperative fluoroscopy (Study II) were found to bring the femoral tunnel position closer to an empirical femoral tunnel reference.

In sum, Paper I and II adds to the critique of the transtibial technique for femoral tunnel placement and displays that avoidance of overly anterior tibial tunnel placement (by the anti-impingement guide) can lead to a high incidence of posterior tunnel placements. Further, the importance of a multitudinous approach for outcome

evaluation is emphasized. Study III and IV shed light on one plausible reason for a learning curve of the AM portal approach for ACL reconstruction. Using per- or postoperative evaluation of tunnel placement can help avoid an unwanted variation in femoral tunnels – but ultimately the results needs to be linked to finite outcome evaluation to establish the clinical impact.

List of publications

I.   Inderhaug E, Strand T, Fischer-Bredenbeck C, Solheim E. **Long-term results after reconstruction of the ACL with hamstrings autograft and transtibial femoral drilling** (2013) *Knee Surg Sports Traumatol Arthrosc* 21:2004-2010*

II.   Inderhaug E, Strand T, Fischer-Bredenbeck C, Solheim E. **Effect of a too posterior placement of the tibial tunnel on the outcome 10–12 years after anterior cruciate ligament reconstruction using the 70-degree tibial guide** (2014) *Knee Surg Sports Traumatol Arthrosc* 22:1182-1189*

III.   Inderhaug E, Larsen A, Strand T, Waaler PA, Solheim E. **The effect of feedback from post‑operative 3D-CT on placement of femoral tunnels in single‑bundle anatomic ACL reconstruction** (2014) *Knee Surg Sports Traumatol Arthrosc* DOI: 10.1007/s00167-014-3355-0*

IV.   Inderhaug E, Larsen A, Strand T, Waaler PA, Harlem T, Solheim E. **The effect of intraoperative fluoroscopy on the accuracy of femoral tunnel placement in single-bundle anatomic ACL reconstruction** (Submitted)

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Introduction

Anatomy

The first known description of the anterior cruciate ligament (ACL) goes back almost 4 000 years from early Egyptian scrolls. Only later did the name "cruciate ligaments" (together with the posterior cruciate ligament) – from its inherent macroscopic appearance – appear [156]. A progressing body of literature, with a spur in interest in the last few decades, provides a thorough description of its size, shape and functional anatomy.

Microscopic anatomy, innervation and blood supply

The multiple fibres of the ACL are parallel-running collagen fascicles. The fibres microscopic appearance is conventionally segregated into *distal, middle* and *proximal* parts based on their content of connective tissue (fibroblasts and collagen) and cells [56]. Other significant constituents are the glycosaminoglicans (GAG – holding the bulk of water in the ligament), gluco-conjugates and variants of elastin.

The vascularization of the ACL is primarily through the middle genicular artery (MGA) originating from the popliteal artery and entering at the posterior aspect of the articular capsule [102]. Running just beneath its synovial membrane, the MGA diversifies into a web-like structure that ensheath the ligament throughout. In close connection to the vessels surrounding the ligament, is the nervous innervation originating from the posterior articular branches of the tibial nerve [11]. The majority of nerve fibres have a vasomotor function, but some are also mechanoreceptors (Ruffini, Paccini and Golgi-like receptors) with important roles in postural and proprioceptive functions of the knee. Their importance in muscular feedback systems become apparent in patients with a torn ACL – where quadriceps muscle weakening can, in part, be seen as a results of a disrupted so-called "ACL reflex" [107].

Macroscopic anatomy

In the centre of the tibiofemoral joint, enveloped distally by the tibial plateau and proximally by the femoral intercondylar notch, the ACL has its main vector of fibres in an anteromedial to posterolateral direction [68]. The mid-substance of the ligament is often described as having an oval or flat shape with a diameter about 11 mm [68]. With a mean length of 32 mm – and a variable length of fibres dependent on insertion in the tibial and femoral attachment – the structural arrangement is heavily debated [156, 169, 179, 189]. Even though several studies have failed to reproduce such findings [12, 56, 179] – a division into an anteromedial (AM) and a posterolateral (PL) bundle (named after the location of their tibial insertion) is still dominant [169, 187].

The femoral attachment is on the posterior aspect on the medial wall of the lateral femoral condyle – with the lateral intercondylar ridge ("residents ridge") as its anterior border and the posterior articular margin of the lateral femoral condyle as its posterior border. The size of the insertion – the so-called "footprint" – varies in its description between $46 - 230$ mm^2, and is predominantly described as having an oval shape [41, 57]. The tibial insertion of the ACL is contained posteriorly by the tibial spines, with some of its anterior fibres inserting underneath the intermeniscal ligament, and the main bulk of fibres inserting directly medial to the anterior horn of the lateral meniscus. A recent study described in detail the tibial insertion of 111 cadavers knees and a found a "footprint" size ranging from 86-131 mm^2 [169].

The classical view of the ACL fibres running in a straight line from their femoral to their tibial insertion has recently been challenged by a newfound differentiation in histological and dynamic fibres appearance [169, 179]. So-called "fan-like extension fibres" (related to the femoral attachment) and "indirect inserting fibres" (in the tibial attachment) does perhaps point towards a differentiation in dynamic function of the constituents in the anterior cruciate ligament.

Biomechanics

The primary function of the anterior cruciate ligament is to restrain anterior translation of the tibia relative to femur – but its intricate structure and compilation points towards other functions in controlling native knee kinematics. For better understanding the paradigm held by many researchers when exploring the biomechanical function of the anterior cruciate ligament, the debate around the ACL "bundles" has to be mentioned. The view of the ACL as two distinct and separable bundles, namely the anteromedial (AM) and the posterolateral (PL) has been dominating the literature the last few decades, and has influenced biomechanical studies as well as the surgical approach used in patients with ACL injuries [5, 68, 189]. The names, AM- and PL- bundles, are referring to the differing tibial insertion sites of these structures.

Some authors have proposed a further subdivision of the functional fibres, describing an intermediate (IM) bundle - with distinct functions of each of the AM, IM and PL bundles [7, 148]. On the contrary, authors of early literature – but also some more recent publications – have not been able to find such distinct bundle divisions – and has therefore chosen a different approach when describing its dynamic function [12, 56, 152, 169]. The distinct fibre-bundle division theory has clear advantages in exploring functional anatomy – but, as stated by critiques, may represent an overly simplification of complex anatomy [169].

"Reciprocal function" of the AM and PL bundle in restraining anterior tibial translation

The AM-bundle is found to be the longer of the two (bundles) – described variably as 28-38 mm long [69, 199]. The shorter PL-bundle (about 18 mm long) is somewhat more horizontally orientated than the AM bundle in the intercondylar notch, but their relative position to each other does vary with the degree of flexion in the knee. Studies on the differential behaviour of the AM and PL bundle describes their

behaviour throughout the knee range-of-motion. From extension towards flexion the AM-bundle tightens whilst the PL-bundle slackens [8] – towards extension, the PL bundle invariably tightens. In light of these findings, a "reciprocal action" of the AM and the PL bundle has been proposed [7, 68, 195]. By examining in-situ forces in the two bundles throughout knee flexion, the same tendency – of AM tension increase towards flexion and PL tension increase towards extension – has been found [164, 195]. Other efforts to understand ACLs functions on knee kinematics include selective cutting (of anatomical structures) studies – and its primary function, namely resisting anterior tibial translation has been described [6, 35, 61]. Further, when examining the individual bundles contribution to this restraint, Amis and Dawkins found that the AM bundle had a dominant role at 90 degree of flexion, whilst the PL bundle was dominant at 20 degree of flexion [7].

The role of ACL in resisting internal rotation of the knee

As noted in a review by Amis, there has only recently been substantial interest in ACLs role in controlling rotational laxity – and the literature is less extensive in this area than in its role in resisting anterior translation [8]. Studies that have investigated sequential cutting of the AM bundle, PL bundle and the whole ACL have, however, described only a slight (and often non-significant) increase in internal rotation in response to partial or total resection of the ACL [52, 62, 199].

In simulating the clinical "pivot shift sign" – often thought of as a clinical prerequisite in diagnosing an ACL injury – combined internal rotation and valgus torque is applied to the knee [52, 106, 141]. Kondo et al. found significant changes in anterior translation when they undertook sequential cutting of AM-bundle, PL-bundle and the whole ACL – and examined the effects on kinematics under such a combined loaded state [106]. There was, however, no effect (n.s.) on the internal rotation of the knee – neither in response to a partial cutting nor to a total section of the ACL.

Although the "pivot shift" is first and foremost associated with the ACL tear, some studies indicate that the involvement of peripheral anterolateral structures of the

knee, in addition to the ACL injury, is necessary for the pivot shift to appear [134, 177]. Radiological findings like the "Segond fracture" or concomitant iliotibial band injuries point towards significant damage to the anterolateral soft tissues at the time of the ACL injury [70, 130, 182]. Biomechanical studies have explored the stabilizing role of these structures, and serial cutting of intra- and extraarticular structures has identified the deep and capsule-osseous layers of the ITB as the important restraints to internal rotation – therefore effectively counteracting the pivot shift [192, 194].

Epidemiology and predisposing factors for ACL injury

Epidemiological findings from ACL registries

The most extensive overview of causes of ACL injuries, and outcomes after surgery, can be found in several nation-wide ACL registries in the Scandinavian countries and in the US [71, 117, 127, 129]. However, it is important to bear in mind that these registries predominantly hold information on patients that have been surgically treated – and accumulated data on non-surgically treated ACL injured patients, or even untreated ACL patients, are less available.

Looking at incidence rates for ACL surgery in the general population, the Scandinavian registries reported from 32 to 38 surgeries per 100,000 inhabitants in the period from 2004 to 2007 [71]. However, in the high-risk group of approximately 16-39 years of age, a somewhat higher incidence of about 71-91 per 100,000 was found. Except in the youngest population group (10-19 years), men dominate in all age groups (57-60%). The mean age at surgery was found to be 23-27 years.

A study comparing data from the MOON Cohort (Multicenter Orthopaedic Outcome Network) and the Norwegian registry presented data from almost 5,000 ACL reconstructions [127]. The most common causes of injury in the MOON cohort were related to basketball (20%), soccer (17%), American football (14%) or skiing (7%). In the Norwegian registry, the most common causes were injuries related to soccer (42%), handball (16%) and downhill skiing (10%). Work accidents accounted

for 3% of injuries in both registries. Cultural differences in sports participation will affect rates of injury but, inevitably, certain sports are more risk prone than others.

Injury mechanisms and predisposing factors of ACL injury

The distinction between contact and non-contact injuries is important in assessing probable concomitant damage, but the majority of ACL injuries are known to happen in non-contact situations [65]. From what is known about injury mechanism, sports that include sudden decelerations and lateral cutting manoeuvres are more (ACL injury) risk prone [90]. The injury mechanism does, however, vary from sport to sport. An example is alpine skiing, where several mechanisms are described as leading to an ACL tear [59]. The most common – called "the phantom foot" - happens when the skier falls backwards and has a sudden internal rotation of the knee due to a carving turn of the ski. Other injury mechanisms include: a sudden anterior translation induced by the rigid ski boot, hyperextension, hyperflexion or combinations of hyperextension and internal rotation. With multidirectional loadings applied to cadaver knees, Levine et al. induced ACL damage in 15 of 17 knees by the combination of tibial internal rotation, valgus force, anterior tibial translation and axial compression [116]. Thus, this was proposed as the most common combination of forces that will cause the ACL to tear. The investigators did, however, fail to differentiate between different degrees of injury, and could neither explain the pattern of the tear.

In order to make interventions aimed at reducing ACL injuries, it is paramount to gain knowledge on the risk factors. From the registry studies on patients undergoing surgery we have information about which type of sport that resulted in the injury. It is known that female athletes are, in general, more at risk – female-to-male injury rates have been described for several sports. This was exemplified in a study by Myklebust et al. where female handball players had twice the risk (of sustaining an ACL injury) compared to their male counterparts [143]. Other authors reporting on basketball, soccer, baseball and lacrosse have found ratios of 3:1, 4:1, 4:1 and 1.4:1 respectively (female-to-male ratio) [1, 82].

Some authors propose that risk factors for non-contact ACL injuries can be seen as external or internal – based on whether they are environmental or intrinsic to the patient. Dai et al. have summarized a range of such risk factors across a series of studies [45]. In addition to the above-mentioned type of sports, external factors can include; shoe/surface interface, knee bracing and weather. Proposed internal factors include; lower extremity alignment, femoral intercondylar notch size, posterior tibial plateau slope, patella-tendon-tibia shaft angle, hormonal variation (e.g., female menstrual cycle) and neuromuscular control. Of the internal factors, the latter (neuromuscular control) has been seen as having the largest potential when aiming to making preventive intervention programmes [149, 178]. Another review by Alentorn-Geli et al., looking predominantly at risk factors in male athletes, concluded that most of risk-factors are either environmental or anatomical, e.g., dry weather conditions, artificial turf or higher posterior tibial slope might increase the risk for ACL injury [4]. Although some distinct risk factors can be identified, it is also important to state that most ACL injuries are likely to have a multi-factorial aetiology.

Diagnostics and clinical evaluation

Whether the patient is seen in a general practice, by a team sports doctor/physiotherapist or an orthopaedic surgeon, diagnosing the ACL injury (especially in the acute phase) can sometimes be challenging. Risk factors, as discussed above, can give a clue to whether such an injury is likely or not, but a more thorough patient history should include injury mechanism, onset of effusions, functional limitations and any feeling of the knee "giving way" [94, 112, 166]. History taking can sharpen the clinical suspicion, but is on its own relatively poor in making an exact diagnosis without further clinical examination [29, 140]. In an effort to establish accuracy of clinical examination Simonsen et al. analysed a series of 118 patients about to undergo arthroscopy due to effusions and clinical signs of ligament injury [170]. The specificity and sensitivity of the preoperative clinical examination were 0.75 and 0.62 respectively. These figures improved only slightly if an additional examination was performed during anaesthesia.

The most common, and well described, clinical tests for diagnostics include the Lachman test, anterior drawer test and pivot shift tests. A review of seventeen clinical studies examined their predictive value, using either MRI or arthroscopy as the gold standard for diagnosis [166]. Pivot shift had a favourable positive predictive value whilst Lachman had a good negative predictive value. Anterior drawer, however, was found to be of unproven value. A more recent review, including data from 28 studies, found a pooled sensitivity of 85% and a pooled specificity of 94% of the Lachman test. The pivot shift had a specificity of 98% but a sensitivity of only 24% [20]. Somewhat contrary to the previous review, the latter found a good sensitivity and specificity of the anterior drawer test, but only in chronic cases of ACL injury.

The increasing use of diagnostic knee imaging, in particular the use of MRI, has been seen as a result of reduced cost and better availability over the latter decades [153, 172]. Radiographs are primarily used to rule out gross fractures of the femur or tibia, but the finding of a Segond-fracture or a tibial eminence fracture can be a radiographic sign of ACL injury [14, 37, 53, 97]. Stress-radiography, using serial radiographs with and without loading of the knee, can be a useful supplement in clinical diagnostics. Several techniques for diagnosing ACL, PCL and other ligament injuries (by stress-radiography) have been described [95].

MRI has emerged to become the gold standard in radiographic evaluation of intraarticular pathology [40, 72, 172]. It will readily visualize the cruciate ligaments from multiple views (sagittal, horizontal, coronal) so that their integrity can be assessed by direct visualisation [97]. Some authors have described ACL specific protocols to make more refined and detailed diagnostics. Using oblique views, these protocols are proposed to reliably find, e.g., partial bundle ACL tears [145, 175]. Particular bone-bruise patterns in the lateral tibiofemoral compartment has been described as an indirect sign of ACL tear and can be demonstrated in nearly 80% of the patients [154]. Other indirect signs are buckling of the PCL and anterior translation of tibia [97]. Several studies have examined the sensitivity and specificity of MRI using arthroscopic evaluations as the gold standard for diagnosing an ACL tear. Ranges of 87-99% and 83-99% have been reported for the sensitivity and

specificity, respectively [144, 146, 167]. Besides good predictive value of ACL injury, the MRI examination is helpful in diagnosing concomitant soft tissue injuries, meniscal injuries and cartilage injuries. This will be particularly helpful when planning a surgical intervention.

Natural history of ACL deficiency

The main effect of an ACL injury is a change in tibiofemoral joint laxity, with an increased posterior translation and external rotation of femur relative to tibia [132]. These kinematic effects inevitably affect shear forces and contact stresses in the knee because of the shift in articulating tibial and femoral areas. Cartilage that is not adapted to load bearing can therefore be subjected to a substantial change in contact pressures. Although these effects come from the kinematic changes, they will be amplified by any concomitant meniscal or cartilage injuries. A common opinion is that that the resulting long-term effects include risk of further injuries, stretching of secondary restraints for AP and rotational laxity and ultimately an increased risk of developing OA.

From registry data, we know that concomitant meniscal and cartilage injuries are commonly found in patients undergoing ACL surgery. The Scandinavian registries have reported concomitant meniscal injuries in 35-55% of the ACL patients and cartilage injuries in 17-27% [71]. Both types of lesions increase the risk of developing OA [120]. Further, the ACL injury in itself poses a risk for sustaining further meniscal injuries as demonstrated in a meta-analysis by Snoeker et al. [173]. A delay in ACL reconstruction of more than 12 months was found to increase the risk of meniscal injury. The overall odds ratio (OR) of a medial meniscal tear was 3.5 while the OR for a lateral meniscal tear was 1.49.

An important mechanism of further injuries is the neuromuscular deficit found in ACL injured patients [24, 197]. These deficits have also, in themselves, been found to give an inferior knee function. Eitzen et al. found that a preoperative quadriceps weakness of 20% or more (compared to the non-injured knee) predicted both inferior

knee rating scores (using the Cincinnati knee score) and a lasting quadriceps weakness 2 years after ACL reconstruction [58]. Although these patients were surgically treated, the findings are probably valid for non-surgically treated patients too. The authors' interpretation was that specific intervention should address such severe muscular deficits to prevent further injuries.

Besides the evident muscular wasting, growing evidence indicate that the ACL injury also leads to changes in peripheral and central neural pathways [42, 186]. A study by Kapreli et al., comparing chronic ACL insufficient patients to healthy controls, found diminished sensorimotor cortical activity when using fMRI to look at central neural responses [99]. This reduction was thought to arise from a deafferentation in response to the peripheral nerve disruption happening at the time of the injury. Such findings have catalysed a change in attitude for rehabilitation after ACL injury - where "re-learning" of movement patterns might be as important as strengthening peripheral neuromuscular function.

After an ACL injury, the risk of early-onset OA has been described as rising to a 10-fold level of that found in a normal non-injured population [67]. As most patients are young at the time of injury, significant symptoms from the OA may occur from the age of 30 to 50 years. These patients have been described as "young patients with old knees" and represent a major challenge in choice of treatment since they are often considered too young for a joint replacement. A comprehensive review by Lohmander et al. looked at data from 127 publications assessing incidence of radiological OA after ACL tear [120]. At 10-20 years after the injury, an incidence of 10-90% was reported. Because of the heterogeneity of the included studies, a mean incidence rate could hardly be estimated – but an overall long-term risk of at least 50% was suggested. The study did, however, include a mix of different treatments and an even higher incidence could probably be expected if the patients had received no treatment at all. In sum, development of OA after ACL injuries should be attributed to a multitude of factors. Amongst these are the injury mechanisms, any concomitant lesions, individual anatomy, choice of treatment and – not to forget - patient compliance.

Management of ACL injuries

Management of ACL injuries have been heavily debated through the years and both operative and non-operative treatments have been found successful. While athletic young patients might prefer surgery – it has been discussed that patient dependent factors such as older age, more sedative occupations or lower general levels of activity could pointing towards a non-operative approach [30]. Such an approach may include physical therapy, activity modification and bracing during activities. Several studies have compared operative versus non-operative treatment, and a recent systematic review by Smith et al. summarized across a range of these [171]. In conclusion, there seems to be a rationale for trying non-operative intervention before surgical treatment – perhaps with the exception of young and physically active patients who (with an unstable knee) will be at great risk for sustaining new injuries the articular cartilage and menisci. However, a review by Delincé et al. pointed out that both operative and non-operative treatments of today fail to restore native knee kinematics and that all patients should be informed that the risk of further knee lesions remains high – particularly if returning to pivoting sports [50].

Evolution of modern ACL surgery

Historical efforts of ACL reconstruction date back to early 20th century with the likes of Robson, Groves and Smith utilizing strips of the iliotibial band (ITB) to replace the torn native ACL [34]. Further evolution included various intraarticular graft materials before a gradual turn towards extraarticular reconstructions was seen during the 60´s and 70´s [53, 115, 126]. With the finding of inferior clinical results of these procedures, the intraarticular techniques using auto- and allografts again gained popularity towards a dominant position throughout the 1980´s and 1990´s [46, 124]. Pioneering techniques were often developed in parallel in different parts of the world. A commonly used technique involves using a medial third of the patellar tendon [39]. Clancy et al. carefully described how the graft – a flat tendon on square bone-blocks – should be placed in eccentric graft tunnels so that the tendon itself would have a

resultant position in the centre of the tibial and femoral ACL insertions. By using an open, medial parapatellar approach guide wires could be accurately positioned to achieve these graft tunnel positions.

With the revolutionary evolution of arthroscopy, first as a purely diagnostic tool and eventually, arthroscopic assisted techniques for treating different types of intraarticular knee injuries, the morbidity of knee surgery was significantly reduced. Pioneers such as Watnabe, O´Connor and Dandy (amongst others) popularized these techniques (involving the arthroscope) among the common orthopaedic surgeon [47].

Development of drill guides was a prerequisite for the less invasive arthroscopic approach, e.g., in ACL reconstructions. Both tibial and femoral guides could be introduced through small incision to direct a guide wire so that graft tunnels could be reamed in the desired positions. This so-called "two-incision" technique – named because of the use of a separate incision over the lateral condyle for reaming the femoral tunnel (outside-in) – was considered the mainstay in arthroscopic ACL reconstruction [76, 160].

From a transtibial technique to the "anatomic approach"

The transtibial approach (TT) for ACL reconstruction, also called the "one incision technique" or "coupled drilling" technique, was gradually introduced throughout the 1990´s [84, 113, 136, 137]. By using an offset aimer to guide the femoral graft tunnel placement (and reaming in the opposite direction, inside-out), one could avoid making an additional lateral incision and further decrease morbidity of the surgery. This aimer was positioned through the pre-reamed tibial tunnel, thereof the name "transtibial" femoral reaming. The resultant femoral tunnel position was acknowledged to be more proximal and posterior in the femoral notch as the offset aimer used the back wall of the epicondyle for reference [73, 87]. The femoral tunnel position would be predetermined by the tibial tunnel placements since the transtibial reaming allowed for limited adjustment. Although studies found no clinical benefit over the "two incision" technique, the technique gained popularity due to its

relatively quick and consistent surgical approach [76, 100, 160].

With several anatomical studies exploring the more comprehensive ACL anatomy, the native insertions of the ACL were elaborated [139]. Due to the realisation that the typical TT femoral tunnel placement would, at best, only reproduce a small part of the femoral footprint, its was criticised for being an "non-anatomic" technique [15, 79, 108]. In reaction to these findings, the goal of being more "anatomic" when reconstructing the ACL was proposed. An "anatomic" reconstruction was first a denotation of a technique where the AM-bundle and PL-bundle were reconstructed separately (double-bundle) - with the use of two sets of femoral and tibial tunnels [156, 187]. Later it has also been known to include single-bundle reconstructions, where only one femoral and one tibial tunnel is used [33, 56]. Anatomical landmarks displaying the femoral attachment of the ACL would guide the femoral tunnel placement, and an accessory anteromedial portal was typically recommended to get a more direct view of the remnants of the ACL [33, 188].

Several biomechanical studies have found a knee kinematic closer to that of the native ACL when comparing the "anatomic" approach to the transtibial technique [102, 193, 195, 198]. In a patient-level study Mohsen et al. randomized 320 patients to anatomic single-bundle, double-bundle or transtibial ACL reconstruction [11, 91]. At mean 54 months after surgery they found significant differences in KT-1000 evaluation and incidences of pivot shift favouring the two anatomic techniques. Further, small differences favoured double-bundle over the anatomic single bundle technique (e.g. 1.2 mm vs. 1.4 mm in KT-1000) – but these are questionably of clinical significance. A Cochrane review comparing double-bundle with single-bundle ACL reconstruction across 17 studies concluded that there was some limited evidence that double-bundle reconstruction had better objective outcome (KT-1000, pivot shift, IKDC scores) and a possible protective effect of further knee injuries [107, 183]. With the added technical complexity of the double-bundle procedure - also considering potential revision surgery – critiques have questioned whether the possible small benefits of the procedure (as compared to an anatomic single-bundle procedure) justifies common use of the technique [68, 77, 174].

Graft tunnel placement and clinical outcomes

Although changes in graft tunnel position often accompany other changes in surgical techniques, these are rarely examined directly besides in time-zero studies – including cadaveric or early postoperative studies. Fewer studies have stratified tunnel placements and link these to clinical outcomes – an important basis for recommendations of "safe tunnel placements".

By performing MRI scans in 56 ACL reconstructed patients at 6 months after the surgery, Howell et al. assessed the clinical effect of tibial tunnel positioning [85]. Thirty of these patients were found to have signs of graft impingement at the follow-up evaluation. Graft impingement was defined as signal changes in the anterior aspect of the ACL due to impingement from the femoral roof. When assessed on sagittal radiographs, the "impingent group" had a tibial tunnel position 12-23 mm from the anterior edge of the tibia – and was found to have problems regaining their full extension. Based on these findings, the authors recommended to assure that the tibial tunnel was centred approximately 22-28 mm from the anterior edge of the tibia – corresponding to the anatomical centre point of the ACL. Pinczewski et al. performed clinical evaluation of 200 ACL reconstructed patients 7 years after their surgery [158]. Eleven per cent of patients experienced re-rupture of the ACL graft during that period. When relating the failures to graft tunnel placement on postoperative radiographs, significantly more of those who failed were found to have a posterior tibial tunnel (50% or more of the total AP distance of the tibial plateau). Another interesting finding was a clear relation between vertical graft inclination, rotational instability (as measured by pivot shift examination) and signs of lateral OA.

The effects of erroneous femoral tunnel placements have been examined in several follow-up evaluations [2, 18, 103, 158]. Most noticeably in a study by Aglietti et al. [2]. They evaluated 89 patients 7 years after ACL reconstruction and found an overall satisfactory outcome in 83% of patients. In a subgroup where the femoral

tunnels were placed anterior on the Blumensaats line (from 0 to 50% of the distal-proximal distance) (N=9) – a troubling 63% of patients experienced graft failure. Although not as evident as in the study by Aglietti, Behrend et al. presented similar finding in a study evaluating 50 patients at a mean 19 months after surgery [18]. There was a significant lower IKDC score in patients with an anterior femoral tunnel compared to patients with tunnels that were defined as normal, i.e. tunnels positioned at 75% of Blumensaats line +/- 7%. Other studies, like one by Khalfayan et al., have investigated how combinations of femoral and tibial tunnel placements might relate to clinical outcomes [103]. If the femoral tunnel was positioned at least 60% along the Blumensaats line and the tibial tunnel was positioned at least 20% along the tibial joint line, than 69% of their patients had good or excellent Lysholm score and 79% had a KT-1000 max manual side-to-side difference of 3 mm or less. If the radiological criteria were not met, these figures were reduced to 50% and 22%, respectively.

From transtibial to anatomic – for the better?

The rationale for a change in surgical approach from the transtibial to the anatomic approach was to achieve more anatomic graft tunnel placements and to reduce the levels of residual pivot glide – found in patients treated with the former method [16, 41, 57, 108, 139]. The basis for critique of the transtibial technique included very few clinical studies, and none with comprehensive follow-up evaluation. Such evaluations, including detailed patient-level data, would shed light on any proposed improvement. Since ACL surgery is one of the most commonly performed orthopaedic procedures – and performed in a young active patient population – technical advances leading to improved outcomes can have a major impact. A recent study from the Danish ACL registry found a somewhat unexpected doubled revision rate after a major changed from the transtibial to the anatomic single bundle technique [159]. This troubling finding has been proposed to result from a significant learning curve of the new technique, but without any patient level data to support such a claim.

In light of these recent developments, the proposed aims of the current thesis are as described in the next section.

Aims of thesis

1. *To examine the long-term clinical outcome after the transtibial approach for ACL reconstruction* (Study 1)

2. *To investigate the impact of tibial tunnel placement on clinical outcomes with the use of an "anti-impingement" tibial drill guide* (Study 2)

3. *To evaluate femoral tunnel placement by a surgeon novel to the principles of anatomic ACL reconstruction – comparative to transtibial femoral tunnel placements* (Study 3)

4. *To evaluate the effect of (1) postoperative feedback from 3D-CT, and (2) intraoperative fluoroscopy on femoral tunnel placement in the anatomic single-bundle ACL reconstruction* (Study 3 and 4)

Methods

Study design

Study I and study II were performed as retrospective case studies of patients surgically treated for ACL insufficiency at Haraldsplass Deaconess Hospital (HDS) in the period from 1999 to 2001. Eligible patients were invited for a follow-up evaluation involving questionnaires, clinical evaluation by an independent examiner and a radiographic evaluation. Patient evaluations were performed at the outpatient clinics of Haraldsplass Deaconess Hospital in Bergen, Hospital of Southern Norway in Kristiansand and Lovisenberg Deaconess Hospital in Oslo.

Study III and IV involved a prospective cohort of patients undergoing ACL surgery at the Teres Bergen Hospital (TB) in the period 2012-2014. Patients were enrolled for the study at the time of surgery and were postoperatively given an appointment for CT evaluation. No other patient intervention or evaluation was performed.

Patient inclusion and exclusion

For study I and II all (consecutive) patients who underwent ACL reconstruction at HDS, using a double-strand semitendinosus and gracilis tendon graft and a transtibial technique involving the use of the 70-degree tibial drill guide (also called the anti-impingement guide) in the period 1999-2001, were included. In study III and IV all (consecutive) patients who underwent isolated ACL reconstruction using a double-strand semitendinosus and gracilis tendon graft were included. Two different surgical techniques (to be described) were used.

For all studies, patients who underwent reconstruction using other grafts (e.g. patellar tendon), patients undergoing revision surgery or patients who had concomitant ligament or chondral surgery were excluded from the evaluation.

Concomitant meniscal sutures and partial menisectomies were, however, allowed in all studies.

Surgical technique

In all cases, an initial arthroscopic examination was performed to diagnose and treat any concomitant intraarticular pathology and to resect the torn ACL. Thereafter, the semitendinosus and gracilis tendons would typically be harvested through a longitudinal medial, parapatellar incision using a blunt, open-ended tendon stripper.

Study I and II: In the transtibial technique, the tibial tunnel was positioned using the 70 degrees tibial guide with the knee in full extension (Howell tibial guide, Arthrotek Inc., Warsaw, Indiana) [89, 113]. A moderate notchplasty was performed in all cases. The femoral tunnel was drilled aided by size-specific femoral aimers (Arthrotek Inc., Warsaw, Indiana) placed through the tibial tunnel with the knee held at a flexion angle of about 70-80 degrees. An additional femoral U-guide (Arthrotek Inc., Warsaw, Indiana) was used to ream a transverse tunnel for the femoral graft fixation. Femoral fixation of the graft was done with the BoneMulch screw (Biomet, Warsaw, Indiana). The knee was then repeatedly extended and flexed to allow stress relaxation of the graft. A moderate tension load was applied to the graft while it was fixed outside the tibial tunnel with a multi-spiked WasherLoc (Biomet, Warsaw, Indiana) and a compression screw.

Study III: all AM-portal technique ACL reconstructions were performed using a uniform single-bundle anatomic technique [32, 33]. A high lateral and a high medial parapatellar portal were used for visualization and instrumentation. An accessory AM portal was placed for unrestrained access to the femoral ACL insertion. Femoral tunnel placement was based on the bony landmarks and femoral remnants of the native ACL [33, 60]. A micro-fracture awl was used to demarcate the centre of the femoral footprint, aiming for a centre-to-centre ACL reconstruction. The knee was then moved to maximal flexion before the femoral tunnel was drilled over a guide pin with a graft-sized reamer. For femoral fixation an EndoButton CL (Smith &

Nephew Endoscopy, Andover, Massachusetts) was used, and for tibial fixation a Biosure screw (Smith & Nephew Endoscopy, Andover, Massachusetts) was used.

A control group of patients reconstructed with a transtibial technique was included for comparison of femoral tunnel placement to those in the anteromedial portal technique (AM). In this control group the tibial tunnel was placed by a tibial drill guide (Accufex, Smith & Nephew Endoscopy, Andover, Massachusetts) positioned in the central tibial footprint, slightly medial to the insertion of the anterior horn of the lateral meniscus. Through the tibial tunnel, a guide pin would be placed guided by "over-the-top" femoral aimers (Smith & Nephew Endoscopy, Andover, Massachusetts) before the femoral tunnel was drilled with a graft-sized reamer. A 5 mm offset aimer was used for ACL grafts sized 7 and 8 while a 6 mm aimer was used for graft sized 9 and 10 mm. The femoral fixation device was an extra-cortical EndoButton CL (Smith & Nephew Endoscopy, Andover, Massachusetts) while the tibial fixation was a Biosure screw (Smith & Nephew Endoscopy, Andover, Massachusetts).

Study IV: The AM-portal technique described in study III was also used in study IV.

Outcome evaluation

Patient reported outcome measures (PROMs)

IKDC (International Knee Documentation Committee) subjective score is an 18-item questionnaire that measures knee function, symptoms and sport activities. As suggested by its name, a committee consisting of members of the American Orthopaedic Society for Sports Medicine (AOSSM) and the European Society for Sports Traumatology, Knee Surgery and Arthroscopy (ESSKA) created this extensive test battery with the goal of standardizing measurements of patient outcomes after knee surgery or treatment [92]. Its validity and reliability has been tested and found good [80], and when tested against a battery of other knee-specific quality-of-life

measurements, the IKDC subjective score was found to contain most of the items that were important to patients when evaluating outcomes [180].

Lysholm score was first published in 1982 and is amongst the most widely used rating scales both clinically and for research purposes [125]. The score contains eight knee-specific items: *limping, locking, pain, stair climbing, use of support, instability, swelling and squatting*, and has been found to be a outcome measure after knee surgery [133].

The Tegner Activity Scale was developed as a complementary scaling system of activity in sports and work intentioned to be used with the Lysholm score [181]. A recent revisited examination of the responsiveness of this test-battery performed by Briggs et al. displayed good and reliable values for the score systems [31].

Clinical evaluation: Lachman test, KT-1000 Arthrometer and pivot shift

The Lachman test is performed with the patient lying in a supine position with the knee flexed to about 20 degrees [184]. While supporting the femur with one hand, an anterior translation is performed by pulling the tibia anteriorly relative to the femur. The degree of laxity is felt as a relative movement and was in the present study graded by the IKDC criteria as *normal*: up to 2 mm translation, *nearly normal* (1+): 3-5 mm translation, *abnormal* (2+): 6-10 mm, and *severely abnormal* (3+): 11 or more mm [138]. The Lachman test is described as the most sensitive way of eliciting increased anterior translation in the ACL deficient knee, and is recommended used instead of the anterior drawer test [168].

The KT-1000 Arthrometer (MedMetric Corp, San Diego, US) was developed to objectivise testing of anterior translation. The device is securely strapped to the patient's leg and testing is performed under standardized conditions (of 15, 20 and 30 pounds as well as a maximum manual pull) [48]. Results can be reported as in the Lachman test, according to IKDC criteria, but also summarized as mean values across groups [13, 55, 157]. If summarized, the uninjured knee is typically used as a

reference and reporting is performed as an injured-to-normal value (I-N-value). The latter way of grading (using the I-N index) has been recommended as the most appropriate way of reporting results [10].

Rotational instability is evaluated using the pivot shift test. It requires a combined dynamic movement to be elicited [134]. Although controversies exist, and a consensus on the "gold standard" of performing the test still is lacking, most clinical test resemble each other in execution and grading [123, 142]. The technique used in the current work was the flexion-rotation-drawer test described by Noyes et al. [151]. Noyes described this test as more sensitive than other comparative techniques – although such a difference has not been documented. Several studies have found the pivot shift test to have a good predictability of knee instability [104, 105]. A conventional grading of *normal* (0), *pivot glide* (1+), *pivot shift* (2+) and *gross pivot shift/subluxation* (3+) has been used [138].

Radiographic evaluation

In study I a trained musculoskeletal radiologist graded the level of OA development using the IKDC grading system [138]. Sagittal and slightly flexed coronal radiographs were acquired at the time of follow-up for the purpose of OA grading. Four levels were used to denote the radiological changes (*normal, mild, moderate* and *severe)*. In a recent comparison of intraobserver reliability and arthroscopic correlation across six commonly used systems the IKDC grading provided the best combination of intraobserver reliability and correlate to perioperative findings [191].

In study II tibial tunnel placement resulting from the use of the "anti-impingement" tibial guide was measured on sagittal and coronal radiographs. The Amis and Jakob line (AJ) refers to a line drawn parallel to the medial tibial plateau on a strict sagittal radiograph [9]. The crossing of a central line in the tunnel and the AJ line is reported as a percentage (from anterior to posterior) of the total AP distance. Anatomical studies has used this line to map the position of intraarticular landmarks, including the ACL, so that the AJ line can be used as a referencing tool [101]. A

recent study by Haasper et al. examined the effect of rotation around a central tibial axis and accuracy of tunnel measurements [74]. They concluded that up to 20% mal-rotations could be accepted without affecting accuracy of tunnel measurements.

Study III and IV used postoperative 3D-CT measurements to analyse femoral tunnel position. Such measurements are considered gold standard due to the clear and accurate visualisation of bony structures [27, 147]. All CT scans were performed on an extended knee and both a standard and a bone algorithm were used. After image 3D rendering (reconstruction) was completed, the images were placed in a true lateral view and the medial femoral condyle was removed to permit visualization of the inside of the lateral femoral condyle. Using a custom-made template – based on the Bernard and Hertel (B&H) grid – tunnel position could accurately be measured using Mdesk 3.4.2.2. (RSA BioMedical, Umea, Sweden). The Bernard and Hertel grid (also known as the Quadrant method) was first published in 1996 as an individualized way to measure femoral graft tunnels position [22]. Although first published for use on radiographs, several authors have also applied it for CT measurements [27, 43, 49]. A series of anatomical studies - exploring the ACL insertion sites – have made projections of them onto the B&H grid so that references for graft tunnel placement can be made [41, 156, 185].

Statistics

All statistical analyses were performed in SPSS (SPSS Inc., Chicago, Ill, USA) and an a priori significance level of 0.05 was chosen to denote statistical significance. Normality of data was assessed visually and tested (by Shapiro-Wilk test) where necessary.

In study I, mean, standard deviation and frequency distributions were used for descriptive analysis. A paired samples t-test was used to test data from the same patient, while an independent samples t-test was used to test means across several groups defined in the study. ANOVA analysis was used for comparison of equality of the means – e.g. in Lysholm score across different grades of pivot shift. Further

bivariate correlations were used to look for linear relationships between several preoperative factors and the final Lysholm score. Finally chi-square analysis was used to test for differences in frequency of OA based on concomitant meniscal surgery or presence of pivot shift at follow-up evaluation.

In study II, mean, SD and frequency distributions were calculated for normal data while median and range was calculated for skewed data. Paired samples t-tests were used for comparison of repeated data while independent samples t-test was used to compare means across groups. In non-parametric data, the Mann-Whitney U test was used for between group comparisons. ANOVA analysis was used for testing of subjective data across groups classified according to pivot shift grading, while chi-square statistics were used to test different laxity findings across subgroups of tunnel placements.

In study III, intraclass correlation coefficients (ICC) utilizing Chronbach alpha statistics was used for testing of intra-observer and inter-observer reliability of the CT measurements. Independent samples t-test was used to make comparisons of tunnel placements across groups. Chi-square statistics were used to compare demographic data between groups. Further a post hoc power analysis was performed to examine the probability of detecting difference of 5% in the x-axis of the B&H grid. With a group size of 50 and a SD of 8, a statistical power of 84% for detecting such a difference was found.

In study IV, chi-square statistics were used to test for differences of frequencies in the demographic data. Intra-observer and inter-observer reliability was measured using the intraclass correlation coefficient (ICC) using Chronbach alpha statistics. Further intra-group differences in tunnel placements were measured using independent samples t-test.

Ethics

The regional ethical committee (Regional Etisk Komite Helse Vest) did review and

approve of all four studies. Study I and II was approved in 2011 (REK ID: 3366) while study III and IV was approved in 2014 (REK ID 2014:264). In all four studies participation was dependent on patients giving their voluntary informed consent. Pregnant women and women who could not rule out that they were pregnant, were excluded from radiological examination. In study I and study II, any patients having significant problems with their knee at the time of follow-up would be offered an extra evaluation by a knee surgeon at the outpatient clinic.

Summary of papers

Paper I: Long-term results after reconstruction of the ACL with hamstrings autograft and transtibial femoral drilling

Aims: To evaluate long-term outcomes after ACL reconstruction using a transtibial technique *ad modum* Howell and to identify potential predictors of inferior outcome at long-term follow-up.

Patients: The first 96 patients treated for ACL insufficiency by this transtibial technique were eligible for inclusion (Figure 1). Of these, 83 patients (86%) were evaluated – 47 male and 36 female.
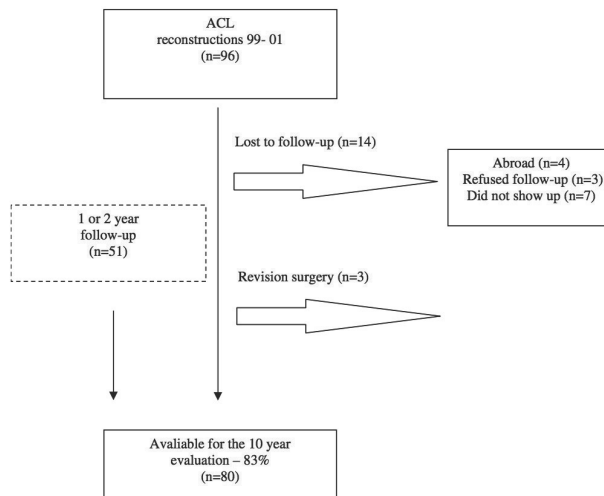

FIGURE 1: Inclusion flowchart for study I and II

Methods: An independent examiner performed the clinical evaluation including: Lachman, Pivot shift, KT-1000 evaluation and range of motion measurements using a goniometer. Lysholm score was performed by interview, but also completed by the patients along with IKDC subjective score and Tegner Activity Scale. Radiological examination was performed with coronal and sagittal radiographs to evaluate OA using the IKDC classification.

Results: Three patients had undergone revision surgery at the time of follow-up; and another 9 patients had undergone partial meniscectomy, hardware removal or second-look arthroscopy due to persisting symptoms. Six patients had moderate OA at radiographs, none severe OA. None of the patients had undergone any knee replacement.

The overall Lysholm score was 87 (SD 11) and the IKDC subjective score was 83 (SD 14.9). There was a significant difference in patient reported and interview-based Lysholm score (89 versus 87) (P=0.01) – but this difference was hardly of clinical significance. A high linear correlation between the IKDC subjective score (R=0.80, P=0.01) and the Lysholm score was found. When comparing the mean Lysholm score at 10 year with those either at 12 months or 24 months (available in 49 patients) – no differences could be demonstrated (n.s.).

Eight per cent of patients were found to have KT-1000 values of 5 mm or greater in I-N difference. Fourteen per cent of the patients had a Lachman of 2+ and 20% of patients had a positive pivot shift test (2+). Patients with 2+ pivot shift were found to have a significant lower Lysholm score (P=0.03) than patients with negative or 1+ pivot shift. No severe restrictions of ROM were found, but 5 patients had a moderate extension deficit.

There was a significant higher incidence of OA (P=0.05) at follow-up among those who had a partial meniscectomy at the time of ACL surgery compared to the other patients. Further, there was a significant difference in Lysholm score of 82 versus 89 (P=0.03) dependent of whether the right or the left knee, respectively, was

treated. No differences in IKDC 2000 or Lysholm scores were found dependent on overweight, smoking, meniscal resection or pre-operative Tegner score (n.s.).

Conclusion: Good outcomes, mean IKDC subjective and Lysholm scores of 83 and 87 respectively, were found in ACL reconstructed patients 10 years after surgery. A high incidence of pivot shift, of 20%, was consistently correlated to inferior PROMs – and adds to the critique of the transtibial technique.

Paper II: Effect of a too posterior placement of the tibial tunnel on clinical outcome 10-12 years after anterior cruciate ligament reconstruction using the 70-degree tibial guide

Aims: To examine the effect on tibial tunnel placement of the 70-degree tibial "anti-impingement" drill guide and correlate these to clinical findings at minimum 10 years after ACL reconstruction.

Patients: The same patient cohort of 83 patients used in paper I was included in paper II (Figure 1).

Methods: Sagittal and coronal radiographs were performed to assess tibial tunnel placement. On sagittal radiographs, the AP placement of the tunnel was measured along the AJ line (Figure 2), and a posterior tibial tunnel placement was defined as 50% or more of the AP-distance. On coronal radiographs the inclination of the tibial tunnel was measured as the angle relative to a line across the tibial plateau (Figure 3), and defined as steep if found to be 75 degrees or more in inclination. The tibial tunnels were graded as having absent, moderate or severe impingement – dependent on the tibial tunnel placement relative to an extension of the Blumensaats line on sagittal radiographs. Potential relations between clinical findings, subjective scores (Lysholm and IKDC subjective) and radiological parameters were explored.
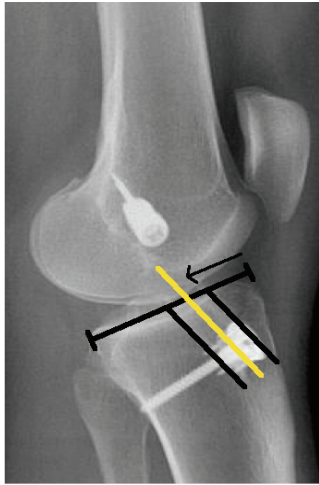
Figure 2 – Sagittal assessment of the AP-position of the tibial tunnels along the Amis and Jakob line
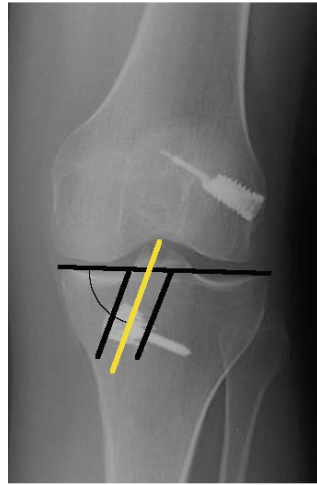
Figure 3 – Assessment of the steepness of tibial tunnels was done in the coronal plane

Results: Mean tunnel placement along the AJ-line was 46% (SD 5) and the mean tunnel inclination was 71 degrees (SD 4). When assessing whether the tibial tunnel had any signs of impingement, eight patients were found to have moderate impingement; but no patients were found to have severe impingement. No differences (n.s.) were found in the subjective scores or clinical findings (n.s.) between patients with moderate impingement and patients with absent impingement.

A total of 24% of all patients had a posterior tunnel position as assessed in the AJ-line, and 14% had a steep tunnel inclination as assessed in the coronal plane. We found no differences (n.s.) in subjective scores when comparing sagittal and coronal tunnel placement considering anterior versus posterior and steep versus normal tunnel placements. A significant difference was, however, found between anterior and posterior tunnel placement – with a higher incidence of 2+ pivot shift in the posterior tunnel group (P=0.02).

Conclusions: A high incidence (of 24%) of posterior tibial tunnels, defined as 50% or more of the AP-distance of the AJ-line, was found at the radiological evaluation of ACL reconstruction using the 70-degree tibial drill-guide. These patients were found

to have more rotational instability (2+ pivot shift) – with associated inferior subjective scores – than patients with normal rotational laxity.

Paper III: The effect of feedback from postoperative 3D-CT on placement of femoral tunnels in single-bundle anatomic ACL reconstruction

Aims: To examine the reliability of intraarticular landmarks in guiding placement of the femoral tunnel in single-bundle anatomic ACL reconstruction, and to evaluate any potential learning effect from feedback on the femoral tunnel position from postoperative 3D-CT measurements.

Patients: One hundred and seventy-two consecutive patients were prospectively included in the study; all surgically treated for ACL deficiency with reconstruction by the same surgeon at a single centre. Eighty-one per cent of patients were available for evaluation. No difference was found in age or gender between groups (n.s).

Methods: The first 47 patients (TT group) were treated with a transtibial surgical approach whilst the next 125 patients were treated with a single-bundle anatomic approach. When changing to the AM-portal technique, the remnants of the native ACL and the bony landmarks on the inside of the lateral epicondyle were used as guidance for tunnel placement (AM1 group). Thereafter, feedback on tunnel placement from postoperative CT was introduced (AM2 group). Femoral tunnel position was measured using the Bernard and Hertel grid and compared to an empirical anatomical centre. Any effect of the feedback was measured as the high-low distance, the deep-shallow distance and a hybrid "absolute distance" from the empirical centre. Two independent examiners, not involved in patient treatment, performed all measurements.

Results: When comparing the postoperative tunnel positions to the empirical anatomic centre, a significant reduction in the absolute distance of the femoral tunnel position was found when changing from the transtibial technique to the AM-portal

technique (P=0.004). A further reduction in the absolute distance was found during the feedback period – with a mean tunnel position closer to the ideal centre in AM2 as compared to AM1 (P=0.001).

Conclusions: Anatomical landmarks and remnants of the torn ACL were found unreliable for accurate femoral tunnel placement in the AM portal technique, therefore an aid for tunnel placement is recommended if novel to this technique or if in a learning situation. Further, postoperative CT scans were efficient in improving the femoral tunnel placement in an experienced surgeon in the midst of changing from a transtibial to an anatomic approach for femoral tunnel placement.

Paper IV: The effect of intraoperative fluoroscopy on the accuracy of femoral tunnel placement in single-bundle anatomic ACL reconstruction

Aims: To evaluate any potential effects on the accuracy of femoral tunnel placement by the use of intraoperative fluoroscopy (as an aid in single-bundle anatomic ACL reconstruction).

Patients: A prospective consecutive series of 81 patients were included in the study – all treated for ACL deficiency by a single surgeon using a single-bundle anatomic ACL technique. Eighty-one per cent of patients were available for the postoperative evaluation and were therefore included in analyses. Forty-four per cent of patients were men and the mean age at surgery was 32 years. No differences (n.s.) in demographics between the two groups in the study were found.

Methods: An experienced ACL surgeon, novel to the intraoperative fluoroscopic technique, was introduced to its use. By postoperative 3D-CT analysis, femoral tunnel placements were compared between a control group of 48 patients who underwent ACL reconstruction without fluoroscopy, and a group of 33 patients who were reconstructed with the fluoroscopic assist. The Bernard and Hertel grid was used for tunnel assessment. Any possible effects on accuracy of femoral tunnel placement was measured as mean tunnel placements and compared to an empirical

anatomical centre in terms of the high-low placement, the deep-shallow placement and a hybrid "absolute distance" from an empirical anatomic centre. Two independent examiners, not involved in patient treatment, performed all measurements.

Results: The inter- and intra-rater reliability of tunnel evaluation on postoperative 3D-CT were both found to be excellent. Tunnel placements in the *fluoroscopy-assisted* group and the *non fluoroscopy-assisted* group are presented in Figure 4. When comparing the high-low position between the *fluoroscopy-assisted* group and the *non-fluoroscopy assisted* group, a significant difference (P=0.001) of the femoral tunnel was found, in which the *fluoroscopy-assisted* group had a mean femoral tunnel position closer to the ideal tunnel centre. There were no differences (n.s.) in femoral tunnel position in the absolute distances (12.5 versus 9.8) or in the deep-shallow position between the groups.

Figure 4 – Template CT showing femoral tunnel placement in the Bernard-Hertel grid as compared to an ideal anatomical centre before and after fluoroscopy [a][b]
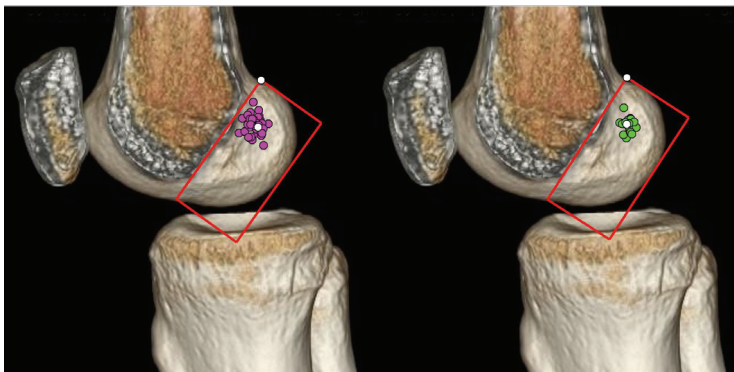
a)   *White dot* represents anatomical reference of 27% in deep-shallow and 34% in high-low directions [27]
b)   *Purple dots*= before fluoroscopy, *green dots*= after fluoroscopy

Conclusions: In the current study, the use of intraoperative fluoroscopy had a significant positive effect on femoral tunnel placement by bringing the tunnel

position closer to an ideal position – an empirical anatomic centre. In a learning situation, or if performing a low volume of annual ACL reconstructions, using the anatomic approach for tunnel placement, the authors hold that fluoroscopy can be a reliable aid for securing a desired femoral tunnel position.

Discussion

Methodological considerations

Study design

The use of a retrospective approach, as in paper I and II, makes the studies less robust for controlling causality due to a potential selection bias. Evaluation using a prospective patient cohort would be preferable in that sense, but is more resource demanding and was not viable for the current work. Since all data have been prospectively registered in an internal database we believe that the selection bias is minimised and that the results are therefore reliable. A good follow-up rate of the patient cohort, including 86% of eligible patients, aids to giving a correct picture of the outcomes in patients treated with ACL reconstruction *ad modum* Howell from 1999 to 2001 at our clinic.

Another strength of studies I and II is the long mean follow-up time of 10 years. Most studies evaluating outcomes after ACL surgery have a shorter follow-up time, e.g., 1-2 years after surgery. Revision surgery, and additional surgery that could be related to the initial ACL injury, continues to occur after the initial return to sports/activities. The continuing evaluation (beyond the first 1-2 years after surgery) of these patients is a prerequisite for getting a comprehensive view of various measures of outcome including: revision rates, development of osteoarthritis, level of function and objectively assessed knee stability.

The present use of an independent examiner also adds to the reliability of the results of the clinical examination. It will help avoid bias that might result from a surgeon who examines his or her own patients.

Studies III and IV were conducted as a prospective cohort of consecutive ACL reconstructed patients where the surgeon was exposed to (1) postoperative CT feedback and (2) feedback from intraoperative fluoroscopy. The prospective nature of

the study made it ideal to measure potential effects of the exposures on postoperative tunnel placements. Due to travel distances, there was unfortunately a certain loss to follow-up during the study (19%). This prevents a complete picture of the outcome. There was, however, no differences (n.s.) in demographic data (age, gender) between included patients and drop-out, thus there is no reason to believe that included patients are not representative for patient surgically treated for ACL insufficiency from 2012 to 2014 at the clinic.

Another limitation of study III and IV (also described as a potential weakness of cohort studies) is the risk of confounding factors affecting the outcomes. Since the AM-portal technique was new to the participating surgeon, there might be an effect of repeat surgery on femoral tunnel placement. In study IV, a group of patients was included before any feedback was commenced (AM1). A comparison of femoral tunnel placement in all three variables (high-low, deep-shallow and mean absolute distance) between the first half and second half of that group did not show any difference in mean tunnel placement (n.s.). The authors therefore hold that repeat surgery is therefore less likely a confounder to the effects of postoperative feedback and intraoperative fluoroscopy.

Outcome evaluation

Traditionally, evaluation of outcome after ACL surgery was often limited to a clinical examination, where evaluation of anteroposterior stability of the knee was viewed as one of the most important variables [98]. Today, with an evolution of new validated measures, the focus is on using several simultaneous approaches (including PROMs, functional measures, clinical and radiological evaluation) for patient evaluation. This multitudinous approach is reflected in the current work.

The PROMs used in study I and II, namely Lysholm score, Tegner score and IKDC subjective score, are among the most commonly used questionnaires when evaluating ACL surgery. They give a comprehensive view of function based on the patient's own perception of the knee symptoms and function. Lysholm score has been

used as the primary PROM at our clinic over time and was therefore included to allow for comparison of results over time. The choice to also include IKDC subjective score was based on indications of a so-called *ceiling effect* in the Lysholm score. Findings such as those by Blonna et al. and Bengtsson et al. of unusually high Lysholm score in ACL injured patients relative to other patients, and a ceiling effect of 64% - 70%, has questioned whether Lysholm is appropriate for following ACL injured patients over time [19, 28]. Further, a work by Risberg et al. investigated the ability of Lysholm to detect changes over time when evaluation ACL surgery [163]. It was found to perform poorly when compared to IKDC and Cincinnati score at 3, 6, 12 and 24 months after surgery.

Tegner Activity Scale was published as a complement to the Lysholm score and is a scaling system where patients grade their level of activity from 0 to 10 based on a list of activities/sports [181]. In the current studies, it was the most direct measure of the level of function patients had before surgery and at the follow-up evaluation. The Tegner score does, however, seem to have some weaknesses and a revised way of measuring level of activity should perhaps be considered. The authors propose that a system that would (1) integrate scoring for more than one sport, (2) include a scaling of what level patients returned to within the sport, and (3) adding an investigating variable of why patient did not return to the same level - would give a more sophisticated approach. Also the Tegner Scale seems to have some discrepancies, since a sport like elite handball - in the authors experience one of the most demanding activities for an ACL deficient knee - is not classified at a top level. Study I and study II did not include any functional testing of the knee, and inclusion of hop testing or isokinetic strength testing would give a more in-depth view of proprioceptive and muscular function [162].

Assessment of rotational laxity is widely used, and many efforts have been made to objectivise (much like using a KT-1000 device) the way of measuring the "pivot shift" [23, 83, 122, 123]. Technologies like accelerometer devices, video analysis and kinematic measurement have been proposed as aids to standardize across examiners. However, there seem to be a lack of consensus on how to perform this

examination correctly. A study by Musahl et al. involving 12 expert knee surgeons revealed a great variation in technique and performance of pivot shift examination [142]. Even after the surgeons were given an instructional introduction to a standardized method, distinct differences were still evident when a new comparison of techniques was performed. Such variability, in execution of testing and assessment of rotational laxity, makes is hard to compare findings across clinical studies.

Studies III and IV investigated the effect on femoral tunnel placement of feedback from 3D-CT and use of intraoperative fluoroscopy. Effects were measured on postoperative CT scans, comparing the femoral tunnel placements to an empirical ideal femoral footprint. Although the use of 3D-CT for evaluating tunnel placement is relatively new, use of postoperative radiographs for controlling graft tunnels positions is well known. A paper by Pinczewski et al. described radiological landmarks for both tibial and femoral tunnels on postoperative sagittal and coronal radiographs [158]. Although this method was found to give a good indication of the resultant tunnel placement, there was only a moderate agreement on femoral tunnel positions between observers. An intraclass correlation coefficient (ICC) of 0.73 (corresponding only to a *substantial* agreement according to Landis et al. [110]) was described. Unpublished work from our clinic has found an ICC for femoral tunnel measurement of 0.64 on standard radiographs. In comparison, the ICC from intra-observer comparisons in the current studies ranged from 0.92 to 0.99, indicating the high level of accuracy that can be found when measuring on 3D-CT.

This accuracy of CT scans does, however, come with a cost. Although the current work did present the recorded level of radiation, it is known that patients are exposed to a higher effective dose (ED) under a CT scan than during a simple radiograph. Although modern scanners have reduced the exposure, extrapolation indicates that a CT of the knee still equals to two chest radiographs [153]. Postoperative CT scans should perhaps therefore only be used for selected cases – for quality control, during change of surgical techniques and in a learning situation.

Results

Long-term results after ACL reconstruction

Aggregated data on outcome after ACL surgery, like registry studies, commonly use revision surgery and knee replacement as endpoints. There are, however, indications that these endpoints account for only some of the "failures" that occur after surgery. Clinical follow-up evaluations have the benefit of gaining in-depth insight using a broader approach for outcome evaluation. A recent systematic review by Crawford et al. analysed data in 14 clinical long-term follow-up studies [44]. Failure, as defined in the individual papers, was found in an average of 6% of patients (ranging from 0% to 13%) at minimum 10 years follow-up. When adding broad criteria for clinical failure such as; minimum 2+ pivot shift, IKDC objective grad C or D or KT-1000 I-N difference of 5 mm or more, the accumulative rates of failure rose to a mean of 12% (ranging from 3% to 30%). Although these rates seem to be higher than what is commonly reported [66, 155], Crawford et al. still considered that the numbers could underestimate the reality as no PROMs or functional tests were included in their study. In paper I (of the current thesis), revision surgery had been performed in 4% of patients. If this had been defined as the only endpoint measure (of failure), there would have been far less failures than if 2+ pivot shift, as was found in 20% of patients, also had been used.

The high incidence of 2+ pivot shift was somewhat surprising in light of relatively good mean Lysholm and IKDC subjective scores. When looking at the Tegner Activity Scale there has, however, been an evident reduction in activity from a preoperative median score of 7 to a median score of 5 at the final evaluation. This reduction can in part be seen as a natural transition to a more sedate lifestyle with increasing age (10 years in the current study), but may also be interpreted as an overall reduced knee function compared to preoperative levels. By adapting to a lower level of activity, the patients can have a (self-assessed) satisfactory knee function, whilst objective tests would reveal an unstable knee. This emphasizes the

additive effect of using both PROMs and clinical examination to evaluate results after surgery.

When assessing results after ACL surgery, osteoarthritis (OA) is seen as a definite outcome measure. The current work revealed a higher incidence of OA in patients that had a partial meniscectomy at the time of surgery. Still, the overall rate of OA was low. Inclusion of a non-operatively treated control group would have given a better insight into any protective effect of ACL surgery. This was the aim of a recent work by Chalmers et al., where studies involving both operative and non-operative managements were compared [36]. They identified 27 patient cohorts with a total of 1,585 patients that had undergone reconstruction and 13 cohorts with 685 patients that had undergone non-operative treatment – mean follow-up time was 13.9 years. Their meta-analysis revealed that patients treated with an operative approach had fewer meniscal injuries, less need for secondary surgery and a significant improved level of activity (measured by Tegner Activity Score) compared to patients that were treated with a non-operative approach. They found no differences in Lysholm score, IKDC scores or the development of OA between the groups.

As noted by Chalmers, the on-going evolution in surgical techniques makes long-term evaluation challenging. Given that a minimum of 10 years, preferably more, is required to fully assess OA development after any intervention in the ACL injured patient, the recommended surgical techniques may have changed into something dramatically different when the results are reported. In a study by Strand et al. – one of few with more than 20 years follow-up time – a series of 140 ACL reconstructed patients were evaluated [176]. Although the study gave important knowledge of secondary injuries and the development of OA, the technique used for repairing the ACL, namely a primary suture of the torn ligament, was no longer in use at the time of publication. Changes in other relevant factors, like rehabilitation, treatment of concomitant injuries or policy on return to sports might also affect the final outcome. Therefore, short- to mid-term follow-up evaluation will often be a compromise – between reporting on appropriate outcome parameters on one side and not presenting out-dated technical data on the other side.

Tibial tunnel placement related to clinical outcome

An overly anterior tibial tunnel placement is a feared complication in ACL surgery. As described by Howell et al. it can lead to impingement of the ACL graft from the femoral roof and result in loss of extension in the postoperative period [86, 88]. Studies analysing reasons for revision surgery has confirmed such detrimental effects (of too anterior placement) [93, 150, 200]. It is therefore easy to understand why an "anti-impingement" guide like the one used in Paper I and Paper II became popular among knee surgeons. As such a guide was used, the finding of radiological *moderate* impingement in 8 patients in Paper II (meaning that parts of the tibial tunnel were slightly anterior to an extension of the Blumensaats line) was somewhat unexpected. This patient group was, however, not found to have inferior clinical results as compared to the rest of the patient population.

In a retrospective case-series by Howell et al., not using the anti-impingement guide, 47 patients were classified according to the same radiological criteria for impingement [88]. In cases with *severe* radiological impingement (meaning that the posterior border of the tibial tunnel was anterior to the extension of the Blumensaats line), 4 out of 4 patients were found to have a failure of the reconstruction, whilst in the 14 cases of *moderate* radiological impingement 4 patients had graft failure. In the final 29 patients – where no radiological impingement was found – 3 cases of clinical failure did occur. While that study showed a relationship between radiological *severe* impingement and clinical failure, the patient sample was not large enough to conclude regarding *moderate* impingement and risk of failure. In conclusion, the current radiological methodology used for assessing impingement seems to be rather crude, and should probably only be used as a predictive tool in cases where *severe* impingement of the ACL graft is found.

As many as 24% of patients included in paper II were found to have a *posterior* tibial tunnel placement as assessed along the AJ-line. This can be linked to the use of the anti-impingement guide. The avoidance of a far anterior tunnel placement, as such, came at the cost of a relatively high incidence of posterior tunnel

placement. An interesting finding was that two of the three patients who were revised at the time of the follow-up had a *far posterior* tibial tunnel of 64% and 67% along the AJ-line. Although these findings align with those of another study – where revised patients were found to have a significantly more posterior tibial tunnel position than non-revised patients [158] – it would not be appropriate to draw any conclusions based on so few cases.

Several factors can be seen as contributors to the higher incidence of 2+ pivot shift in the *posterior* tibial tunnel group (in Study II). A biomechanical study by Bedi et al. compared ACL reconstruction using a central tibial tunnel placement to a more posterior tibial tunnel placement [16]. They found that the knee with a posterior tibial tunnel was less able to control anterior translation and rotational laxity as compared to the more central tibial tunnel position. This was believed to be due to a more vertical graft placement if using a posterior rather than a central tunnel position. An additional contribution in the current study could be the transtibial femoral tunnel placements. Given that the typical transtibial femoral tunnel is described as relatively posterior and proximal on the condylar wall, this would probably add to the vertical orientation of the graft [16, 54]. Current recommendations of tibial tunnel placements are somewhat variable, but will often involve a position in the central part of the native footprint – guided by an intraarticular landmark like the anterior horn of the lateral meniscus [32, 33, 189]. Such a position would give a more horizontal graft position that would be biomechanically more favourable – and more "anatomic".

Learning curve of the AM portal technique

The consecutive patient series reported in Paper 3 represents an experienced ACL surgeon's transition from the TT technique to the anatomic single bundle technique – where the most important difference is the approach for femoral tunnel placement. Although several papers have reported on differences in the typical transtibial and AM-portal femoral tunnel position, none have reported on the transition between the techniques. The study can perhaps therefore be interpreted as a report on the "learning curve" of femoral tunnel placement using only available intraarticular

landmarks as guidance. The improvement seen over time in relative tunnel placement as compared to the "ideal tunnel centre" can be attributed as caused by several factors – but most importantly due to the postoperative feedback from CT scans (Figure 3). A confounding factor could possibly be repeat surgery over time, but with two relatively large groups surgically treated with and without feedback on tunnel position, AM1 (N=77) and AM2 (N=48) respectively, the authors hold that this is not the dominant effect in the study.

One important limitation of the current study was the inclusion of only one surgeon. A recent publication from Wolf et al. looked at graft tunnel positioning performed in cadaveric knees by 12 surgeons with differing level of expertise [190]. A fictional femoral footprint was superimposed on the knees and tunnels were denoted as "anatomic" if inside of the fictional footprint boundaries, and "non-anatomic" if outside of these boundaries. Overall 82% (55/67) of femoral tunnels were positioned within the boundaries of the footprint, and was therefore denoted as successful. Surprisingly there was no difference in tunnel position accuracy dependent on the level of experience (assessed as the annual number of ACL reconstructions and years of experience) in the surgeons. Unlike the current work, none of the surgeons were new to their technique of preference and a "learning curve" of tunnel placement was therefore probably not captured in that study. Although 82% of surgeons placed the tunnel within the boundaries of the ACL insertion, this can represent a significant variation since the ACL "footprint" is of a considerable size [169]. It is also known that varying the tunnel placement within the native footprint will have significant effects on knee kinematics. Thus, this type of measure for successful tunnel placement is probably a bit crude.

Use of aids in assisting femoral tunnel placement

Fluoroscopy is a commonly used tool in orthopaedic surgery, and its use to assist graft tunnel positioning in ACL reconstruction have formerly been described by several authors [75, 111]. The recent technical advances in surgical navigational systems have probably overshadowed this older and cruder technique. The continued

efforts to reduce surgical error has driven the evolution of computer assisted surgery (CAS) – which has been explored extensively and is found to reduce levels of misalignment in procedures such as knee replacement [21, 165]. A recent cost-effectiveness assessment from Margier et al., evaluating computer assisted navigation in ACL surgery, found an effect on reducing operating times in junior surgeons, but no clinical benefit at 1-2 year follow-up evaluation [131]. In that study, as in several other studies evaluating CAS, the added costs of equipment and extended time in the OR prevents the technology from being cost-effective. In comparison, the use of intraoperative fluoroscopy adds very little cost and time to ACL surgery. The procedure described in Study IV, requires a standard fluoroscopic device (that is commonly available in most orthopaedic departments) as well as a template for comparison of the intraoperative findings to that of the ideal position (Figure 5). Although the current study did not record the time used on the fluoroscopic assist, it is – in the authors' experience – relatively quick to master the technique, and therefore only a few minutes will effectively be added to the operating time.

Figure 5 – Intraoperative use of fluoroscopy to secure femoral tunnel placement using a common fluoroscopic device and a generic template for tunnel position

The empirical central femoral footprint applied in the current work is based on anatomical findings across a range of studies, but represents a simplified approach to

anatomical variation [27]. The inside of the distal femur, more specifically the femoral notch, is known to exhibit a wide variation both in terms of shape and size [121, 147]. The risk is, therefore, that this "one size fits all" approach will in some cases misplace tunnels due to the natural variation of knees. One could argue that the current empirical anatomical footprint does, to a certain extent, take this variation into account since it is based on an average across a range of anatomical studies. The avoidance of severely misplaced tunnels is, however, the main effect of using fluoroscopy and can therefore justify use of the technique. The reduced variation seen throughout study III and IV does, however, need to be linked to more definite outcome measures to show its patient-level effect.

The improvement in femoral tunnel placement, relative to the ideal/empirical ACL centre, was only found in the high-low position (not in the deep-shallow or in the total absolute distance) in study IV. Since paper III, involving feedback on tunnel position from postoperative CT scans, preceded introduction of the fluoroscopy it could be argued that the effect would probably have been larger if fluoroscopy was the only aid used for tunnel placement. Rather than concluding that one approach is superior to the other, the importance lies in appreciating the effect of having some sort of aid for guiding tunnel placement when new to the anatomic approach to femoral tunnel placement.

General considerations

The ultimate goals of ACL surgery is: (1) to restore the function of an ACL deficient knee, (2) to enable the patient to return to previous – or to the desired – level of activity and (3) to prevent the detrimental effects of knee instability. In ACL surgery, as in most areas of patient treatment, the outcome depends on a multitude of variables. Pinczewski et al. used a schematic approach for a range of these, and by categorizing them as *intrinsic* or *extrinsic* the authors described how these variables relate to the patient [157]. Of the factors *intrinsic* to the patient, preoperative function, concurrent intra-articular injuries and pathological joint laxity are

important. Of the *extrinsic* factors, choice of ACL graft, surgeon experience, correct graft position, choice of graft fixation and postoperative rehabilitation needs to be considered. Although some factors are non-modifiable, at least after the injury has happened, a surgeon should bear this multitudinous approach in mind at all times of patient treatment. Of the modifiable, mostly *extrinsic* factors, optimal graft choice, optimal graft fixation and the best postoperative rehabilitation are all subjects of on-going debate [24, 25, 46, 109, 114, 128, 155]. In the current thesis the two areas that have been extensively investigated are (1) the graft position and (2) surgeon experience – the latter displayed through the change from the transtibial technique to the anteromedial portal technique.

Much like Danish ACL surgeons have changed their technique for femoral graft tunnel position, an international survey found that 63% of North American and 82% of international ACL surgeons now prefers the AM portal technique [159]. With multiple cadaveric studies highlighting the difficulty of consistently achieving a femoral graft tunnel placement in the native footprint (i.e. an anatomic tunnel position) in the TT technique, the proposed benefit of changing to the AM-portal drilling is that of enabling a more "anatomic" femoral tunnel placement [63, 135]. This effect was evident in a high-quality review by Riboh et al. [161]. They included cadaveric, anatomical and clinical studies for meta-analysis and meta-regression comparing the two techniques. The AM portal technique resulted in a mean tunnel position that was 2.7 mm closer to the centre of the femoral footprint. Biomechanical studies displayed a difference – in favour of the AM portal technique – in Lachman and simulated pivot shift. The clinical studies could not find any difference in IKDC or Tegner scores, but there was a small and clinically non-relevant difference in the Lysholm score (0.63 point). Although the time-zero studies found several benefits – these were, in other words, not found to translate into a clinical improvement.

A more recent review by Liu et al. had a somewhat different focus when comparing the TT and the AM portal technique [118]. Nine studies with a total of 769 patients were included on the basis that physical examination and scoring systems were used for evaluating the outcomes. When looking at the clinical examination, the

AM portal technique was favourable due to: a higher proportion of negative Lachman, a higher proportion of negative pivot-shift and less anterior translation as measured by KT-1000. The same significant findings were evident in: VAS scoring, IKDC total score and Lysholm scores. Although statistically significant, all the latter were well below the minimal clinical important difference (MIC) for the respective rating systems. Relatively small differences were found between the techniques, but the main conclusion was that ACL reconstruction using the AM portal approach was superior to the transtibial approach.

It is important to note that there are very few static "truths" in the world of research. Several recent evolvements should therefore be mentioned. First of all, several authors have emphasized how recent changes in the transtibial techniques have made the current TT approach more "anatomic" than the techniques that were dominantly used in the 1990´s [26, 78, 161]. By modifying the technique, some authors have displayed how they can now obtain (TT) tunnel placement within the footprint of the femoral ACL [26, 96]. Further, although the clinical difference between the AM and the TT technique has never been definitive, some recent clinical studies suggest that there is no difference in outcomes between techniques. Lee et al. retrospectively matched 52 patients treated with the AM-portal approach and 52 patients treated with the TT approach [96]. At a mean follow-up of 24 months, there were no significant differences in pivot shift evaluation, KT-2000 testing, Lysholm score, IKDC subjective score or Tegner activity score. Another study by Youm et al. randomized 40 patients to either AM-portal reaming or a modified TT reaming of the femoral tunnel [196]. The follow-up evaluation was conducted at 24 months after surgery and included KT-1000, pivot shift examination, Lysholm, IKDC subjective score and IKDC total score. There were no differences in any of the outcomes at the final evaluation. In the two studies above there were only small differences in the resulting tunnel placements – a possible explanation of why no clinical differences were found.

The Danish ACL registry reported on outcomes in a transitional period from the TT technique to the AM-portal technique – where the use of the AM-portal

technique increased from 13% (in 2007) to more than 40% (in 2010) [159]. In a sense, the "learning curve" of Danish ACL surgeons was therefore captured. It has also been discussed whether the effective change in tunnel position would change the knee kinematics and that an anatomic graft position would face greater tensile strengths during knee loading. At 4 years postoperative with evaluation of a total of 9,239 ACL reconstructions, a relative risk of revision in the AM technique of 2.04 compared to the TT technique was displayed. Although detailed patient-level data – such as tunnel placement – was not available in that study, one could speculate whether some of the effects found in Paper III could also have been seen in that population.

The notion of a "learning curve" is well known from other areas of surgery. The importance of repeat surgery has been acknowledged, and its effect on improving outcomes has been well documented in areas such as urology. Studies investigating robotic systems for prostatectomy have found that a plateau in levels of complications (e.g. nerve lesions leading to urinary incompetence) could be reached after 150-250 cases [3, 51]. Recommendations based on these findings where that simulator use and comprehensive mentoring-programmes would be important if aiming to train experts surgeons - and avoid complications at the same time. In arthroscopic surgery few such studies have been performed. One report by Liu et al. suggested that 60 cases of would be needed to master an endoscopic technique, while about 150 cases would be required to reach the advanced level [119]. Another study, by Hohman et al., investigated how many ACL reconstructions a recent consultant knee surgeon would have to perform to reach a plateau in the variation of femoral and tibial tunnel placement [81]. Much like in paper III, postoperative radiological evaluation (using radiographs) was performed. Through 200 cases, the femoral tunnel position did exhibit considerably less variation after 75 cases. In contrast, the tibial tunnel placement continuously improved after more than 100 cases. It was not clear whether the surgeon was blinded to the radiographs or not, and whether he aimed for any "ideal" radiographic position. The authors proposed that 100 cases of ACL surgery –

additional to those encountered during formal training – would be required to refine the technique.

The results from study III and IV suggest that using only anatomical landmarks and the remnants of the torn ACL can result in an unwanted variation of femoral tunnel placement when changing to the AM-portal technique. Further, there seems to be an effect of introducing aids (feedback from CT scans or fluoroscopy) to help guide the tunnel placement. Other aids, like computer-assisted surgery, or the "ruler-method" have also been found to help achieve consistency in tunnel placement [27, 131] and could therefore also be considered. If there are ways to reduce the time to mastery of ACL surgery, this is an important message to purvey. With the knowledge that 85% of American surgeons perform less than 10 ACL surgeries per year [64], and that many colleagues in-training are about to endeavour on their consultancy, we think there might be a future role for any aids – including intra- or postoperative radiological feedback – to help reduce a learning curve.

The current thesis have reported on results from a formerly extensively used technique for ACL reconstruction, and have investigated the transition to a new technique by evaluating the resultant femoral tunnel placement – also as an effect of introducing aids for guiding the placement. Knowledge of the effects of differing graft tunnel position and of the effect of changing techniques for ACL surgery are only pieces of the jigsaw puzzle that makes out the current knowledge database on ACL surgery. This brings us back to Pinczewskis model with both *internal* and *external* factors that affect patient outcomes. Tunnel placement, as one of the *external* factors, should be optimized at time of surgery, but is only one of many steps that needs perfection to restore knee function and help the patient back to their desired level of activity. The multitudinous approach enveloping factors both *internal* and *external* to the patients emphasizes how we need to go beyond the details – and have a holistic approach to any patient treatment.

Future perspectives

The current work has answered some research questions, but has also inspired some new ones. Most studies that have investigated "safe-zones" for femoral and tibial tunnel placements are of older date, and have used methodologies with a variable accuracy. At present a large cohort of patients are being enrolled in a study where CT evaluation complements a detailed clinical outcome evaluation at Haraldsplass Deaconess Hospital. Hopefully this cohort will contribute to further insight into prerequisites for a successful ACL reconstruction – including tunnel placement. Further, there are, to our knowledge, no long-term evaluations that evaluate results after the AM-portal technique. A study alike paper I, from the same clinical environment, would give an answer to whether the change of technique has benefited the patients in our region. Although studies from large international knee centres might give an idea of results, evaluation of own patients is imperative if aiming to improve outcomes.

Given a learning curve, like the one seen in paper III, any change in surgical techniques should be well considered, with a clear and documented advantage to future ACL injured patients. Aspiring surgeons should hold a conservative and critical attitude when encountering new technical advances. *Conservative* since not all technical benefits will reflect into patient outcomes. The benefit to the patient should be imperative when making decisions about surgical techniques. *Critical* in reading published literature on ACL surgery, both in assessing quality of the work but also when interpreting and generalizing from results. In improving ACL surgery, basic science (including cadaveric and kinematic studies), patient level studies and registry data complement each other for the best of patients. Also, it is important to bear in mind that a statistically significant finding does not always translate into a clinically relevant finding.

A quick search in literature databases (including PubMed) looking for papers on treatment of ACL injuries, results in about 12 000 published papers. There is an increasing interest in this topic with a peak in publication during the last decade.

Although recent research seems to unveil new technical skills and proposed benefits for the best of future ACL injured patients, it is important to also keep in mind the historical work of pioneering colleagues. Therefore, in light of the recent spur in interest for the classical bone-patellar-bone reconstruction – and a revisiting of the importance of anterolateral structures of the knee – it seems appropriate to conclude like one of the true pioneering ACL surgeons did in a recent editorial [38]:

"The quest continues"

- William G Clancy -

Conclusions

1. Good subjective outcomes, a low revision rate, and a low incidence of osteoarthritis were found at a 10-year follow-up of patients who underwent ACL reconstruction with a transtibial technique.

2. There was a significant higher Lysholm score in patients that had surgery to their left knee compared to their right knee – but no differences were found when assessing; smoking status, overweight, preoperative Tegner score and concomitant meniscal resection.

3. The transtibial technique led to a high incidence of patients 2+ pivot shift (20%), these patients displayed significantly poorer Lysholm scores than patients with normal rotational laxity.

4. Use of the "anti-impingement" tibial drill guide led to a high incidence (24%) of patients with a *posterior* tibial tunnels (defined as 50% or more posterior on the tibial plateau), these patients had a higher incidence of 2+ pivots shift, in which significantly poorer PROMs were found.

5. Femoral graft tunnels were found to be significantly closer to the central femoral footprint, as assessed by postoperative 3D-CT, when comparing an anteromedial portal technique to a transtibial technique.

6. The sole use of remnants of the ACL and the femoral bony landmarks (denoted the residents ridge and the lateral bifurcate ridge) were found unreliable for aiding femoral tunnel placement when changing to the AM portal technique.

7. The introduction of feedback from postoperative 3D-CT was found to increase the accuracy of femoral tunnel positioning as compared to an empirical anatomical centre.

8. The introduction of intraoperative fluoroscopy improved the accuracy of femoral tunnel positioning as compared to an empirical anatomical centre.

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