The role of imaging in anterior cruciate ligament reconstruction

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Thesis for the degree of Philosophiae Doctor (PhD)
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Scientific environment

The work leading to this thesis has been performed in the clinical environment of the Radiology Department of Haraldsplass Deaconess Hospital. Funding from Haraldsplass Deaconess Hospital has enabled presentation of results from several studies at national and international conferences. The thesis has been completed whilst holding a position as a radiologist in the Radiology Department of Haraldsplass Deaconess Hospital.

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Abbreviations

2D	two dimensional
3D	three dimensional
ACL	anterior cruciate ligament
ALLC	anterolateral complex
ALL	anterolateral ligament
BTPB	bone-patellar tendon-bone
CT	computer tomography
CT-mip	CT -maximum intensity projection
DS	deep-shallow
HAM	hamstrings
HL	high-low
ICC	Intraclass correlation coefficients
LCL	lateral collateral ligament
MCL	medial collateral ligament
MRI	magnetic resonance imaging
PCL	posterior cruciate ligament
PubMed	National Library of Medicine (online database of medical journals)
REV	revision
T1	type of MRI image
T2	type of MRI image

Abstract

The thesis is composed of results and knowledge from four papers examining the role of imaging after surgical reconstruction of the anterior cruciate ligament of the knee. Post-operative imaging is commonly performed to validate ACL graft tunnel locations after reconstruction, to examine underlying causes in cases with poor outcome or is performed for planning surgery prior to revision of ACL graft.

Paper I examined the differences in measurements of ACL graft tunnel placements between radiographs, CT, and MRI. In about 50 patients, two radiologists measured the tunnel locations in the femur and tibia in all three modalities. We found a significant difference between summation images and image slices for the measurement of the tibial tunnel measurement, and no differences between femoral tunnel measurements. Tibial tunnel placement was about 3% deeper on slice images than on summation images.

In paper II, a radiologist, and an orthopaedic surgeon systematically reviewed literature of reported anatomic femoral and tibial locations of native ACL centres in >200 femoral measurements and >300 tibial measurements. The results were collated to present means, medians, and 5th and 95th percentiles of the tunnel placements in the Bernard & Hertel grid and Stäubli & Rauschning ratio. The defined "normal ranges" could be used as a reference for future studies.

Paper III assessed the ability of two different measurement methods to identify nonanatomic graft tunnel placements on CT images in patients who returned for revision surgery and in patients who had undergone routine post-operative imaging with either hamstrings graft or bone-patellar-tendon-bone graft (BPTB). The ability of Bernard & Hertel grid and Stäubli & Rauschning ratio in tibia to indicate anatomic graft placement were compared with assessment with coronal and sagittal graft angles. It showed that graft angle measurements are a poor indicator for anatomic placement, especially in patients operated with the antero-medial portal technique or

reconstructed with BPTB grafts. Anatomic placement according to graft angles were not well correlated to anatomic placements assessed with grid measurements.

Paper IV assessed the rate and types of knee pathology, including anterolateral complex (ALLC) pathology on MRI in ACL reconstructed knees and assessed possible gender differences. It showed that graft rupture was the most common finding in patients returning for revision surgery and concomitant injuries were less prevalent than previously reported. Further, we showed that interobserver variability for assessment of ALLC is very high, so for now MRI is not useful for evaluating this structure.

To summarise, the thesis showed that many variations in graft tunnel evaluation exist. For graft tunnel placement assessment, CT is by far the most robust modality, be it for scientific studies or in clinical practice. The grid method in the femur and ratio in the tibia are easiest to implement. Graft angle measurements have no value in evaluating tunnel placements. When evaluating soft tissue structures, MRI is reliable for well-established structures such as ligaments and menisci, but currently not for recently introduced anatomic structures such as ALLC.

List of publications

Paper I*

Parkar AP, Adriaensen ME, Fischer-Bredenbeck C, Inderhaug E, Strand T, Assmus J, Solheim E. *Measurements of tunnel placements after anterior cruciate ligament reconstruction — A comparison between CT, radiographs, and MRI.* (2015) Knee 22(6):574-9

Paper II**

Parkar AP, Adriaensen ME, Vindfeld S, Solheim E. *The Anatomic Centers of the Femoral and Tibial Insertions of the Anterior Cruciate Ligament A Systematic Review of Imaging and Cadaveric Studies Reporting Normal Center Locations.* (2017) Am J Sports Med. 45(9):2180-2188.

Paper III**

Parkar AP, Adriaensen ME, Giil L, Solheim E. *Computed Tomography Assessment of Anatomic Graft Placement After ACL Reconstruction A Comparative Study of Grid and Angle Measurements.* (2019) Orthop J Sports Med. 19;7(3):2325967119832594

Paper IV

Parkar AP, Adriaensen ME, Fischer-Bredenbeck C, Giil L, Vindfeld S, Solheim E
ACL graft revision: graft rupture main MR imaging finding prior to revision. (Submitted).

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** Papers II and III are reprinted in this thesis with permission from Sage Publishing.

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Introduction

Anatomy of the anterior cruciate ligament

The knee joint is composed of bones, articular cartilage, ligaments, menisci, synovium, and other supporting soft tissues. Further, many important structures pass the knee joint, mostly in the posterior part, including nerves, blood vessels and tendons. Two strong long bones, the (distal) femur and (proximal) tibia, articulate (with each other). Two fibrocartilage menisci, the medial and lateral are situated in between the bone ends, acting as shock absorbers, and adding to the stability of the joint. There are four ligaments of paramount importance to the stability of the knee, the medial and lateral collateral ligaments, and centrally the anterior and posterior cruciate ligaments. In addition, the tendons from thigh muscles, such as the semimembranosus and semitendinosus support the medial posterior corner, the popliteus tendons and the biceps tendons support the lateral posterior corner. The anterolateral complex, patellar and quadriceps tendons support the anterior knee [92, 138]. These soft tissue structures, together with the retinaculum anteriorly which extends to the patella on each side, encapsulates the knee joint [Figure 1a/b][138]. The motion of the knee joint is mainly flexion and extension (hinge joint), but there is also some degree of rotation possible. The anterior cruciate ligament (ACL) provides stability to the knee joint in preventing the tibia from anterior translation as well as internal rotation [11].

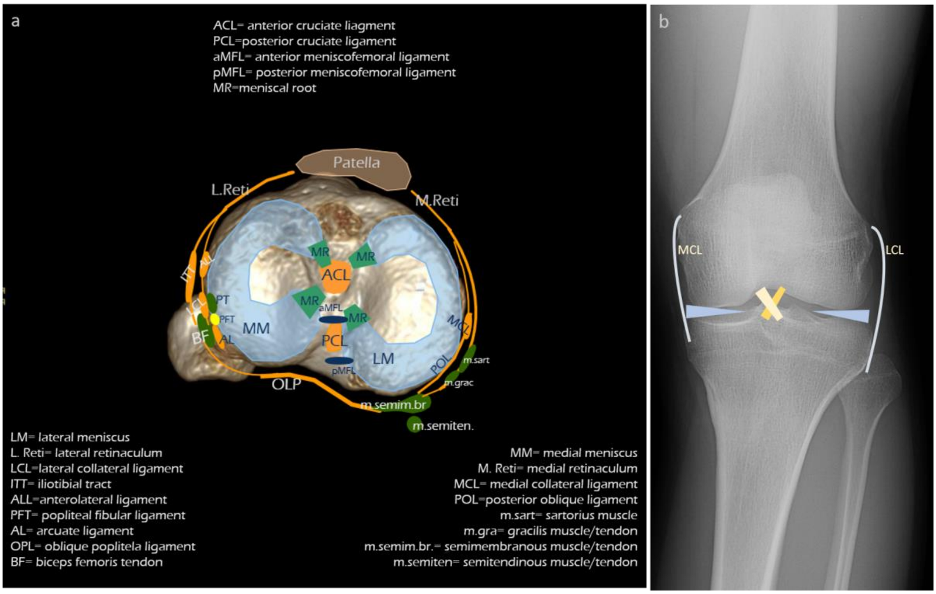


Figure1. a. Schematic axial view of structures of the knee joint. b. Schematic coronal view of menisci, cruciate and collateral ligaments.

The ACL is one of the strongest ligaments in the body. Even so, modern activities such as sports which requires a lot of fast twisting and turning of the knee joint (pivoting), has made it vulnerable for tears. The tensile strength is estimated at 1,725 ± 270 N [81]. The ACL attaches to the medial femur and runs obliquely to the anterior mid portion of the tibia. It consists of two closely knit fibre bundles, the anteromedial and posterolateral bundles. The two bundles shorten and lengthen together during flexion and extension, and fold over one another during rotation [63,122]. The ACL is intraarticular, but extra-synovial. The lack of blood supply hampers healing after injury [81].

ACL injury

A major trauma to the knee, often during sports, may cause the ACL to tear, thus severely affecting knee function. The mode of trauma is often indirect forces acting to internal and/or external tibial rotation or valgus or varus stress or hyperextension [Figure 2].

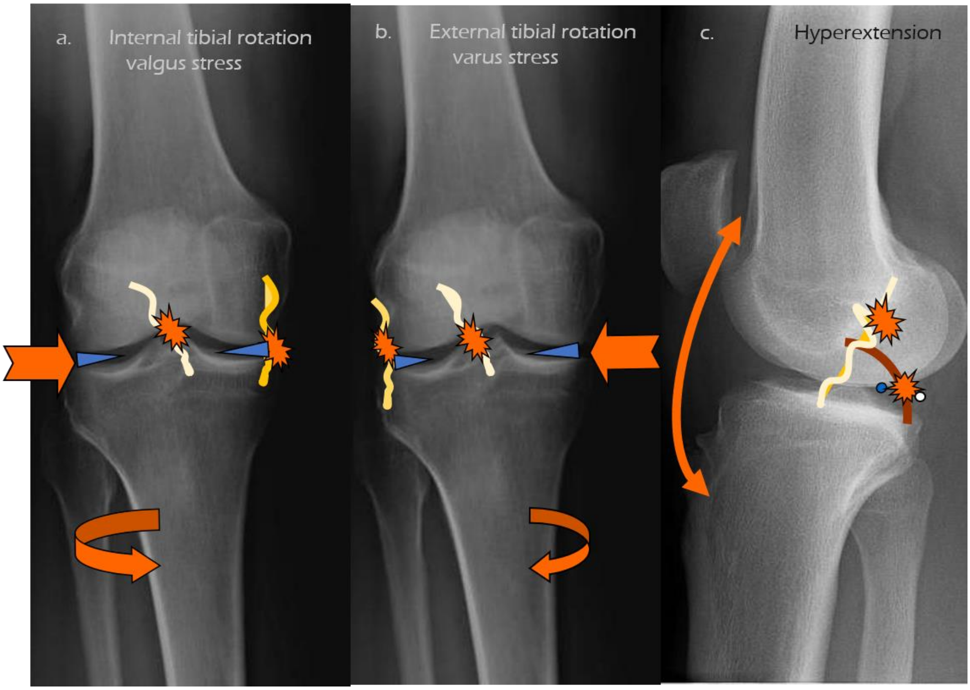


Figure 2. Modes of trauma which cause ACL injury. a. ACL and MCL is often injured in trauma lateral to medial and internal rotation. b. ACL and LCL is often injured when trauma is from medial to lateral and external rotation. c. With hyperextension of the knee both the ACL and PCL tend to rupture.

Such a trauma will often render the knee ACL deficient. Depending on the type and severity of injury the collateral ligaments, posterior cruciate ligaments, the menisci and/or articular cartilage may be injured at the same time. An ACL deficient knee leads to anterior translation of the tibia compared to the femur, especially in the lateral compartment. ACL deficiency alters the load within the knee, with slight anterior subluxation of the tibia in the lateral compartment [94]. The altered load during function eventually leads to early onset of osteoarthritis [14,105].

ACL rupture surgery

As a completely ruptured ACL does not heal on its' own, ACL surgery was initiated to restore the stability (and normal function) of the knee and, secondary, in the long term, to possibly avoid early development of osteoarthritis. The surgery evolved from the early days of repair (by sutures) or non-anatomical plasties to reconstruction of the ACL with various autogenic and allogenic grafts as well as man-made implants of different material. Commonly used grafts are autogenic grafts harvested from bone-patellar tendon-bone (BPTB) or hamstring tendons, either from the ipsilateral or, less often, the contralateral knee. The use of allografts from dead donors reduces the surgical trauma to the patient, but introduces new problems [25]. Unfortunately, up to 25% of ACL reconstruction patients experience an unsatisfactory outcome regarding post-operative knee function [126].

An unsatisfactory result can be categorised according to the symptoms and/or clinical findings evoked, e.g., recurrent pain, loss of motion, extensor mechanism dysfunction and recurrent knee instability; or analytically, examining the possible underlying causes (of failure), such as failure of graft incorporation, too early return to high levels of activity, inadequate rehabilitation, a new trauma or technical (surgical) errors including poor graft placement and unaddressed concomitant abnormalities.

Naturally, the surgeon wishes to keep the failure rates as low as possible. However, some causes of failure, for example, lack of graft incorporation depends on intrinsic individual patient factors which cannot be foreseen by the surgeon. Proper rehabilitation after surgery is mandatory, but the outcome is highly dependent on patient compliance. If the patient does not follow given advice, this may affect the outcome of ACL reconstruction in a negative way.

Other causes, such as failure of addressing concomitant lesions and avoiding technical surgical errors are factors the surgeon can actively influence. In the acute setting, concomitant injuries such as meniscal ruptures may be difficult to diagnose clinically. Further, studies show that menisco-capsular separation and posteromedial meniscal ruptures may be missed during arthroscopy using anterior or anterolateral portals [9, 21,102]. These need to be recognised and reported by radiologists on initial imaging so that the surgeon can address them specifically in the same session as the ACL reconstruction.

For the surgeon, technical considerations include 1) choice of suitable graft, 2) correct graft tensioning, as too taut will limit range of motion, especially extension, and too loose with cause residual laxity, and 3) correct tunnel placement, as it has to provide sufficient stability during knee function without causing impingement of the graft within the intercondylar notch [11,52,53]. The aim for the surgeon is to reconstruct the ACL as close to the native state as possible. Surgical techniques have evolved over the years, currently the aim for the surgeon is called "anatomic" reconstruction [25,109]. Whether or not graft placement (and tensioning) was adequate is tested clinically by a surgeon and can also be observed by the patient when their activity levels increase. Thus, in the early post-operative period, imaging is sometimes used to rate surgical success as "good" or "poor" dependant of the location of the graft tunnels [6,132].

With increasing implementation of "anatomic" reconstruction, there was a need for defining the location of the native ACL insertions in the femur and tibia. Several imaging studies examined the location of the native ACL insertions using different modalities to study the locations. Generally, each study reported slightly different means for the centre location in the femur and tibia. Therefore, there is no consensus, or accepted "normal" range of where exactly the anatomic location of the ACL insertions are [4,16,28,36,37,58,7076,77,91,101,104,127,131,134,143].

The rate of ACL reconstruction has increased steadily in the past few decades [3,30,144]. This has caused an increase in (routine) post-operative imaging assessment. Routine post-operative imaging is considered useful as an operator-independent baseline examination [43,67,100].

History of anterior cruciate ligament imaging.

ACL rupture was first described in the late 1830s and the first report of surgical repair was published in 1895 [25,117]. However, the diagnosis in the early days was purely clinical and, thus, dependent on the examiner's experience. Thus, more operator-independent or objective, tools were therefore sought after. Depicted on radiographs, ACL injury may be associated with femoral impression fractures and avulsion fracture of the lateral tibia, called Segond fracture [20]. The earliest article cited in PubMed describing radiographs in knee injuries dates from 1952 [84]. The first paper on specific ACL rupture diagnosis on imaging were in the mid-1960s [72,73]. The described imaging method entailed injection of contrast media in the knee joint and indirect depiction of ACL rupture. In the 1970s stress radiographs were used to show the translation of femur against the tibia in the lateral compartment [31,41,59,60]. In 1981 computer tomography (CT) entered the scene, and imaging shifted to better visualisation of the ligament, albeit, still using arthrography [113]. The advent of magnetic resonant imaging of ACL in 1985 heralded in a new era of direct imaging non-invasive visualisation of the ACL [6].

MRI was the first non-invasive method to accurately depict the ACL fibres and objectively describe any rupture of the structure without the use of intra-articular contrast [15,22,79,111,112,135]. Since then, technological advancements in MRI have vastly improved the image quality, and thus accuracy of diagnosis on imaging. Even so, the gold standard for ACL evaluation, rightly so, still is a clinical examination, especially when performed by an experienced examiner, where a full knee examination is performed [114,129].

The first paper describing post-operative radiographs after ACL reconstruction was published in 1986 [23]. The paper described assessment of graft tunnel placement on front and lateral radiographs, and suggested evaluating the intraosseous tunnels, the bone block (of patellar tendon grafts) and bone block donor sites and fixation hardware [23]. A rush of papers followed using radiographs, CT and MRI in the late 1980s and early 1990s [26,54,78,90,108,133]. MRI was primarily used to assess the degree of intactness of the graft fibres. By 1997, imaging was increasingly being used as an indicator of successful surgical reconstruction. As the need to standardise and compare surgical outcomes evolved, the report from a workshop with orthopaedic surgeons from twelve countries, was published a consensus paper by Amis and Jakobs in 1998 [11].

This paper was the start of an era where graft tunnel placement and assessment on post-operative imaging could be standardised [11]. The authors advised the use of radiographs to assess graft tunnel placement. They also suggested to apply a grid method to describe the femoral graft tunnel placement (Bernard & Hertel grid), and a ratio (Stäubli & Rauschning ratio) for tibial tunnel placement [16,127]. The tibial ratio had been developed on MRI, but this was not problematised in the consensus paper, as the paper recommended using radiographs due to easier access. CT was not considered in the consensus paper. Further, they recommended that one should use surgical navigation terminology of "deep-shallow" and "high-low" instead of anatomic (radiological) terminology in order to avoid confusion. The terminology derives from the fact that surgery is, in large parts, performed (with the patients' knee) in flexion. Radiographs for ACL graft evaluation invariably are performed in extension. The surgical terminology is unambiguous. In addition, the recommended measurements are independent of the extent knee flexion [Figure 3 a/b].

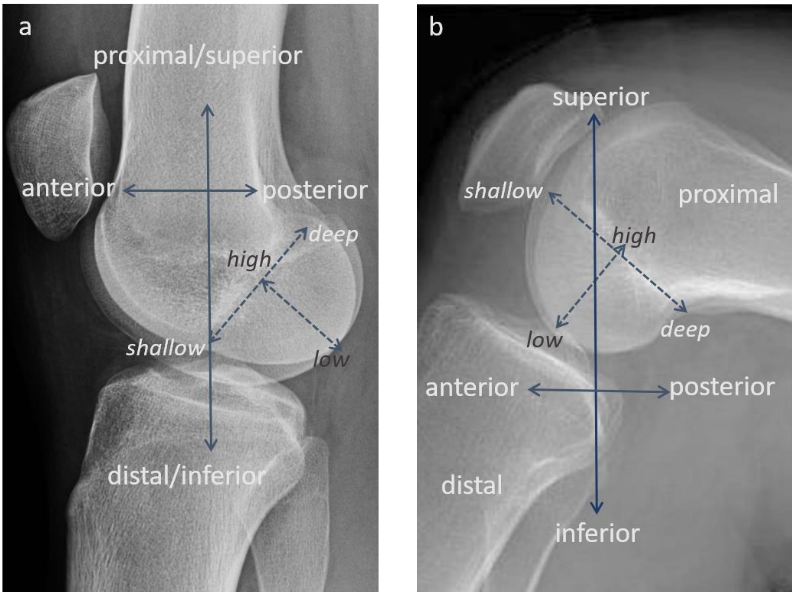


Figure 3 a. Note the similar wording of terminology when the knee is extended. b. Note that "deep-shallow" and "high-low" and superior/inferior remain the same, while the other descriptive terms change in flexion.

This recommendation from orthopaedic surgeons was consistently referred to and used as basis for studies and publications by some scientific groups, while radiologists were late to catch on to this [87,94,100,110]. CT was often discarded in favour of MRI to assess post-operative graft placement, as MRI was preferred due to the lack of radiation [8].

Ahn et al. suggested using graft angles to quantify ACL tunnel placement on MRI in a study where the ACL was reconstructed with the transtibial technique [8]. Thus, a new measurement method was introduced. From the year of 2000 and onwards, the orthopaedic and radiological communities' comprehension of imaging evolved in somewhat diverging directions. Radiologists focussed mainly on MRI and how to best use this modality to answer clinical queries regarding (the quality of) graft fibres, and graft placement evaluation indirectly using angle measurements and anatomic landmarks [87,94,110,140]. Conversely, orthopaedic surgeons often assessed outcome of surgery on imaging by using the grid method and tibial ratio, but were using different radiological modalities: radiographs, CT and MRIs [51,61,86]. As new surgical techniques were introduced, studies reported the efficacy of various surgical techniques as either “good” or “poor” according to how close to the anatomic insertion their tunnel placements were [2,18,33,95,130]. Imaging was used to “objectively” assess the anatomic placement. However, as there were so many different modalities used, comparing study results and efficacy of surgical techniques was very difficult, as each modality has its own strength and weakness.

Imaging modalities, strengths, and weaknesses

Regarding primary evaluation after trauma, ACL reconstruction, and post-operative imaging, there are different groups of queries. After trauma, the main queries are the degree of ACL pathology, meniscal ruptures, other collateral ligament and soft tissue, and bone pathology, including avulsions [98,141]. The second query is the post-operative assessment of the reconstruction to serve as a baseline examination for future reference and to assess the location of canals and fixation device. The third query is to evaluate the knee joint in cases of clinically unsuccessful reconstruction and to assess the knee joint prior to a revision of ACL graft. For baseline examinations, radiographs are commonly used. Assessment prior to revision is complicated. Before planning the revision, the surgeon has a number of queries to solve: “Is the graft intact? Are the graft tunnels located in the right place? Are the tunnels widened? Hardware or fixation device complications? Are there untreated concomitant injuries?”

Although, graft intactness may be assessed clinically or during arthroscopy, the post-operative queries about cannot be answered by a single method and requires a multi-modality approach for overall evaluation and final diagnosis.

Radiographs

The prime strength of radiographs is the readily availability. They are inexpensive and easy to perform and, nowadays expose the patient to relatively little radiation

[85]. Preoperatively, they can show avulsed attachments or distinct femoral impression after valgus trauma, but soft tissues are not depicted on radiographs, thus radiographs only indirectly shows ligament injury through malalignment of tibia and femur [Figure 4] [20,98].After ACL reconstruction, radiographs may be used to assess tunnel widening and tunnel location [51]. The tunnels are visualised as areas of low density in the early phase and with thin lines of sclerosis in the later phase. Fixation devices are relatively easy to assess if they are radio opaque. The weaknesses of radiographs include the lack of direct assessment of soft tissues. It is not possible to directly evaluate the graft, the other knee ligaments, menisci nor the articular cartilage. During examination, slight rotation can lead to reduced diagnostic accuracy, therefore they are susceptible to examiner variability. Finally, radiographs are 2D summation images of bony structures, with a lot of overlapping of anatomy.

CT - computer tomography

CT delivers very detailed images of submillimetre thickness, and the data can be used to create 3D images of bony structures. This means tunnel locations can be easily determined without worrying about overlapping anatomic structures. However, it exposes the patient to a slightly higher radiation dose compared to radiographs [99]. The tunnels are seen in detail even on early post-operative imaging. The tunnels and radio-opaque fixation devices are easily depicted, as is any tunnel widening. The images do not depict soft tissues with sufficient detail and thus graft intactness cannot be readily assessed. Visualisation of menisci requires injection of contrast into the joint, making it an invasive procedure, and thus it has some limitations considering assessment prior to ACL graft revision surgery.

MRI - magnetic resonant imaging

The main advantage of MRI is being the most superior modality to evaluate soft tissue structures. After trauma the ligament rupture can be evaluated directly [Figure 4]. The ACL graft is visualised as a high signal band in the first 2 years after reconstruction, running obliquely in the knee joint, in the front (coronal) plane from lateral femur to centre of the tibia and in the lateral (sagittal) plane from the posterior femur to the midportion of the tibia. In the later phases it becomes low signal, resembling the native ACL. If cases of graft rupture, this is seen as a defect in the (graft) band or, later, as a complete lack of structures in the central part of the knee. MRI also shows any bone contusions as well as the status of the other ligaments, the menisci, and the articular cartilage. There is a disadvantage due to the artefacts created by any inserted metallic fixation devices. Exact depiction of cortex is necessary to correctly measure tunnel location. Further, femoral tunnel location is not easy to measure on MRI due to lack of 3D depiction of the condyles [99].

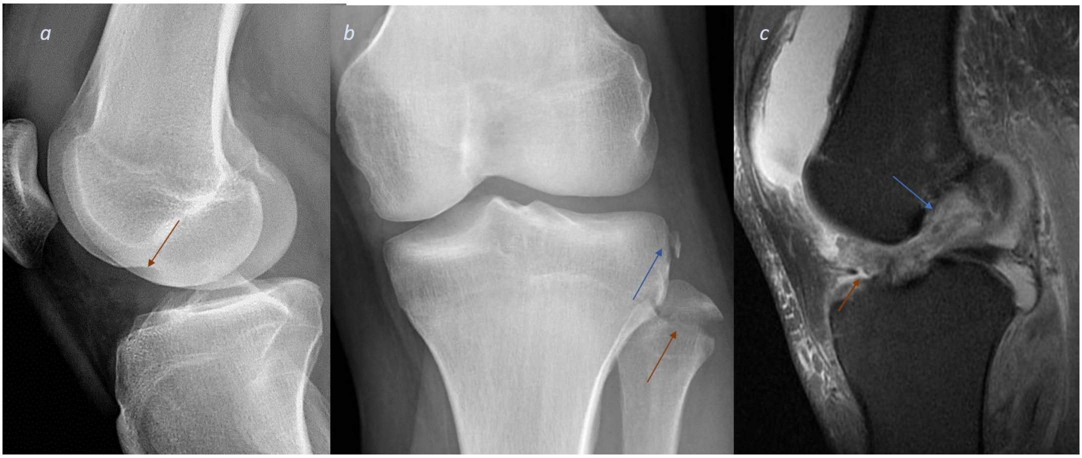


Figure 4a. Lateral radiograph showing the distinct lateral femoral impression associated with valgus trauma and ACL rupture. 4b. Coronal radiograph showing a Segond fracture (blue arrow) and fibula head avulsion (red arrow), which have 95% and 90% association, respectively, with ACL rupture. 4c. The ACL is thickened (blue arrow) with a ruptured part of the ligament lying anteriorly (red arrow).

Measurement methods

Early on, post-operative imaging after ACL reconstruction was mostly used to evaluate the surgical outcome with regards to the degree of correctness of tunnel placement. Soon, several various measurements methods were devised for examiner-independent measurement to quantify and compare success between varying techniques. Tunnel placements were viewed in the frontal and lateral plane. Tibial tunnel assessment was relatively straightforward, with ratio measurements in the lateral plane, and angle measurements [43,52,127]. The femoral tunnel placement could be assessed according to a clock view in the frontal plane, either at approximately 11o'clock for the right knee and 1 o'clock for the left knee. It was also considered to be in correct location if located at the intersection of lines from the posterior cortex and intercondylar roof (called Blumensaats' line) in the sagittal/lateral plane[7,16,143]. Graft tunnel angles were also measured as an indication of correct/incorrect tunnel placement. Finally, graft angles, i.e. the angle of the part of the graft in between the tunnels in the knee joint on MRI were used to indicate successful reconstruction [8,100]. Studies were done on radiographs, CT and MRI, and the results were compared without knowledge about the actual differences in measurements or modalities.

Recent developments and challenges in post-operative ACL imaging

CT and MRI technology has developed over the years. CT used to be a modality deemed to give too much radiation. However, in recent years, the technical improvements have reduced the radiation doses for a knee examination to the levels of a few days background radiation [99]. 3D CT is gaining in popularity as is depicts osseous structures with fine details [1,5,142]. MRI is now able to deliver 3D images as well, however the images are not as sharp as on CT [32]. Future developments will highly likely be able to create thinner slice images sharp enough to compete with CT and render soft tissue structures in greater detail. However, this is yet to reach clinical practice. Ultrasound has no room in evaluation of ACL, due to its' deep location between two large osseous structures.

Currently, the most challenging issues regarding ACL reconstruction imaging are how imaging can keep up with new clinical queries and incorrect usage of modality and measurement methods. Since the introduction of direct visualisation of ACL fibres, preoperative ACL imaging focussed on diagnosing the ACL rupture and concomitant injuries of collateral ligaments, menisci, and bone bruises. In recent years there has also been a focus on the anterolateral ligament structure, as a key stabilising structure, although this is hotly debated in the orthopaedic community [24,27,34,35,45,71,92,124,125].Lack of repair of concomitant injuries is considered as a possible cause for failure of the ACL reconstruction. It is a challenge for radiologists to assess even more subtle structures on MRIs. Further, the different methods and imaging modalities used to assess post-operative success of surgery hampers direct comparison of study results. It is not possible to directly compare results from two studies presenting “good tunnel placement” when they are performed with different modalities and measurement methods. Some groups used grid measurement, others used angles, some used radiographs, others CT and others again MRI [5,7,42,72,79]. The abundance of various possibilities caused confusion, especially for radiologists, trying to choose measurement methods to apply in their reports [36,44,86,94]. There is no orthopaedic consensus on which modality is the gold standard. The 1998 Amis and Jakob paper recommends grid measurements. The radiological papers referred mainly to measurement angles, and thus the orthopaedic and radiological communities were divergent paths. Several questions were yet to be answered.

- How does choice of modality influence measurements?

- Where are the normal ACL insertions?

-Which modality is best to answer clinical queries in post-operative imaging and pre-revision imaging?

-Which measurement methods are best correlated to clinical practice?

-What can imaging expect to find on post-operative examinations?

With these queries in mind, the aims of the thesis are outlined in the following section.

Aims of thesis:

1. To compare differences in modalities in assessing femoral and tibial tunnel placements (study I).

2. To determine where the native ACL insertions are (study II).

3. To compare usefulness of graft angles versus grid measurements in clinical practice (study III).

4. To examine the type of ACL graft findings and extent of concomitant injuries to vital structures on MRIs prior to ACL revision (study IV).

Methods

Study design

Studies I, III and IV were based on retrospective case series of patients who had undergone ACL reconstruction and/or ACL graft revision between 2011 and 2018. The patients had been routinely examined with pre-operative radiographs and/or post-operative CT. Some patients had also been examined with MRI either post-operatively or prior to revision surgery as part of the clinical work-up. The patients were not exposed to additional radiological examinations for scientific purposes.

Study II was a systematic review of literature examining native ACL footprint locations.

All four studies were performed at Radiology department of Haraldsplass Deaconess Hospital in Bergen, Norway.

Inclusion and exclusion criteria

In study I, patients, who were clinically assessed for possible ACL revision surgery were eligible for inclusion. We included patients examined with at least two or more modalities post-operatively, radiographs, CT and/or MRI between January 2011 and June 2013. Patients with only one type of examination were excluded.

Study II included papers which examined the location of ACL native footprints in the femur according to the Bernard & Hertel grid and in the tibia according to the Stäubli & Rauschning ratio. Papers which addressed post-operative imaging or not assessing normal footprints were excluded.

Study III was mainly a CT study. It included patients who either had undergone (A) post-operative CT after a primary ACL reconstruction between January 2011 and December 2015; or (B) pre-operative CT prior to revision surgery between January 2011 and December 2017. Patients had undergone reconstruction with either bone-patellar-tendon or hamstring grafts. Cases of other graft types, such as quadriceps were excluded. Knees with multiple ligament reconstructions or known graft ruptures were also excluded.

Study IV evaluated knee MRI findings in patients prior to ACL graft revision between January 2014 and November 2018. Patients with previous reconstructions of additional ligaments such as posterior cruciate ligament or medial and lateral collateral ligaments were excluded.

Imaging assessment

In studies I, II, and III the reference measurement methods applied were the Bernard & Hertel grid to assess femoral tunnel placement and the Stäubli & Rauschning ratio to assess the tibial tunnel placement. The Bernard & Hertel grid measures the placement in two directions, the deep-shallow and the high-low. The measurement is performed in the lateral or sagittal view in all three modalities. On radiographs, first the intercondylar roof is identified, then the centre of the tunnel centre is identified, and placement given as a percentage in the deep-shallow direction only, as the high-low direction was not easily depicted. On CT, a 3D virtual image was first created using software available on the CT machine (AW Server, GE Healthcare, Chicago, Illinois, USA). Then, the medial femoral condyle was digitally cut off, and the image rotated to show the medial side of the lateral femoral condyle. Both the deep-shallow and high-low measurements was performed.

On MRI the single slice which showed the tunnel opening was chosen and the measurement was done only in the deep-shallow direction as the high-low could not be done correctly due to the lack of 3D visualisation.

The Stäubli & Rauschning ratio is only done in one direction (anterior-posterior) and is also performed in the lateral or sagittal view. On radiographs, the ratio is done directly on the lateral image. On CT and MRI, the midline image with the tunnel opening had to be chosen first, before doing the actual measurement.

For study III, graft angles were assessed in the coronal and sagittal planes. In the coronal plane, the slice where most of the graft was visible was chosen, then a horizontal line was placed along the tibial plateaus, and the angle between then was measured. In the sagittal plane, the slice where most of the graft was visible was chosen, then a horizontal line was placed along the tibial surface and the angle between them was measured.

For study II, a search was performed in PUBMED on November 29th in 2015. The Search terms were the following: ‘‘ACL’’ and ‘‘insertion anatomy’’ or ‘‘anatomic footprint’’ or ‘‘radiographic landmarks’’ or ‘‘quadrant methods’’ or ‘‘tunnel placement’’ or ‘‘cadaveric femoral’’ or ‘‘cadaveric tibial.’’ Papers in a Non-English language were excluded. Studies that reported the location of the ACL footprint according to the Bernard & Hertel grid in the femur and the Stäubli & Rauschning method in the tibia were included. From these the reported means of measurements were collated and weighted means, weighted medians, and weighted 5th and 95th percentiles were calculated.

Statistics

All data was analysed primarily with SPSS Statistics (version 22 to 24, IBM Corp., Armonk, NY, USA). In study I the Bland-Altman analysis were done in R 3.0.2. (R Core Team, general public license). The plots were created in MATLAB 7.10 (MathWorks Inc., Asheboro, NC, USA.). Mean, standard deviations, medians and ranges were used for descriptive analysis of demographics.

Intraclass correlation coefficients (ICC) were used to assess inter-observer agreement between each modality and between each measurement method [120]. The scale used for the ICC interpretation was the following: values below 0.75 poor agreement, between 0.75 and 0.90 moderate agreement, and above 0.90 high agreement [64, 107]. The variations between the modalities were assessed with Bland–Altman plots of the means of measurement pairs and were presented with their limits of agreement. Missing values were left empty and not estimated.

In study II, the data from each included study were compiled to produce weighted means, weighted medians, and weighted 5th and 95th percentiles were calculated of the anatomic femoral and tibial centres.

In study III, mean, standard deviations, medians and ranges were used for descriptive analysis of tunnel placements in ACL reconstructed knees. Means of previously reported graft angles were collated and weighted means were calculated in SPSS. The dichotomous variables were assessed with the Pearson chi-squared test. The combined assessments of grid in two directions or angles in two planes were classified in ordered categories (anatomic, partial anatomic, or nonanatomic), which were assessed with the weighted kappa. Continuous variables were assessed with the analysis of variance or Kruskal-Wallis test according to an assumed normality of data.

In study IV, chi-squared was performed for simple dichotomous results, Fishers exact test for multiple variables, Cohens Kappa was used for agreement in two categories, and weighted Kappa for agreement in multiple categories.

Ethics

The regional ethics committee reviewed study protocols which was the basis for study I and IV in 2014 and decided that the projects did not need to be evaluated by the committee (REK 2014/2149) to be undertaken. Study III was evaluated in 2017 (REK 2017/2434) and informed consent was also waived.

Summary of findings

Paper I. Measurements of tunnel placements after anterior cruciate ligament reconstruction — A comparison between CT, radiographs, and MRI.

Aims: to compare measurements of tunnel placements between radiographs, CT, and MRI in a clinical setting and to assess if measurements between modalities could be used interchangeably, further, to assess the reliability of each modality in order to suggest a possible “gold standard” modality.

Patients: 46 patients were included, 30 females and 16 males, who had undergone 46 radiographs, 45 CTs, and 30 MRIs.

Methods: Two experienced radiologists measured tunnel placements in the femur and tibia according to the Bernard & Hertel grid and Stäubli & Rauschning ratio. The high-low direction was only possible to perform on 3D CT. For each measurement, the inter-observer agreement was assessed with intraclass correlation coefficients (ICC). Then inter-modality differences were visualised with Bland–Altman plots. In addition, radiation data for CT studies were collected.

Results: the inter-observer agreement for the femoral tunnel in the deep-shallow direction was ICC=0.64 on radiographs, ICC=0.86 on CT and ICC=0.75 on MRI. For the high-low direction on 3D CT the ICC was 0.84.

The tibial tunnel inter-observer agreement for radiographs was ICC=0.92, for CT-mip ICC=0.91, for CT and MRI ICC=0.87.

There was no difference between modalities in the femoral tunnel measurements. In the tibia, there were differences between radiographs and CT (−3.9%), radiographs-MRI (−3.6%), CT–CTmip (3.2%) and CTmip–MRI (−3.1%).

The effective radiation doses varied between 0.025 and 0.045 mSv, mean and median was 0.033 mSv.

Conclusions: CT is the most robust modality, for tunnel measurements according to the Bernard & Hertel grid and Stäubli & Rauschning ratio, as complete assessment of all measurements are only possible on CT, as well as it is consistently reliable. There are differences in the tibial ratio measurements between summation images (radiographs or CT-mips) and single slice images (midsection slice of MRIs or CTs). Effective radiation dose from CT was lower than previously reported.

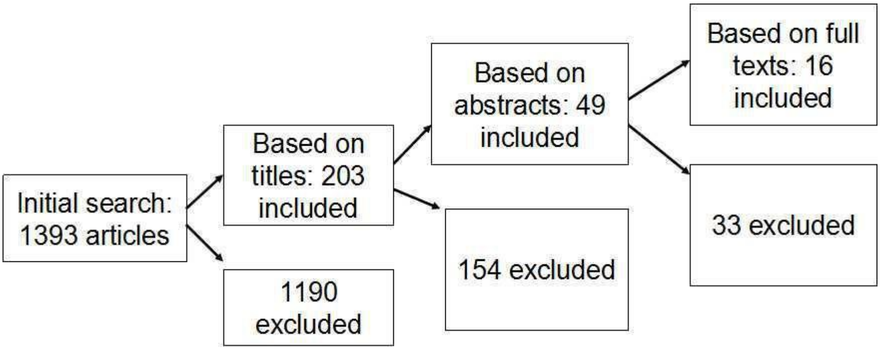
Paper II. The anatomic centres of the femoral and tibial insertions of the anterior cruciate ligament a systematic review of imaging and cadaveric studies reporting normal centre locations.

Aims: to define the anatomic centres of the femoral and tibial ACL footprints and assess the mean, median, and percentiles of normal centres through a systematic literature search.

Included studies: 16 studies on cadaveric specimens or a healthy population which had measured the ACL footprints according to the Bernard & Hertel gird in a total of 218 knees and Stäubli & Rauschning ratio in a total 300 knees were included.

Methods: A literature search was performed in the PubMed/Medline database in November 2015. The search terms for the systematic review were as follows: ‘‘ACL’’ and ‘‘insertion anatomy’’ or ‘‘anatomic footprint’’ or ‘‘radiographic landmarks’’ or ‘‘quadrant methods’’ or ‘‘tunnel placement’’ or ‘‘cadaveric femoral’’ or ‘‘cadaveric tibial.’’ Only English-language articles reporting the location of the ACL footprint according to the Bernard & Hertel grid in the femur and the Stäubli & Rauschning method in the tibia were included.

Results: The first search result showed 1393 articles. After reviewing the titles, 203 were examined further. After reading the abstracts, 40 were chosen for reading the full text articles, and finally after reading the full texts the final 16 articles were selected. A flow chart showing the process is presented below.



Data collated from these articles was used to calculate the anatomic location of the ACL footprints in the femur and tibia.

The weighted mean of the femoral insertion centres was 29% in the deep-shallow (DS) direction and 35% in the high-low (HL) direction. The weighted median was 26% for DS and 34% for HL. The weighted 5th and 95th percentiles for DS were 24% and 37%, respectively, and for HL were 28% and 43%, respectively. The weighted mean of the tibial insertion centre in the anterior-posterior direction based on measurements in 300 knees was 42%, and the weighted median was 44%; the 5th and 95th percentiles were 39% and 46%, respectively.

Conclusion: There are slight differences between the weighted means and medians in the femoral and tibial insertion centres. To avoid falsely excluding acceptable post-operative tunnel placement by using a “too narrow” window of anatomic footprint location based solely on means, we recommend the use of the 5th and 95th percentiles when considering postoperative placement to be ‘‘in or out of the anatomic range”.

Paper III. Computed Tomography Assessment of Anatomic Graft Placement After ACL Reconstruction A Comparative Study of Grid and Angle Measurements

Aims: To compare the ability of grid measurements and angle measurements to identify anatomic versus non-anatomic tunnel placement on CT performed in patients undergoing ACL reconstruction.

Patients: A total of 100 knees undergoing primary reconstruction with a hamstring graft (HAM group), 91 undergoing reconstruction with a bone–patellar tendon–bone graft (BPTB group), and 117 undergoing revision ACL reconstruction (REV group) were included. These patients were examined at the radiology department from 2011 to 2017.

Methods: On CT tunnel placement according to Bernard & Hertel and Stäubli & Rauschning were assessed in all knees. In the same knees femoral and tibial graft angles were measured. Then the tunnel placements were deemed "anatomic" or "non-anatomic" according to normal ranges previously published.

Results: The combined Bernard & Hertel and Stäubli & Rauschning grid classified 10% of the HAM group, 4% of the BPTB group, and 17% of the REV group as non-anatomic ($P < .001$). The angle assessment in the coronal and sagittal planes classified 37% of the HAM group, 54% of the BPTB group, and 47% of the REV group as non-anatomic. The weighted kappa between angle measurements and grid measurements was low in all groups (HAM: 0.009; BPTB: 0.065; REV: 0.041).

Conclusion: The agreement between grid measurements and angle measurements was very low. The angle measurements seemed to overestimate nonanatomic tunnel placement. Grid measurements were better in identifying mal-positioned grafts.

Paper IV. ACL graft revision: graft rupture main MR imaging finding prior to revision.

Aims: To assess the rate and types of knee pathology on MRI in ACL reconstructed knees and to assess the rate of anterolateral capsular structure (ALLC) pathology. We hypothesized that MRI would demonstrate a similar rate of ACL graft, meniscal and/or chondral pathology, as previously observed in surgical/clinical studies.

Patients: 171 patients who underwent pre-operative knee MRI and first revision ACL surgery between January 2014 and November 2018 were eligible for inclusion in the study. Patients with previous multi-ligamentous surgery were excluded, leaving 119 patients who were finally included (51 males, 68 females). Average age was 27.5 years (SD 8.7).

Methods: MRIs were examined for pathology in graft, ligaments and ligamentous structures, menisci and articular cartilage. Inter-rater variability was calculated in 100 randomly chosen cases. Intra-rater variability was assessed in 50 randomly chosen cases, with a minimum 3-month time gap between first and second assessment.

Results: No MRI pathology was seen in 17% of knees. Complete graft rupture was seen in 24%, partial rupture in 22% and intact graft fibres in 54%. MCL was abnormal in 6%, LCL in 3%, anterolateral capsule in 28%. The PCL was abnormal in 8%. Pathology was seen in both menisci in 2%, lateral meniscus 10% and medial meniscus 34%. Articular cartilage was normal in 87% and abnormal in 13%.

The inter-rater agreement for assessing structures was graft = 0.795, menisci = 0.742, MCL = 0.712, cartilage = 0.522, LCL = 0.490, PCL = 0.135 and anterolateral capsule = 0.100. The intra-rater agreement for assessing structures was graft = 0.701, LCL injury = 0.645, PCL = 0.634, menisci = 0.560, MCL = 0.540, anterolateral capsule = 0.399, cartilage = 0.187.

Conclusion: MRI demonstrated that graft rupture was the single most common abnormal finding. Concomitant pathology was observed on MRI in about two thirds of cases. Inter-observer variability on MRI is acceptable for assessment of graft fibres, but not for anterolateral capsule pathology.

Discussions

Methodology

Study design

Three studies, paper I, III and IV, are retrospective studies. In studies I and III, the aims of the studies were comparisons of measurements or measurement methods. Assessment of surgical outcome was not an objective, thus a prospective study with clinical correlation would have been of no consequence.

Each modality yields a specific image or images. Radiographs are 2D images with summation of the examined structure. CT images are 2D tomography (or slices) of the examined area. The data from CT can further be used to create 3D images. MRI are 2D slices of the examined structure which are obtained in 3 planes. Some MRI machines are able to deliver data for 3D images, but our studies did not include 3D MRI images, as 3D images of MRI cannot be produced in retrospect.

One could argue that the quality of the image is dependent on the radiographer performing the examination, and would be a significant bias, as in a clinical setting the examinations were performed by very many different radiographers. However, all examinations are performed according to a specified protocol, even in the clinical setting in our department, reducing the bias. Further, radiographs and CTs are relatively straight forward to perform. MRI is challenging, even with a standardised departmental examination protocol, as a poorly performed examination could deliver slightly flexed or rotated images, which in turn may affect measurements. We anticipated this and chose to use measurement methods that were independent of the level of knee flexion.

The strength of study I was that it is the first study examining and comparing post-operative tunnel placements in three modalities: radiographs, CT, and MRI. All previous studies which compared graft tunnel placements had only compared a modality with anatomic measurements or two pairs. We also studied the inter-observer variability in all measurements, which at times is not performed in smaller studies [26,65]. No measurements were performed in consensus, so the true value of examinations is a clinical setting could be evaluated. Certain variability is expected in manual measurements, but good correlation (>75-90%) is expected before implementing measurements into clinical or radiological practice [64,103]. In the future, artificial intelligence software will highly likely relieve radiologists from this tedious manual task, while producing repeated measurements with even higher accuracy. To date no such software or application has been made available for general and/or universal usage in musculoskeletal radiology.

Paper II was the first study collating anatomic centres of the native ACLs in a high number (>200) of knees. Two physicians, one orthopaedic surgeon and one radiologist, chose the papers to be included in consensus, which reduced bias, as both related fields were covered. This ensured that we did not by mistake exclude papers. Several previous studies had undertaken anatomic and imaging studies reporting means of the insertion sites. However, when means with standard deviations are reported, the outliers affect the results. Thus, the reported means vary considerably. Normal ranges in population are usually given as percentiles, and normal is considered between 5th and 95th percentiles. As many previously published studies were small, medians and percentiles would have been meaningless to present.

We collated and presented the results as weighted means, and most importantly weighted medians, including 5th and 95th percentiles of insertion sites. This was a strength of our paper. Further, we specifically chose papers which had used the exact same measurement methods. Previous studies had incorrectly mixed tibial measurements from Amis and Jakob line and Stäubli & Rauschning ratio. We demonstrated the differences between these two methods and included only Stäubli & Rauschning measurements. In addition, we were able to use measurements from studies reporting measurements from both summation images and single slices, as we adjusted the tibial measurements according to our results from Study I. These considerations led to robust results which can be used in clinical settings.

Paper III compared post-operative graft placements measured with two different methods, grids versus angles. This was performed in over 300 knees in three groups, making it one of the largest studies comparing these methods in a clinical setting. The grid methods are independent of knee flexion, whereas the graft angles were developed to be performed in full extension [8]. However, as it was a retrospective study, it was not possible to make sure that all knees were perfectly extended. As mentioned before, all our radiological examinations are performed using a standardised protocol, and full extension is standard for CT knee. Thus, what may be considered a bias against graft angles, was the main point of the study, that measurements that are so dependent on knee flexion should not be used to indicate anatomic graft reconstruction when applied in a clinical setting.

A strength of paper IV was that it was an MRI study including over 100 patients. We studied the inter-observer variability in 100 examinations and intra-observer variability in 50 examinations. We looked at well-known and well-studied structures such as ACL grafts and the larger ligaments, and menisci, as well as “new” structures such as the anterolateral ligament. The study highlighted the need to thoroughly assess new ideas before implementing them into clinical practice. The ALLC, which consists of multiple layers of capsular structures, is considered to contain a proper ligament, and termed it anterolateral ligament (ALL). ALLC or ALL is a hotly debated structure [71,92,124]. There is no doubt that it exists anatomically, but the clinical importance in knee function is debated. Further the usefulness of MRI for the diagnosis of ALLC/ALL is not yet proven. We know that implementing new evidence knowledge into clinical practice takes several years [88]. Indication for ALL reconstruction is still unclear [126].

To date there are two major groups regarding the ALLC/ALL. Those who believe it is important and those who do not. Some authors, including a consensus group has recommended the reconstruction of the ALL in primary ACL reconstruction [45,125]. Other groups recommend that the ALL should be reconstructed only when there high grade rotational instability or for revision surgery [126,136]. Radiologists have expressed doubt in the ability of MRI to visualise the ALL and the ability of radiologists to identify and correctly report findings [82,106].

The diagnoses of just ACL injury or additional ALL injury is mainly clinical and based on a surgeons' clinical examination. MRI, which often is used as a conjunct to solidify a diagnosis or finding seems to have little or low value in the diagnosis of ALL. Our study showed that the structure is elusive and difficult to assess, even for experienced radiologists. We examined MRIs which were performed several months after initial surgery. Only a handful of examinations were performed due to a new trauma. Chronic ALL injuries may have been missed, this is a drawback of our study, especially as a recent study showed that the time between injury and MRI, affects MRIs ability to visualise ALL pathology [46]. However, our results were in concordance with another recent study which generally low inter-observer reliability [106].

Results

Differences in modalities

As long as humans perform measurements, there will be slight variations in the results. The variations can be minimised by applying standardised methods. After the introduction of the Bernard & Hertel grid and Stäubli & Rauschning ratio in the ESSKA consensus paper in 1998, studies that followed often examined the transference of measurements from anatomy to radiology [2,36,74]. Using the recommended measurement methods, several studies were published, using varying modalities. Most studies had compared anatomic measurements and measurement from one modality. There were no significant differences between anatomy and each of the modalities. However, one cannot automatically conclude that if there are no difference between anatomic and radiographic measurements or no differences between anatomic and CT measurements, there must be no difference between radiographic and CT measurements, even though "anatomy" is considered the gold standard and reliable measurement.

Radiological modalities cannot be used interchangeably, and if used so, this can be a source of unwanted (and unnecessary) variation in measurements. In the radiological community this is known and accepted as a fact. Radiographs are a 2D depiction of anatomy and, thus, summation images, with overlaying structures which in turn reduces the image details. CT delivers images in three planes and can be used to create detailed 3D images of skeletal structures but requires the administration of iodine contrast to depict soft tissue structures in greater detail. CT images can also be “reconstructed” in varying thickness. It is conventional that newer CT machines base their images on 0.5 or 0.625mm thickness, which is the smallest size of a single detector which records information. However, images used to review pathology are reconstructed with 2mm thickness, as this improves image quality. In addition, CT can “reconstruct” images emphasizing different structures, like soft tissues and bone, yielding slightly different images [Figure 4a/b].

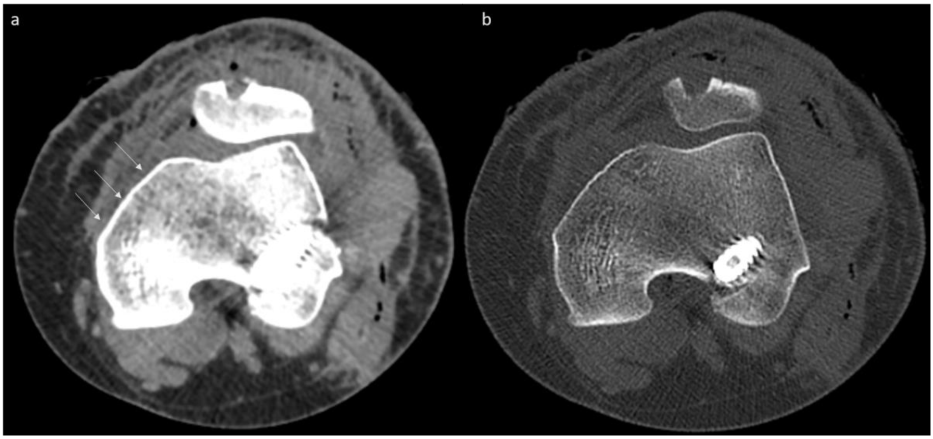


Figure 5. a CT images soft tissue image and bone image of the same slice in the same knee. Note the slightly blurred bone cortex on soft tissue image (arrows), and the lack of soft tissue detail on bone image (image b).

MRI does not expose patients to radiation. It does not require contrast administration for depiction of soft tissues, but cortical structures which are necessary for tunnel placement location are difficult to see, and the cortex is usually thicker compared to CT. There are also many variations in the way images are created on MRI, with the main types being T1 and T2 images (often with suppression of fat) [Figure 5a/b]. MRI image slabs are normally 2-3mm thick, and thinner images are normally not used in musculoskeletal imaging.

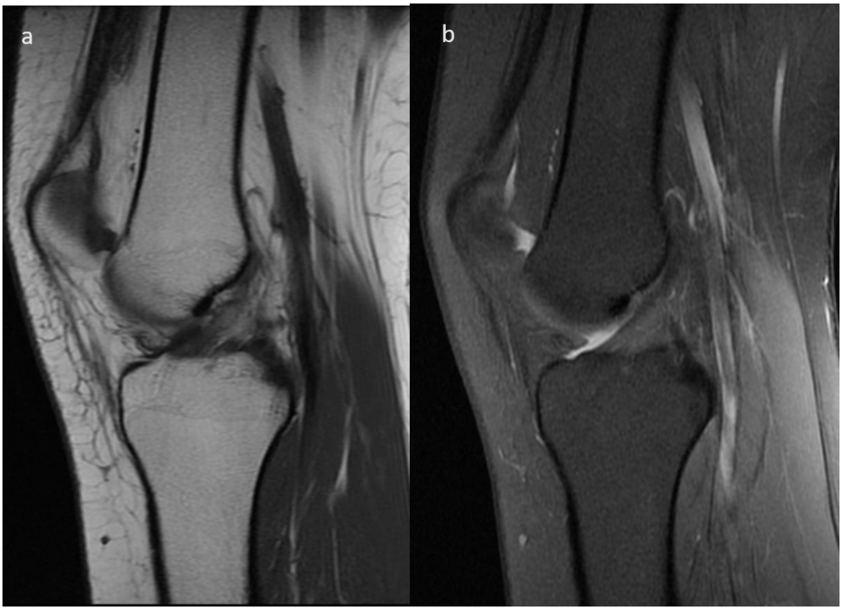
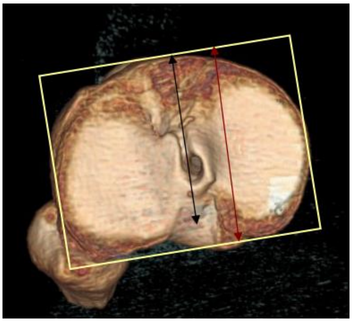


Figure 6.a/b Sagittal T1 weighted and T2 weighted images.

We showed that there were significant differences in measurements performed on summation images and slabs or slices. We quantified the mean difference in measurement between the two types of images and explained how this difference occurred.

Figure7. The difference in tibial tunnel placement changed if the centre line included the whole of the tibial depth (red arrow), as in for instance radiographs, or just the mid-section as in for instance MRI (black arrow).



Hence, we maintain that the first step for improving tunnel placement quantification is to not apply measurements from one modality automatically on another modality (unless comparative studies exist).

Defining normal footprints of ACL

The anatomy of ACL footprint in the femur and tibia is well known and has been studied in detail [89,96]. The footprints are recognised as fan like or "ducks' foot" attachment of fibres to the bone. Ligaments attach to the bone through the periosteum, so called "indirect" attachment or do not go through the periosteum, so called "direct attachment". The direct attachment is stronger as the periosteum is replaced by several layers of tissue (uncalcified fibrocartilage, then calcified fibrocartilage) [13,89]. The ACL has both direct and indirect attachments to the femur and tibia. In recent years there has been a discussion about which part of the ACL is most important to reconstruct, with some stating that the indirect fibres are not as important to reconstruct [122]. Further, the drilled tunnel by default is a rounded structure while the native ACL footprints are triangular or oval like [121,123]. So, a reconstructed ACL cannot exactly replicate a native footprint. Anatomic reconstruction aims to place tunnel as close as possible to the native location. To achieve this the surgeon drills the tunnel centre at the centre of the native ACL footprint. The orthopaedic community are used to "validating" surgical techniques with imaging methods, especially if they were trying to implement changes in surgical techniques [17,80,137].

Many anatomic and imaging studies had measured the ligament centres. Very often the results were similar, but sometimes the differences were substantial, up to 17% difference in ratios [36,70,91,143]. Thus, if a scientific study which used one published paper as a "gold standard" for anatomic placement and validated their surgery as successful, could very well be unsuccessful if they had applied a "gold standard" from a different paper. Another issue was also the presentation of means with or without standard deviations [17,28]. In epidemiology, the use of percentiles is common to include most of the variations in the population and classify them as "within normal range". The anatomic gold standards from previous in literature had not presented the data as percentiles. Our results paved the way for the use of these wider ranges in order to not exclude tunnel placements in the lower and higher percentiles. The presentation of 5th and 95th percentiles of femoral and tibial tunnel insertions was novel in this context.

Differences in measurement methods

From the early 90s onwards, several studies suggested measurement methods for post-operative graft tunnel placement assessment on radiographs. Aglietti et al. suggested to report the placement of the femoral tunnel as a ratio along the Blumensaats' line and the tibial tunnel as a ratio in the anterior posterior direction [7]. Aglietti used the cortical margins in both the femur and tibia as the outer points for measurements. For the tibia, the reference line was placed along the tibial plateaus. [Figure 8a]. Harner et al. suggested reporting placements as a ratio along the Blumensaats line, but using only the intercondylar line as outer points in the femur and the only using the midportion of the tibia as reference [Figure8b][48]. The Bernard & Hertel grid added the placement in the "high-low" direction and reported the femoral tunnel placement as a quadrant, not just a ratio along one direction [Fig [Figure 8c][16].

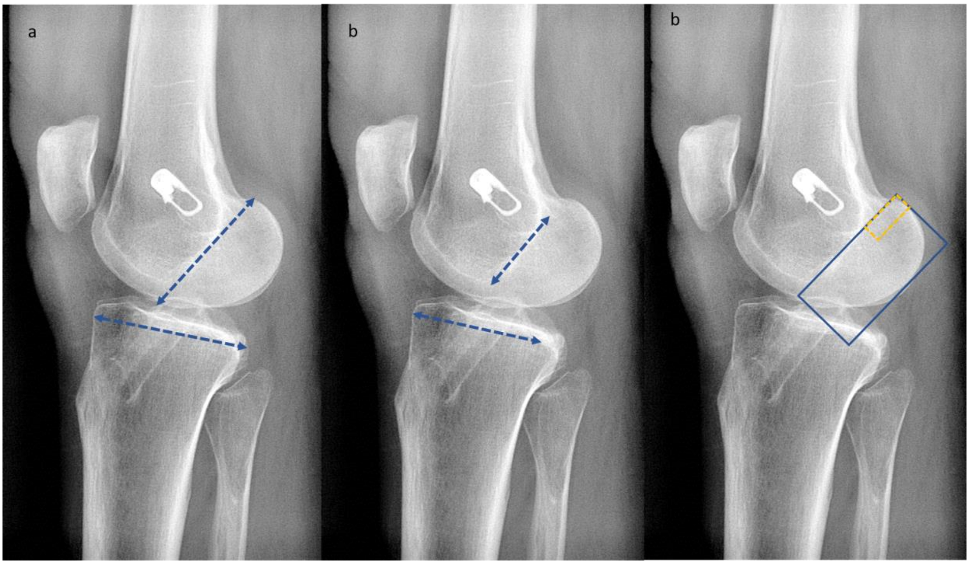


Figure 8a-c. The differences between measurement methods: Aglietti (a), Harner (b) and Bernard & Hertel (c).

Stäubli & Rauschning suggested an anterior-posterior ratio for the tibia, but the reference line was at the maximum depth of the tibial condyles, not along the surface of the plateaus [127]. Amis and Jakob recommended using the medial tibial plateau for the anterior posterior tibial tunnel placement [Figure 9] [11].

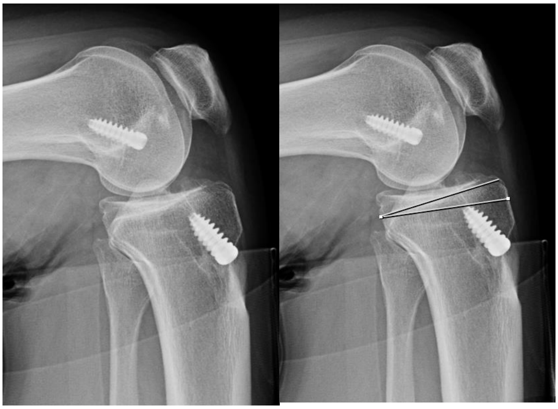


Figure 9. Stäubli & Rauschning line (lower line) and Amis and Jakob line (along the medial plateau, upper line).

The use femoral tunnel placement as “clock face” was also commonly used. The “clock face” is supposed to be placed on images where the intercondylar roof serves as top point, and the opening of the tunnel is seen. However the location of the intercondylar roof can be difficult on slice images even when it is in full extension, so that is can be easily placed slightly off centre [figure 10] [38,47,75]. Some use the clock face in knee flexion, while other use it when in extension [68]. Although, extensively used this method is no longer recommended [38,47].

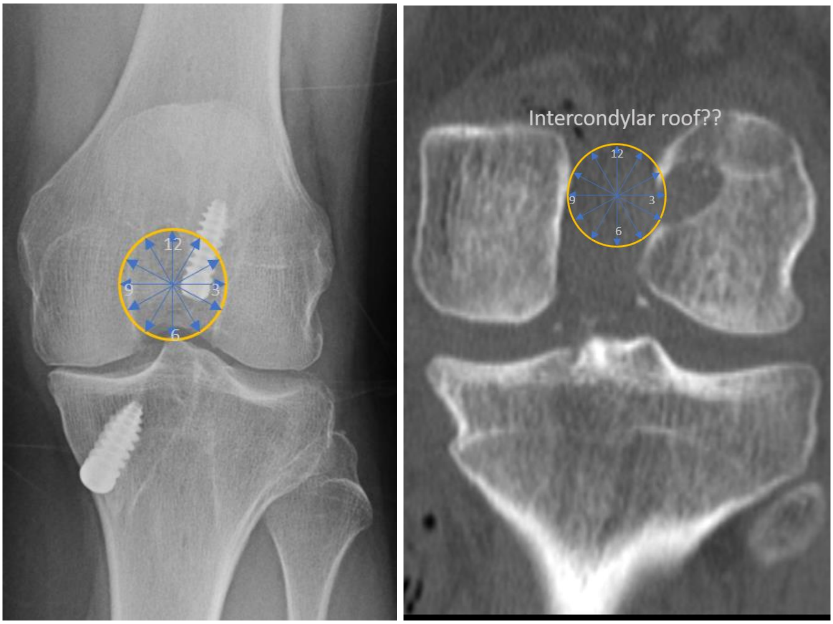


Figure 10a. Superimposed clockface on a radiograph performed in full extension. b The clock face on a CT coronal view in full extension. The intercondylar roof is not seen in the same image as the tunnel opening, making the use of the clock face difficult.

In addition to the measurement of the tunnel openings in femur and tibia, studies also suggested using tunnel angle measurements in the coronal plane on radiographs. In the femur the tunnel angle was measured with the femoral shaft as the centre line [figure 11] [57]. In the tibia the tibial plateaus were the centre line [figure 11][55].

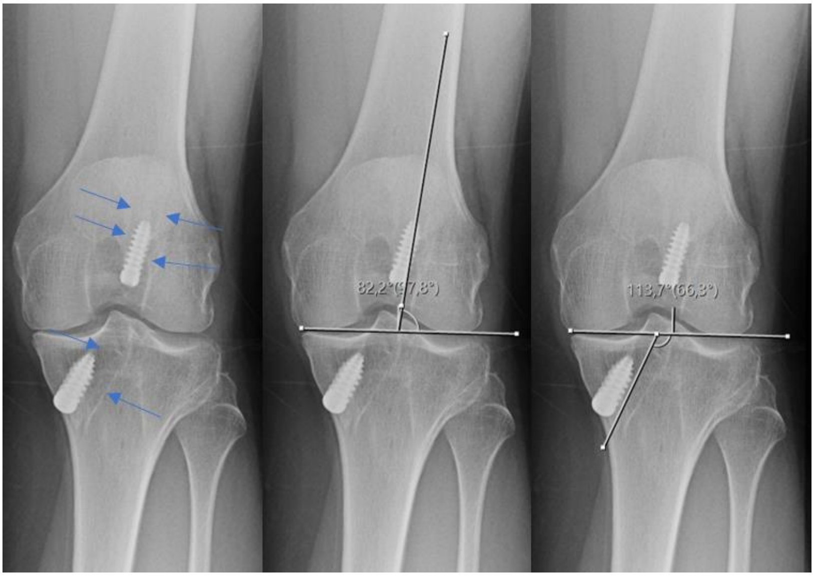


Figure 11. The tunnel wall is discernible as a thin sclerotic line (blue arrows). The tunnel angles are measured along the centre line.

Since the mid-2000s with increasing availability of MRI, graft angles in the coronal and sagittal planes were also used to quantify tunnel placement [Figure 12][8].The problem with graft angles is that they were conceived in the era of transtibial technique, and the main aim was to avoid too steep graft angle, as the aim was “isometric” graft placement. This concept has since fallen out of favour and the aim now is “anatomic” reconstruction [66]. However, radiologist still recommend using graft angles to indicate tunnel placement [42,140].

Figure 12. Graft seen as dark structure in the centre of the knee joint on sagittal and coronal images. Angles are measured along the centre line of the graft.

In the clinical context, the myriad of various measurements methods created a huge challenge. However, some methods very quickly fell out of favour due to difficulties in clinical application. The Harner method had low reliability, probably due to difficulty in deciding where the outer points of the ratio were to be placed. The clock method was also abandoned because it was difficult to implement as slight flexion in the knee altered the position of the tunnel as well as difficulties of using a clock when the femoral notch was “deep” or “elliptical”. Tunnel angles were devised in the transtibial reconstruction era [8]. In this period, the aim was to place tunnel so that the grafts were isometric. Isometric graft placement was aimed at keeping the ACL graft the same length during knee function [12]. This approach was associated with issues of over constrained rotational instability and anatomic graft placement replaced the concept of isometry [39,109]. Graft angles were useful for evaluating isometric graft placement with the transtibial technique [8]. Recent study showed that angles are clinically less important than measuring tunnel apertures [128]. In addition, graft angles, in both planes, are susceptible to significant variations due to even slight flexion in the knee joint [44].

Therefore, the measurement methods selected to examine our hypothesis in our studies were the Bernard & Hertel grid and the Stäubli & Rauschning ratio. These two methods are independent of the degree of knee flexion. Further the tibial measurement was independent of the slope of the tibial plateaus. This means they are easier to implement in clinical practice, as patients often have slightly varied knee flexion or even hyperextension while being imaged. For accurate evaluation of the femoral tunnel 3D CT images should be used as shown in paper I.

However, we should bear in mind that this is still not perfect. The overlaying of the grid on the exposed lateral femoral condyle is still a 2D grid on a 3D image. The depth of the condyle cannot be assessed correctly based on current measuring methods. One can correlate the problem to depicting the earth globe on a 2D surface. In clinical practice, to date, there are no available automated tools or methods which can deliver 100% accurate measurements. This will remain the residual limitation of imaging until newer methods are developed. Until then, consensus on which modality and measurement methods we chose, will improve comparability of results from future studies.

MRI assessment

MRI is considered the gold standard for knee imaging, especially for assessing deep lying structures. In the acute setting, radiographs are considered necessary, while MRIs are reserved for unclear cases or after major knee trauma [69]. Compared with arthroscopy findings the accuracy of MRI in assessing primary ligament injuries is high, and the spectrum and rate of MRI findings are well established [29]. MRI findings in post-operative patients have not been assessed so far. One small study has examined findings after arthroscopy and/or clinical examination [62]. They reported a high rate of concomitant injuries, up to 80%. Our findings differed as we reported a lower rate of concomitant injuries, about 60%, and higher rate of graft ruptures, almost 50%. Considering the controversial anterolateral capsular ligament injuries, we found lower rates of injury compared to previous published rates (44-88%) [24,35]. Our study also examined the inter-observer and intra-observer variability, putting a spotlight on the issue of accuracy in imaging. Clinical examination and/or arthroscopy are the gold standards for assessing knee pathology. When the clinical examination is performed by an experienced clinician the additional usefulness of MRI is limited [10].However, MRI does have a small role in imaging knee trauma as sensitivity of a physical examination can be moderate for diagnosis of lateral meniscus pathology [97].

Post-operative ACL imaging has two major aspects; first, early imaging to assess or evaluate issues such as graft placement or complications of fixation devices, and second, imaging prior to revision. In the radiological community, graft angles are commonly assessed on MRI, however we have shown that graft angles are a poor indicator of anatomic placement. We have also shown that tunnel placements in the femur are not readily assessed on MRI, only tibial tunnel placement is reliably assessed on MRI [99]. Fixation devices are usually assessed on radiographs or CT due to the artifacts metal generates on MRI [119]. Thus, the usefulness of MRI in the early post-operative phase or as a baseline examination is not substantiated.

Clinical evaluation after ACL reconstruction can be challenging. The patient may present with loss of motion in the knee joint and differentiating between the various underlying causes can be difficult. Several causes, such as inadequate rehabilitation, capsulitis, non-anatomic graft placement or focal arthrofibrosis (Cyclops lesions), presence of unaddressed concomitant lesions, to mention a few, have been reported as contributing factors [40,126]. Further, after a new trauma or due to non-anatomic graft placement, a total rupture, partial rupture or just elongation of the graft may occur [56,115]. In recent years, the importance of unaddressed meniscal ruptures and possible effect of the rupture of anterolateral structures are also considered important to evaluate on post-operative MRIs [19,125]. However, surprisingly, we found that graft rupture was a frequent finding. In the setting of partial graft injury, MRI is crucial, as it can show partial rupture of graft fibres, which would be difficult to assess clinically as the intact part of the graft will still yield support to the knee joint during examination.

MRI assessment is, unfortunately, not straightforward. MRI criteria for graft ligamentisation and graft impingement are well known and established. Saupe et al. showed that the graft may have high signal up to 2-4 years after reconstruction [116]. As ligamentisation can take years, care should be taken to avoid over-diagnosing early post-operative changes in the graft as partial graft rupture. Howell et al. reported MRI criteria for graft impingement in 1991, and impingement is still considered important today [54,118]. Graft impingement on MRI can be seen as slight "bowing" or s-shaped graft when the knee joint is extended. The graft seems like it is elongated on MRI in the sagittal view. This is a criterium which is based on the radiologists' subjective evaluation. The assessment of ACL graft rupture is easier because the fibres are either ruptured or they are not. This variation in diagnosis was reflected in the difference in inter-observer reliability, which was significantly lower in graft impingement. Herein lies the one major challenge in MRI assessment. Radiologists are very effective in measuring accurately, as we presented in our first study. The inter-observer reliability was as high as 0.96 [83]. However, when it comes to evaluation without measurements, as is very common in radiology, the reliability can be very low.

This difficult topic in imaging is rarely addressed, and when it is addressed, it can simply deflate all faith in imaging. The few studies that assessed inter-observer variability on imaging in more than 100 radiologists have shown that the variation is substantial and also can lead to varied treatment and follow-up [93,139]. This, understated aspect has to be considered when discussing the low rate of inter-observer reliability of the subtle structure ALLC (or ALL). The structure is hotly debated [24,27,34,35,45,125]. As previously reported by Porrino et al. and Marshall et al., we showed that the diagnosis of ALL has very low reliability.

Is the low reliability of reporting radiologists an underlying cause for this on-going debate? One can expect that the ALL structure is, highly likely, still incorrectly assessed on MRI in the clinical setting. This may lead to underdiagnosis and underrepair. The radiologists lack of experience or knowledge may be the cause. We saw that even when the radiologists were especially searching for this pathology, it was not easy to evaluate. It might explain why the clinical studies reporting correlation of concomitant ALL injury to surgical outcome after ACL reconstruction often have opposing results.

"Established" knowledge is reliably reported. We found that MRI is useful in assessing graft, as inter-rater and intra-rater variability was acceptable for graft evaluation. "New" structures such as ALL will probably take decades to reach the same accuracy as ACL (both native and graft) imaging has. It has been reported that new information needs on average 17 years to be implemented [88]. Orthopaedic surgeons, but also radiologists, need to be aware of the delay in implementing new knowledge into imaging.

Conclusions

- Many various measurement methods for evaluation of graft tunnel placements exist.
- The methods which are independent of knee flexion, such as grid measurements according to Bernard & Hertel and tibial ratio according to Stäubli & Rauschning, should be used.
- CT is currently the most robust modality for measuring graft tunnel placements.
- Femoral graft tunnel placed between 24%-37% in the deep-shallow direction and 28%-43% in the high-low direction can be considered "anatomic".
- Tibial graft tunnel placed between 39% - 47% in the anterior-posterior direction in the midline of a CT or MR image can be considered "anatomic".
- Graft angle measurements are useless in the evaluation of tunnel placements. They do not correlate to anatomic graft tunnel placements and should no longer be used.
- MRI is reliable for well-established structures such as ligaments and menisci, but currently not for newer anatomic structures such as ALLC.

Future perspectives

Imaging has had, currently has, and will continue to play an important part in ACL reconstruction. As surgical techniques continue to develop, imaging will be used to evaluate efficacy of the surgery.

We have shown that mixing modalities and measurement methods causes confusion. In recent years, more studies are using CT and the recommended grid and ratios, though a minority still use inferior modalities and out of date methods. Other groups have started their research in exploring new technology. High-end MRI machines are now able to create sharper 3D MR images. As this technology develops, MRI may be able to replace 3D CT, which would be a great step forward, if this could give us comparable depiction of tunnel placements, with the added depiction of soft tissue, and removal of the radiation dose to the patient. The question is probably not if, but when?

We recommend discontinuation of measurements of graft angles and clock face to evaluate tunnel placements. However, these concepts are very strongly ingrained in the radiological community and literature. A greater effort must be made to disseminate this knowledge and educate radiologists and surgeons alike. Radiologists have to actively seek knowledge in related fields, as we only see what we know. Orthopaedic surgeons can aid this push in knowledge by actively collaborating with their radiological colleagues.

We have shown that it is difficult for radiologists to confidently recognise new structures on MRI, especially when the anatomy and pathology is subtle. This means that the role of MRI in ALLC may never transpire, and it may forever remain an elusive structure on imaging. On the other hand, MRI technology is forever improving and new possibilities such as diffusion tensor imaging may open an entirely new field in musculoskeletal imaging. It is important to not dismiss new knowledge and possibilities, and to keep an open, but critical and forever inquisitive mind.

The physicist Max Planck wrote in 1948 in his “Scientific autobiography”:

“Eine neue wissenschaftliche Wahrheit pflegt sich nicht in der Weise durchzusetzen, daß ihre Gegner überzeugt werden und sich als belehrt erklären, sondern vielmehr dadurch, daß ihre Gegner allmählich aussterben und daß die heranwachsende Generation von vornherein mit der Wahrheit vertraut gemacht ist.”

(From Wissenschaftliche Selbstbiographie, Johann Ambrosius Barth Verlag, Leipzig, 1948, S.22)

Translated into English it rendered: *A new scientific truth does not triumph by convincing its opponents and making them see the light, but rather because its opponents eventually die, and a new generation grows up that is familiar with it*.

(From Scientific autobiography, and other papers: with a memorial address on Max Planck. Philosophical Library, 1949, pg. 25, Planck, M., Laue, M. von, & Gaynor, F.)

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Measurements of tunnel placements after anterior cruciate ligament reconstruction — A comparison between CT, radiographs and MRI

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ABSTRACT

Background: A non-anatomic placement of the femoral and tibial tunnels may affect outcome in anterior cruciate ligament (ACL) reconstructions. Tunnel placements are validated with varying imaging modalities. We compared measurements of tunnel placements between radiographs, computed tomography (CT) and magnetic resonance imaging (MRI) in a clinical setting, assessed the reliability and aimed to decide on a possible "gold standard".
Methods: All patients who had undergone at least two of three modalities, radiographs, MRI and CT, after ACL reconstruction between January 2011 and June 2013 were included. Two radiologists measured tunnel placements according to a standardized protocol. Interobserver agreement was assessed with intraclass correlation coefficients (ICC), the intermodality differences with Bland–Atman plots. Radiation data for CT studies were collected.
Results: Forty-six CTs, 45 radiographs and 30 MRIs were reviewed. Femoral inter-observer agreement for radiographs was ICC = 0.64, for CT ICC = 0.86 and for MRI ICC = 0.75. Tibial inter-observer agreement for radiographs was ICC = 0.92, for CT-mip ICC = 0.91, for CT and MRI ICC = 0.87. No intermodality differences between the femoral measurements were observed. In the tibia, there were differences between radiographs and CT (−3.9%), radiographs-MRI (−3.6%), CT–CTmip (3.2%) and CTmip–MRI (−3.1%). The effective radiation doses varied between 0.025 and 0.045 mSv, mean and median was 0.033 mSv.
Conclusion: There were differences in the tibial measurements between summation and single slice images. Only 3D–CT depicted the femoral tunnel in both directions. CT was consistently reliable in both femoral and tibial measurements. Effective radiation dose from CT was lower than previously reported. CT can safely be used in routine clinical practice to evaluate tunnel placements after ACL reconstruction.
Level of evidence: Level III — study of diagnostic test without a universally applied "gold standard".

1. Introduction

Anterior cruciate ligament (ACL) reconstruction is a commonly performed procedure and the results are generally good. However, poor or unsatisfactory outcome sometimes occur and may be related to the surgical technique, inadequate rehabilitation or a recurrent trauma [1,2]. Knowledge and recognition of common early and late complications improve the clinical outcome [1]. There is still some debate about which surgical technique is superior in the long term, as outcomes seem to be similar [3]. The outcome after surgical reconstruction is commonly evaluated by a physical examination as well as by using clinical scoring systems [4]. Since the publication of the proceedings of an European workshop on ACL reconstruction in 1998 which indicated "optimal" positions of the ACL placements in the femur and tibia, cadaver studies have examined the anatomic footprint of the ACL [5–10]. In recent years non-anatomic tunnel placement is recognized as an important cause for failed surgery [2]. Evaluation of the "anatomic" placements of the tunnels necessitates the use of imaging studies. Post-operative imaging has increased in popularity [11–21].

The accuracy of imaging to depict tunnel placements has been validated for radiographs, CT and MRIs in cadaver studies [22,23]. As neither the orthopedic nor radiological community has agreed on a gold standard for imaging tunnel placements post-operatively, tunnel placements have been evaluated with varying modalities in clinical practice as well as in scientific studies [21,22,24]. The variations in modalities and the type of measurement methods used make comparison of

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different studies difficult. In addition, one study indicates a difference in visibility and measurements (of tunnel width) between modalities [25]. The difference in reported femoral tunnel placements between studies has been as high as 15% [12]. Some of the differences are undoubtedly due to varying surgical techniques [26], but some of the differences may be due to systematic variations between modalities. Knowledge about how the modalities compare with each other in clinical practice is still scarce. The objective of our study was to compare measurements of tunnel placements between radiographs, CT and MRI in a clinical setting and to assess if measurements between modalities can be used interchangeably. A further objective was to assess the reliability of the methods by evaluating the inter-observer agreement and to suggest a possible “gold standard”.

2. Material and methods

All patients clinically assessed for potential ACL revision surgery between January 2011 and July 2013 who had undergone at least two of the following three modalities: CT, MRI and radiographs, were included. Patients who had only undergone one modality were excluded. The study was presented to the regional ethics committee. As all imaging examinations had been requested as part of the regular treatment plan in a clinical setting, patient informed consent was waived. All images were retrieved from our picture archiving system (IMPAX, Mortsel, Belgium). The radiographs and MRIs were performed on various 1.5 T systems, the CTs were all performed on a 64-slice machine, technical parameters tube voltage 100 kV, tube current 80 mA, slice thickness of 0.6 mm.

2.1. Method for measurements

Two qualified musculoskeletal radiologists (radiology experience 12 years and >25 years) assessed the tunnel placements, blinded to each other's findings, according to the following methods:

(1) The placement of femoral tunnel was measured in the Bernard and Hertel grid indicating both the deep–shallow and high–low measurements on volume rendered 3D-CT [27]. On MRI and radiographs, only the deep–shallow measurements could be assessed as the high–low centers of the femoral tunnel could not be confidently measured on neither radiographs nor MRIs (Fig. 1).

(2) The tibial tunnel placement was measured using the method first described by Stäubli and Rauschning, and popularized by Amis and Jakob (the Amis and Jakob line) [23,28] (Fig. 2). For CT there was a further measurement on a minimal intensity projection images (CTmip) (Fig. 2d).

All tunnel placement measurements were recorded as percentages. The measurements were performed in the IMPAX.

2.2. Radiation data collection

The radiation doses from radiographic examinations could not be retrieved from the system. CT radiation doses in each case were collected from IMPAX and recorded as dose length products (DLP) in milliGray centimeter (mGycm). The effective dose (ED) was calculated using the correlation coefficient for CT knee in adults: 0.0004, using the recommended formula ED = DLP × 0.0004 [29].

2.3. Statistical analysis

The inter-observer agreement of each modality and of each measurement method was calculated as intraclass correlation coefficients (ICC) [30]. The scale used for the ICC interpretation was: values below 0.75 poor agreement, between 0.75 and 0.90 moderate agreement, and above 0.90 high agreement [31].

The variations between the modalities were assessed with Bland–Altman plots of the means of measurement pairs, and given with their limits of agreement. Missing values were left empty and not estimated. All computations were done in SPSS 22 (IBM, New York, USA) or R 3.0.2. (R Core team, general public license). The plots were created in MATLAB 7.10 (MathWorks Inc., Asheboro, NC, USA.).

3. Results

Thirty of the included patients had undergone all three modalities, another 15 patients had undergone CT and radiographs, and one patient had undergone only CT and MRI. Thus, a total of 46 patients were included; 30 females and 16 males, median age of 23.5 years and mean age of 27 years (range 17–52 years).

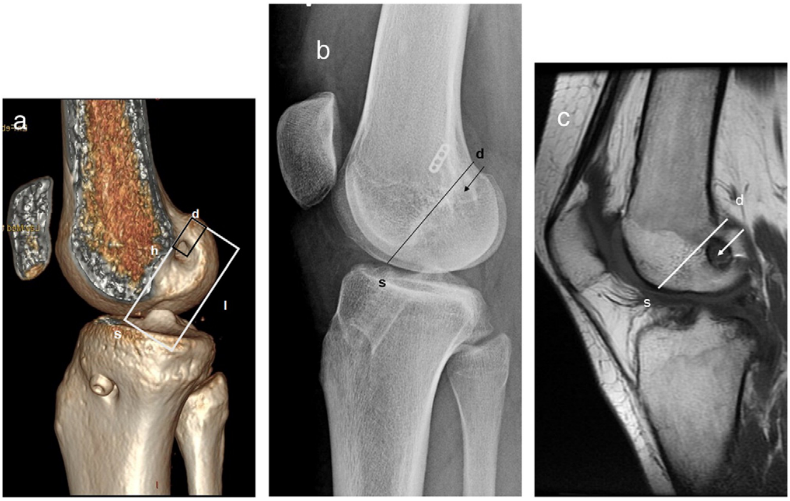

Fig. 1. The method for measurement of the femoral tunnel placement. a) 3DCT image, tunnel placement in the deep–shallow and high–low directions indicated with a box/grid. b) Deep–shallow measurements on a lateral radiograph. c) Deep–shallow measurements on a sagittal MRI. d = deep, s = shallow, h = high, l = low.

Fig. 2. Measurement of the tibial tunnel placement measured as a ratio of the tibial depth in the anterior–posterior directions. a) On a lateral radiograph. b) On a CT-mid-sagittal slice image. c) On a mid-sagittal MRI. d) On a CT-mid-sagittal image.

3.1. Inter-observer agreement

3.1.1. Femoral tunnel

The agreement was poor for the deep–shallow measurements on radiographs (ICC = 0.64). The agreement for measurements on MRI (ICC = 0.75) and 3D-CT (ICC = 0.86) was moderate. The additional inter-observer measurement of the femoral tunnel in the high–low directions on 3D-CT yielded also moderate agreement (ICC = 0.84) (Table 1).

3.1.2. Tibial tunnel

The agreement of the tibial tunnel measurements was high for radiographs (ICC = 0.92) and CT-mip (ICC = 0.91), and moderate for CT (ICC = 0.87) and MRI (ICC = 0.87) (Table 1).

The 95% confidence intervals of the ICCs of the femoral and tibial measurements are presented in Table 1.

3.2. Inter-modality measurements

3.2.1. Femoral tunnel

The means of the tunnel placement measurements in the three modalities were: radiographs 32.1 (SD 6.4%), 3D-CT 33.4 (SD 7.4%) and MRI 30.6 (SD 7%). The Bland–Altman plots for the measurement pairs radiographs–CT, radiographs–MRI and CT–MRI are presented in Fig. 3. There were negligible differences between the pairs radiographs–3D–CT (mean difference 1.47), radiographs–MRI (mean difference −0.32) and 3D–CT–MRI (mean difference 2.27), and a broad range in the limits of agreement.

3.2.2. Tibial tunnel

The means of the tibial tunnel placement were; radiographs 43.9 (SD 6.7%), CT 47.8 (SD 7.3%), CTmip 44.6 (SD 6.7%) and MRI 48.3 (SD 6.7%). The Bland–Altman plots for tibial tunnel are presented in Figs. 4 and 5. Here the differences between the measurement pairs were larger than in the femur; radiographs-CT (−3.92%), radiographs–MRI (−3.63%), CT–CTmip (3.24%) and CTmip–MRI (−3.14%). The differences between the remaining pairs were notably smaller; radiographs–CTmip (−0.76%) and CT–MRI (0.13%). These remaining measurements were also more clustered and with narrower limits of agreement.

Table 1
The ICCs of the inter-observer agreement given with their 95% confidence interval.

	ICC[a]	95% CI[b]	
Femoral tunnel (deep–shallow measurements)			
Radiographs	0.64	0.2 to 0.8	Poor
3DCT	0.86	0.67 to 0.93	Moderate
MRI	0.75	0.49 to 0.88	Moderate
Femoral tunnel (high–low measurements)			
3DCT	0.84	0.70 to 0.91	Moderate
Tibial tunnel (anterior–posterior measurements)			
Radiographs	0.92	0.86 to 0.96	High
CT	0.87	0.75 to 0.93	Moderate
CTmip	0.91	0.82 to 0.95	High
MRI	0.87	0.56 to 0.95	Moderate

[a] Intraclass correlation coefficient, agreement.
[b] Confidence interval.

3.3. Radiation dose

The CT radiation doses varied from DLP 63 to 112 mGycm. The average and median were 83.4 mGycm and 83.7 mGycm respectively. The ED varied from 0.025 to 0.045 mSv. The average and median ED were both 0.033 mSv.

4. Discussion

4.1. Femoral tunnel

In the femoral tunnel, the agreements for the measurements were moderate for MRI and CT, with CT as the most reliable. Agreement of the measurements on radiographs was poor in our study. This is in accordance with previous studies [24,32]. The poor agreement on radiographs is foremostly explained by the often barely discernible tunnel center on post-operative radiographs (Fig. 1b). Further, it may be difficult to choose the correct depth of the femoral condyles if the images are performed in a slight rotation. The barely moderate agreement for MRI is caused by the difficulty in visualization of the cortical border, as the overlying cartilage is depicted on MRI (Fig. 1c). On 3D–CT the round or oval opening is clearly seen on the lateral condyle wall and the cortical border is clearly depicted (Fig. 1a). 3D-CT is also the only image modality and image type which can depict the femoral tunnel placement in both the deep–shallow and high–low directions. The differences between the modalities were small and not statistically significant. However Bland–Altman plots are based on the means of the two raters. Thus, some of the differences may be diminished, and small variations between the modalities may be obscured.

4.2. Tibial tunnel

Regarding the tibial tunnel, the agreements in the measurements were high on radiographs and CTmip, and moderate on CT and MRI. The center of the tunnel is easily visualized on all modalities. The anterior and posterior borders of the tibia, on radiographs, MRI and all CT

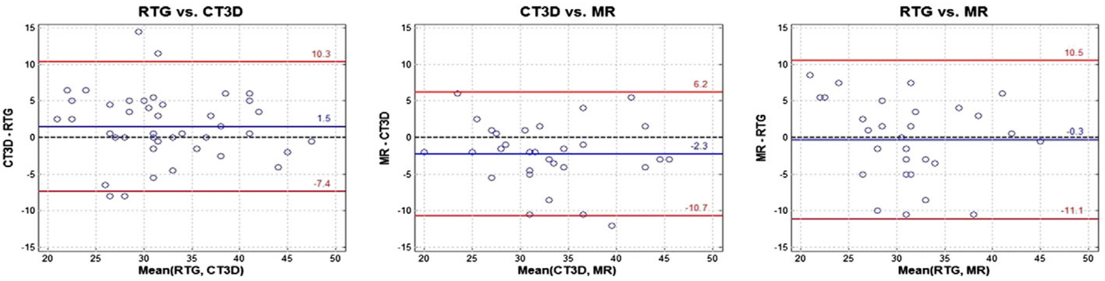

Fig. 3. Bland–Altman plots for intermodality measurements of the femoral tunnel placement in the deep–shallow directions. Slight differences were seen between the first two pairs, but no difference between radiographs and MRI. a) Radiographs–3DCT. b) 3DCT–MRI. c) Radiographs–MRI.

image types, are clearly depicted, although rotation may influence the measurements on radiographs (Fig. 2a, b and d) [32]. In clinical practice on CT and MRI the reader has to scroll through the examination and subjectively decide on which image the center of the tunnel is. The images are normally two to three millimeters thick, and if the readers choose different images, the measurements may be influenced by the difference in the chosen center. In addition the cortical border is blurry on MRIs (Fig. 2c). Radiographs and CTmips are single (summation) images, while CTs and MRIs represent slices. On the slice images the inter-condylar notch marks the posterior border of the measurement, whereas in summation images the condyles are the posterior border (Fig. 6). The intermodality differences seen between the tibial measurement pairs radiographs–MRI, radiographs-CT and CT–CTmip are due to these inherent properties of the modalities, image type and anatomy.

4.3. Clinical significance of results

The clinical significance of differences in measurements of tunnel placements is still undetermined. However, acceptable ranges of placements for the femoral tunnel and tibial tunnel have been defined [23,27]. Thus, deviations from the recommended 43% in tibia may be considered as inadequate tibial tunnel placement. We noted a systematic

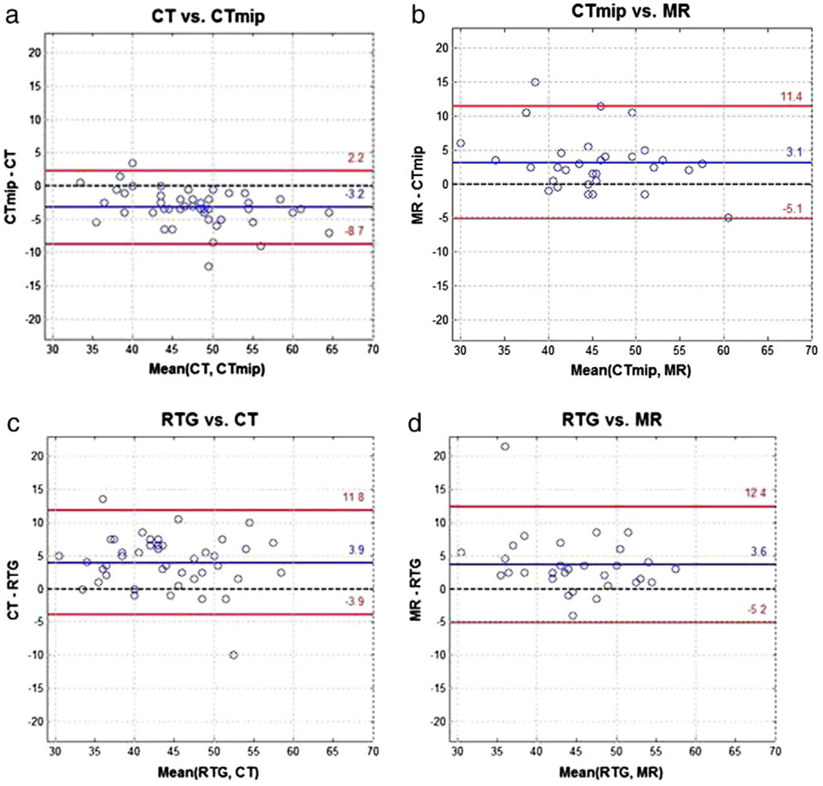

Fig. 4. Bland–Altman plots of the intermodality measurements of the tibial tunnel in the anterior–posterior directions. The differences were significant between these modalities. a) CT–CTmip. b) CTmip–MRI. c) Radiographs–CT. d) Radiographs–MRI.

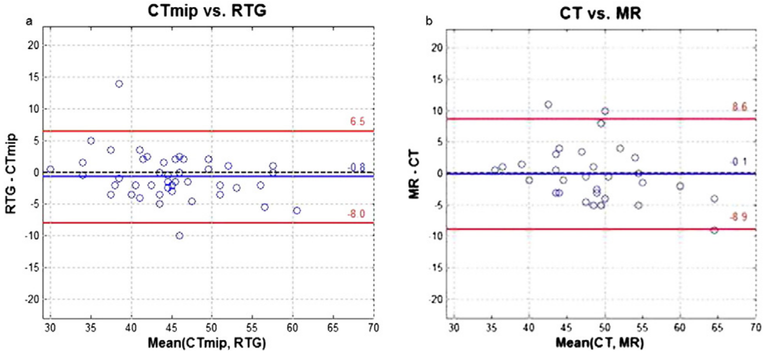

Fig. 5. Bland–Altman plots of the tibial tunnel measurements between a) CTmip and radiographs, and b) CT and MRI, with only small differences between the measurements.

intramodality difference in our series. In 44 out of 46 measurements between CT and CTmip, the measurements on single slice CT were slightly larger (approximately 3%) than the measurements on CTmip images. This trend was also observed in the other inter-modality pairs, the single slice measurements yielded larger measurements than the measurements on summation images. This is due to the anatomy of the tibial plateau, and should be considered when comparing measurements, see also Section 4.2 above.

Similar findings have been observed in previous studies, but as the types of measurements and modalities used varied, a direct comparison is difficult. Hoser et al. indicated that the femoral tunnel placement was a "trend deeper" on CT images compared with radiographs, but used a different method for measurement and did not quantify the difference [21]. Jenny et al. observed mean differences of three percent in the femoral tunnels and of six percent in the tibial placements between CT and radiographs, but their measurements were based on the identification of inserted metal pins in cadavers [22]. Meuffels et al. compared tunnel positions on radiographs, CT images and 3DCT images, but assessed only the reliability of the modalities and not the tunnel placement measurements [24].

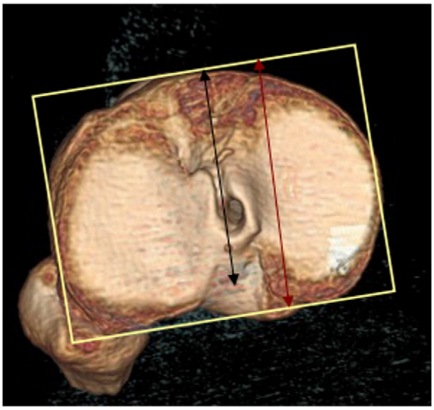

Fig. 6. The variations in the shape of the tibia affect the measurements. The dark line represents the mid-sagittal depth of the tibia used for CT and MR images, which are single slices. The red line represents the depth used when measuring on X-ray and CT-mip images, which are summation images.

4.4. The radiation dose

CT as routine post-operative imaging after ACL reconstruction is often not recommended, with higher radiation mentioned as the main argument against using CT [24,33]. Previous studies have shown that by adjusting the technical parameters of CT machines for extremity imaging it is possible to reduce the effective radiation dose to the knee to the same level as three views of radiographs in adults [34]. Another study reported an average ED for knee radiographs of 0.005 mSv and a chest radiograph of 0.1 mSv [35]. In our series the average radiation dose was much lower than previously reported. We found that a CT knee leads to less radiation exposure than a standard chest radiograph, and equaled about six knee radiographs.

4.5. Strengths and limitations

To the best of our knowledge, this is the first study comparing tunnel placement measurements in clinical practice in both the femur and tibia in three modalities: CT, radiographs and MRI. We also used the measurement methods recommended by Amis and Jakob following an international scientific workshop on ACL reconstruction [28]. However, the smaller number of MRI examinations compared with radiographs and CTs may have influenced the statistics as some measurement pairs were left empty. Further, the lack of an established gold standard for tunnel placement assessments complicated the statistical analysis.

In conclusion, the main finding in the current study is that due to the difference in the tibial measurements between summation and single slice images, the tibial tunnel measurements cannot be used interchangeably between image types and modalities. Only 3DCT can depict the femoral tunnel in both directions. CT showed consistent stable inter-observer reliability in both femoral and tibial measurements. With recommended use of dose modulating techniques, it is possible to reduce radiation doses to the same level as chest radiographs. We therefore suggest the use of CT as the "gold standard" for evaluating tunnel placements after ACL reconstruction in routine clinical practice as well as in clinical studies.

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Original Research

Computed Tomography Assessment of Anatomic Graft Placement After ACL Reconstruction

A Comparative Study of Grid and Angle Measurements

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Background: The anatomic placement of anterior cruciate ligament (ACL) grafts is often assessed with postoperative imaging. In clinical practice, graft angles are measured to indicate anatomic placement on magnetic resonance imaging, whereas grid measurements are performed on computed tomography (CT). Recently, a study indicated that graft angle measurements could also be assessed on CT. No consensus has yet been reached on which measurement method is best suited to assess anatomic graft placement.

Purpose: To compare the ability of grid measurements and angle measurements to identify anatomic versus nonanatomic tunnel placement on CT performed in patients undergoing ACL reconstruction.

Study Design: Case series; Level of evidence, 4.

Methods: A total of 100 knees undergoing primary reconstruction with a hamstring graft (HAM group), 91 undergoing reconstruction with a bone–patellar tendon–bone graft (BPTB group), and 117 undergoing revision ACL reconstruction (REV group) were assessed with CT. Grid measurements of the femoral and tibial tunnels and angle measurements of grafts were performed. Graft placement, rated as anatomic or nonanatomic, was assessed with both methods. Pearson chi-square, analysis of variance, Kruskal-Wallis, and weighted kappa tests were performed as appropriate.

Results: The grid assessment classified 10% of the HAM group, 4% of the BPTB group, and 17% of the REV group as nonanatomic ($P < .001$). The angle assessment classified 37% of the HAM group, 54% of the BPTB group, and 47% of the REV group as nonanatomic. The weighted kappa between angle measurements and grid measurements was low in all groups (HAM: 0.009; BPTB: 0.065; REV: 0.041).

Conclusion: The agreement between grid measurements and angle measurements was very low. The angle measurements seemed to overestimate nonanatomic tunnel placement. Grid measurements were better in identifying malpositioned grafts.

Keywords: anterior cruciate ligament; tunnel position; grid measurement; graft angles

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Anterior cruciate ligament (ACL) reconstruction has evolved constantly since it was implemented in clinical practice more than 3 decades ago.[8] There have been many shifts in surgical trends, with the current focus mainly on anatomic reconstruction.[29] Intraoperative and postoperative imaging is often used to assist and assess graft placement.[13,32,44] Various imaging modalities and measurement methods are used to improve the reproducible assessment of postoperative graft placement.[31,41,47] There is no consensus on which modality to use in clinical practice. The matter is further complicated by the fact that different measurement methods are used on the various radiological modalities for the assessment of femoral graft placement.[10,24,34] The Bernard and Hertel grid is commonly used on radiographs and 3-dimensional computed tomography (3D-CT), with accurate measurements of graft placement in the high-low direction only possible on 3D-CT.[31] There is less controversy regarding tibial graft placement, as measurements are performed in a similar manner in all modalities.[4,31,42] The angle measurements of graft inclination or obliquity are mostly performed on magnetic resonance imaging (MRI).[3,4,27,38,46]

Studies have examined the normal anatomic locations of ACL insertions, which are used to judge postoperative

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placement as either "in" or "out" of the anatomic range.[1,9,11,19,25,34,35] Several studies have also examined the normal angles of the native ACL.[3,5,36] In clinical practice, it is common to perform MRI before primary surgery and revision to assess the soft tissues to detect/identify concomitant meniscal injuries and other ligament injuries. However, some also suggest the use of CT and 3D-CT to aid surgery planning before revision.[15,37] In the clinical setting, it is not common to measure graft angles on CT or grids on MRI, and the methods are not used interchangeably. Recent studies show that there is little difference between angle measurements performed on MRI and CT and grid measurements performed on CT and 3D-MRI.[10,14] However, it is not known if both methods are equally adept in identifying the nonanatomic placement of grafts.

The purpose of this study was to compare the angle and grid measurements of identifying anatomic versus nonanatomic tunnel placement on CT performed in patients undergoing ACL reconstruction. We hypothesized that the rate of nonanatomic placement would be higher in patients undergoing revision surgery compared with primary ACL reconstruction and aimed to assess the ability of the measurement methods to follow this hypothesis.

METHODS

The study was approved by a regional ethics board, and informed consent was waived. From January 2011 to the end of December 2017, all patients who were evaluated for revision ACL reconstruction and who underwent preoperative CT at a single institution were initially included retrospectively. Revision surgery was planned in patients who had an unsatisfactory function in the knee joint; examples of underlying causes were nonanatomic placement of graft tunnels, impingement due to grafts that were too long, or stretching of grafts during a new injury. Potential patients were identified through a manual search in our PACS system. From January 2011 to December 2015, we also included 100 postoperative CT scans obtained after primary reconstruction with either a hamstring graft or bone–patellar tendon–bone (BPTB) graft consecutively as separate groups. Postoperative CT was performed within 1 to 3 days after ACL reconstruction with the knee in full extension. Exclusion criteria were cases with multiple ligament reconstructions, known graft ruptures, or cases with previous revision. Graft ruptures were excluded, as graft angle measurements were not possible to perform without visible fibers on CT.

In all cases, sex, age, and knee laterality were recorded. In addition, the type of surgical technique (anteromedial portal or transtibial) and type of graft used (hamstring or BPTB) were recorded. In the revision group, months since primary ACL reconstruction were also recorded. All CT examinations were performed in our institution on either a 64- or 512-detector CT machine (GE Healthcare). All images were acquired at a tube voltage of 100 kV and tube current of 80 mA with a 0.625-mm slice thickness and reconstructed in 3 planes in soft kernel and bone algorithms with 2 mm–thick slabs.

In all cases, measurements of femoral tunnel placement were performed according to Bernard and Hertel, tibial tunnel placement was assessed according to Stäubli and Rauschning,[42] and ACL graft angles were measured in the coronal and sagittal planes. All measurements were performed and recorded by an experienced radiologist (>15 years; A.P.P.) (Figure 1). Normal ranges for the grid measurements were defined according to the literature: femoral deep-shallow, 24% to 37%; femoral high-low, 28% to 43%; and tibial anterior-posterior, 39% to 46%.[33]

The normal ranges for ACL coronal and sagittal angles were calculated from weighted means from the literature, as presented in Table 1.[3,4,36] The normal coronal angle ranged from 66° to 74°, and the normal sagittal angle ranged from 47° to 59°. Graft placement in the coronal and sagittal planes was dichotomously recorded as "in" or "out" of the anatomic range. Within the revision group, the abovementioned analyses were also performed comparing the anteromedial portal and transtibial surgical approach.

Statistical Analysis

Dichotomous variables were assessed with the Pearson chi-square test. The combined assessments of grid in 2 directions or angles in 2 planes were classified in ordered categories (anatomic, partial anatomic, or nonanatomic), which were assessed with the weighted kappa. Continuous variables were assessed with the analysis of variance or Kruskal-Wallis test according to an assumed normality of data.[48] $P < .05$ was considered significant, but the Bonferroni adjustment was used for multiple comparisons ($P =$ .05, .017, or .08). All statistical analyses were performed with SPSS (v 25.0; IBM).

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Ethical approval for this study was obtained from Regional Committees for Medical and Health Research Ethics (No. 2017/2434/REK sør-øst).

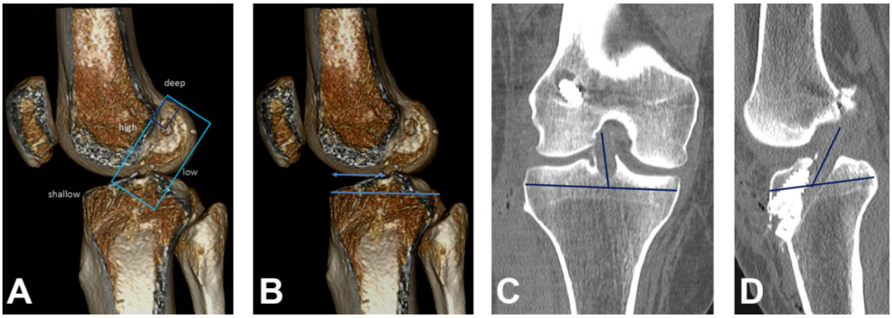

Figure 1. (A) Femoral tunnel measurement according to Bernard and Hertel, as depicted on 3-dimensional computed tomography (CT) after reconstruction with a hamstring graft. The graft tunnel center is 27% in the femoral deep-shallow direction and 35% in the femoral high-low direction (anatomic placement). (B) Tibial tunnel measurement according to Stäubli and Rauschning.[42] The graft tunnel center is 46% in the tibial anterior-posterior direction (anatomic placement). (C) Coronal angle measurement on CT (example of reconstruction with a bone–patellar tendon–bone graft), measured at 80° (nonanatomic placement). (D) Sagittal angle measurement, measured at 60° (nonanatomic placement).

TABLE 1
Normal Ranges of Coronal and Sagittal Graft Angles

	No. of Patients	Coronal Angle, deg	Sagittal Angle, deg
Ahn et al[3] (2007)	50	65.9	58.7
Ayerza et al[5] (2003)	30	–	51.0
Reid et al[36] (2017)	188	74.3	46.9
Weighted mean (5th-95th percentile)		72.5 (66-74)	49.5 (47-59)

TABLE 2
Demographics of Study Groups[a]

	Primary HAM (n = 100)	Primary BPTB (n = 91)	REV (n = 117)[b]	*P* Value
Age, y				.037 (K-W)
Mean ± SD	29 ± 10	26 ± 10	29 ± 9	
Median (range)	28 (14-54)	23 (14-53)	26 (15-55)	
Sex, n (%)				**.009**[c] (χ^2)
Female	45 (45)	40 (44)	73 (62)	
Male	55 (55)	51 (56)	44 (38)	
Laterality, n (%)				.588 (χ^2)
Right	53 (53)	42 (46)	61 (52)	
Left	47 (47)	49 (54)	56 (48)	

[a] Bolded *P* values indicate a statistically significant difference between groups ($P < .05$). BPTB, bone–patellar tendon–bone; HAM, hamstring; K-W, Kruskal-Wallis; REV, revision anterior cruciate ligament reconstruction.

[b] Months to revision surgery: mean ± SD, 50 ± 40; median (range), 36 (9-228).

[c] Pairwise (overall $\boldsymbol{P} < \mathbf{.017}$): HAM-BPTB: $P = .88$, HAM-REV: $\boldsymbol{P} = \mathbf{.01}$, BPTB-REV: $\boldsymbol{P} = \mathbf{.008}$.

RESULTS

All of the primary ACL reconstructions were performed with the anteromedial portal approach. Within the study period, 137 patients were reviewed for revision surgery, of whom 6 were excluded from our study because of a ruptured graft and 14 were excluded because of multiple revisions. The final total of included revisions was 117 cases (REV group). Within the study period for primary ACL reconstruction, 100 cases of reconstruction with a hamstring graft (HAM group) and 91 cases of reconstruction with a BPTB graft (BPTB group) met the inclusion criteria.

There were statistically significant differences in the distribution of sexes between the 3 groups, with more female patients in the REV group (62%) compared with the HAM (45%; $P = .01$) and BPTB (44%; $P = .008$) groups. There was no difference between laterality and age between groups (Table 2).

Grid Assessment

In both the pairwise comparisons of grid measurements and in the rates of anatomic versus nonanatomic placement, there were significant differences in the femoral deep-shallow measurement between the HAM and BPTB groups and between the HAM and REV groups ($P < .001$ for both), in which the mean graft placement in the REV group was shallower than in the HAM and BPTB groups (31% vs 24% and 28%, respectively). The nonanatomic rate in the HAM group was significantly worse than in the BPTB and REV groups ($P \leq .002$ for both) (55% vs 20% and 34%, respectively). In the femoral high-low direction, for both the measurement and the rate of anatomic placement, there were significant differences between the HAM and REV groups and between the BPTB and REV groups ($P < .001$ for all). A significant difference was seen in the tibial measurement between the HAM and REV groups but not in the comparison of the rate of tibial nonanatomic versus anatomic placement. The rate of anatomic placement according

TABLE 3
Results of Grid Measurements[a]

	Primary HAM (n = 100)[b]	Primary BPTB (n = 91)	REV (n = 117)	*P* Value
Femoral deep-shallow, %				**<.001**[c] (K-W)
Mean ± SD	24 ± 7	28 ± 5	31 ± 8	
Median (range)	24 (7-49)	28 (18-47)	30 (11-56)	
Graft placement, n (%)				**<.001**[d] (χ^2)
Nonanatomic	55 (55)	18 (20)	40 (34)	
Anatomic	45 (45)	73 (80)	77 (66)	
Femoral high-low, %				**<.001**[e] (K-W)
Mean ± SD	28 ± 9	30 ± 7	20 ± 14	
Median (range)	29 (0-43)	30 (18-49)	20 (1-65)	
Graft placement, n (%)				**<.001**[f] (χ^2)
Nonanatomic	45 (45)	36 (40)	84 (72)	
Anatomic	55 (55)	55 (60)	33 (28)	
Tibial, %				**.010**[g] (ANOVA)
Mean ± SD	46 ± 6	47 ± 4	49 ± 8	
Median (range)	46 (34-61)	48 (35-60)	48 (24-69)	
Graft placement, n (%)				.138 (χ^2)
Nonanatomic	57 (58)	53 (58)	81 (69)	
Anatomic	42 (42)	38 (42)	36 (31)	
Combined grid assessment, n (%)				**<.001**[h] (χ^2)
Nonanatomic	10 (10)	4 (4)	20 (17)	
Partial anatomic	79 (80)	67 (74)	89 (76)	
Anatomic	10 (10)	20 (22)	8 (7)	

[a] Bolded *P* values indicate a statistically significant difference between groups ($P < .05$). ANOVA, analysis of variance; BPTB, bone–patellar tendon–bone; HAM, hamstring; K-W, Kruskal-Wallis; REV, revision anterior cruciate ligament reconstruction.

[b] n = 99 for tibial and combined grid assessment.

[c] Pairwise (overall **$P < .017$**): HAM-BPTB: **$P < .001$**, HAM-REV: **$P < .001$**, BPTB-REV: $P = .11$.

[d] Pairwise (overall **$P < .008$**): HAM-BPTB: **$P < .001$**, HAM-REV: **$P = .002$**, BPTB-REV: $P = .22$.

[e] Pairwise (overall **$P < .017$**): HAM-BPTB: $P = .413$, HAM-REV: **$P < .001$**, BPTB-REV: **$P < .001$**.

[f] Pairwise (overall **$P < .008$**): HAM-BPTB: $P = .447$, HAM-REV: **$P < .001$**, BPTB-REV: **$P < .001$**.

[g] Pairwise (overall **$P < .017$**): HAM-BPTB: $P = .620$, HAM-REV: **$P = .008$**, BPTB-REV: $P = .301$.

[h] Pairwise (overall **$P < .005$**): HAM-BPTB: $P < .09$, HAM-REV: $P = .412$, BPTB-REV: **$P < .001$**.

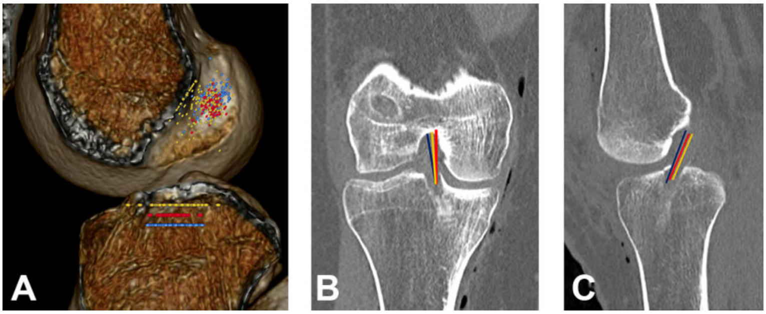

Figure 2. (A) Distribution of femoral and tibial tunnel placement between the 3 study groups. Differences in the mean (B) coronal angle and (C) sagittal angle between the 3 study groups. Blue line = hamstring; red line = bone–patellar tendon–bone; yellow line = revision anterior cruciate ligament reconstruction.

to the combined grid assessment (anatomic, partial anatomic, and nonanatomic) differed significantly between the BPTB and REV groups but not between the HAM and BPTB groups or between the HAM and REV groups (Table 3 and Figure 2A).

Angle Assessment

The coronal angle measurement differed significantly between the HAM and BPTB groups ($P < .001$) and between the BPTB and REV groups ($P = .010$), while the rate of

TABLE 4
Results of Angle Measurements[a]

	Primary HAM (n = 100)[b]	Primary BPTB (n = 91)[c]	REV (n = 117)	*P* Value
Coronal angle, deg				**<.001**[d] (K-W)
Mean ± SD	72 ± 5	76 ± 5	74 ± 7	
Median (range)	72 (59-86)	77 (53-86)	75 (51-87)	
Graft placement, n (%)				**<.001**[e] (χ^2)
Nonanatomic	44 (44)	61 (68)	81 (69)	
Anatomic	56 (56)	29 (32)	36 (30)	
Sagittal angle, deg				.019 (K-W)
Mean ± SD	65 ± 7	63 ± 5	62 ± 8	
Median (range)	64 (51-89)	62 (53-74)	63 (27-82)	
Graft placement, n (%)				**.011**[f] (χ^2)
Nonanatomic	83 (83)	67 (74)	76 (65)	
Anatomic	17 (17)	24 (26)	41 (35)	
Combined angle assessment, n (%)				.137 (χ^2)
Nonanatomic	37 (37)	49 (54)	55 (47)	
Partial anatomic	52 (52)	31 (34)	47 (40)	
Anatomic	11 (11)	11 (12)	15 (13)	

[a] Bolded P values indicate a statistically significant difference between groups ($P < .05$). BPTB, bone–patellar tendon–bone; HAM, hamstring; K-W, Kruskal-Wallis; REV, revision anterior cruciate ligament reconstruction.
[b] n = 100 for combined angle assessment.
[c] n = 91 for coronal angle and combined angle assessment.
[d] Pairwise (overall ***P*** **< .017**): HAM-BPTB: ***P*** **< .001**, HAM-REV: *P* = .061, BPTB-REV: ***P*** **= .010**.
[e] Pairwise (overall ***P*** **< .008**): HAM-BPTB: ***P*** **= .001**, HAM-REV: ***P*** **< .001**, BPTB-REV: *P* = .823.
[f] Pairwise (overall ***P*** **< .008**): HAM-BPTB: *P* = .115, HAM-REV: ***P*** **= .003**, BPTB-REV: *P* = .181.

TABLE 5
Comparison of Grid Versus Angle Measurements[a]

	Primary HAM (n = 100)[b]	Primary BPTB (n = 91)[c]	REV (n = 117)
Grid vs angle assessment (95% CI)			
Overall across groups		0.033 (–0.36 to 0.10)	
Weighted kappa within group	0.009 (–0.11 to 0.127)	0.065 (–0.39 to 0.169)	0.041 (–0.74 to 0.156)
Pairwise kappa			
HAM-BPTB		0.036 (–0.046 to 0.117)	
HAM-REV		0.032 (–0.52 to 0.115)	
BPTB-REV		0.046 (–0.035 to 0.128)	

[a] BPTB, bone–patellar tendon–bone; HAM, hamstring; REV, revision anterior cruciate ligament reconstruction.
[b] n = 99 for combined angle assessment.
[c] n = 91 for coronal angle and combined angle assessment.

anatomic versus nonanatomic placement differed between the HAM and BPTB groups ($P = .001$) and between the HAM and REV groups ($P < .001$). The sagittal angle measurement did not differ between the 3 groups, but the rate of anatomic placement differed significantly between the BPTB and REV groups. The combined angle assessment (anatomic, partial anatomic, and nonanatomic) did not differ significantly between groups (Table 4 and Figure 2, B and C).

Agreement Between Measurement Methods

The overall agreement, assessed with the weighted kappa, between the grid and angle measurements to identify anatomic, partial anatomic, or nonanatomic was low. The pairwise agreement between groups was also low (Table 5).

Comparison of Results Between Surgical Approaches

Within the REV group, we further examined the differences between the transtibial and anteromedial portal approaches. In the femoral deep-shallow measurement and coronal angle measurement, there were no differences. In the femoral high-low measurement, tibial measurement, and sagittal angle measurement, there were significant differences ($P > .001$, $P = .001$, and $P = .002$, respectively). The rate of anatomic graft placement according to the combined grid assessment also differed between the surgical approaches. However, no differences were observed in the combined angle assessment with regard to anatomic versus nonanatomic placement (Table 3 and Figure 3). The agreement, assessed with the

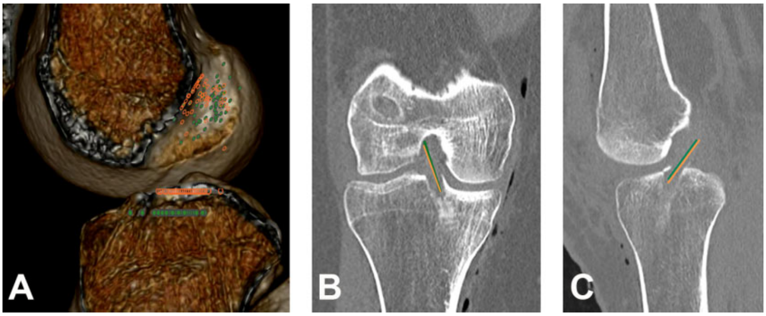

Figure 3. (A) Distribution of femoral and tibial tunnel placement in revision anterior cruciate ligament reconstruction. Differences in the mean (B) coronal angle and (C) sagittal angle in the revision group. Green line = anteromedial portal approach; orange line = transtibial approach.

weighted kappa, between the grid and angle measurements to identify anatomic, partial anatomic, or nonanatomic placement was low in both the transtibial and anteromedial portal approach subgroups (Table 6).

DISCUSSION

The purpose of our study was to compare grid measurements and angle measurements with regard to the anatomic placement of grafts after ACL reconstruction. The major finding of our study was the lack of agreement between the 2 measurement methods in identifying anatomic graft placement.

Technical errors, such as nonanatomic graft placement, are considered a common cause of graft failure, so one would expect the rate of nonanatomic placement to be higher in patients with failed ACL grafts.[28,30] The literature suggests that femoral tunnel placement is more important for a favorable outcome compared with tibial tunnel placement.[6,28] The results of the grid assessment confirmed this assumption, with no difference between the 3 groups in tibial tunnel placement but a difference in the overall femoral tunnel placement. Placement in the femoral deep-shallow direction did not differ significantly between the BPTB and REV groups. This may be explained by the fact that the tunnel aperture on CT in the BPTB group may not represent the true center of the graft, as the bony attachment is a few millimeters thick, thus slightly influencing the grid measurement (Figure 4). Surprisingly, the rate of nonanatomic placement in the femoral deep-shallow direction was highest in the HAM group. In the femoral high-low direction, the nonanatomic placement rate was significantly higher in the REV group compared with the HAM and BPTB groups, as was to be expected. This finding might indicate that anatomic placement in the high-low direction in the femur is more important for outcomes than anatomic placement in the deep-shallow direction and that the surgical technique should aim to avoid nonanatomic placement in the high-low direction.

No difference in the groups was observed in tibial graft placement. Regarding overall nonanatomic graft placement, the highest rate was observed in the REV group (17% in REV vs 10% in HAM and 4% in BPTB). Pairwise comparisons showed no difference between the HAM and BPTB groups, as was expected. However, there was also no difference between the HAM and REV groups. This may be explained by the high rate of nonanatomic placement in the HAM group in the femoral deep-shallow direction, influencing the overall anatomic rate in the grid measurements. There was a significant difference in the combined grid assessment between the BPTB and REV groups.

Angle measurements for assessing postoperative graft placement are often recommended in the literature.[12,13,30,47] In the coronal measurements, we found significant differences between the HAM and BPTB groups and between the BPTB and REV groups. In general, in the BPTB group, we observed a steeper (nonanatomic) coronal angle than in the other groups. The reason for this may again be the bony attachment of the BPTB graft, which when placed caudally in the tunnel will cause a more cranial exit for the tendon, causing it to run a steep slope in the coronal view. There were no differences in the sagittal angle measurements or in the combined angle assessment for anatomic placement between groups. The highest rate of overall nonanatomic placement was seen in the BPTB group (54% in BPTB vs 37% in HAM and 47% in REV).

The 2 grid and the angle methods yielded significantly different rates of nonanatomic placement in the same patients. The explanation for this is a fundamental difference in measurement methods. The angle measurements were devised in the era of the transtibial surgical technique. Technical failure with the transtibial technique was related to "too high" placement of the femoral tunnel and was easily assessed on sagittal images, and a too steep graft angle was introduced as an imaging criterion.[3,39,45] However, it is known that flexion affects the ACL angle in the sagittal plane. A study showed that the sagittal angle of the ACL ranges from 45° to 20° with increasing knee joint flexion.[16] This factor affects the measurements in a clinical setting, as even the slightest flexion during CT or MRI will

TABLE 6
Comparison of Transtibial Versus Anteromedial Portal Approach Within REV Group[a]

	Anteromedial Portal (n = 66)	Transtibial (n = 51)	*P* Value
Femoral deep-shallow, %			.611 (K-W)
Mean ± SD	31 ± 9	31 ± 7	
Median (range)	31 (11 to 56)	30 (20 to 51)	
Graft placement, n (%)			.864 (χ^2)
Nonanatomic	23 (35)	17 (33)	
Anatomic	43 (65)	34 (67)	
Femoral high-low, %			>**.001** (K-W)
Mean ± SD	24 ± 12	14 ± 15	
Median (range)	25 (0 to 45)	12 (–1 to 65)	
Graft placement, n (%)			**.001** (χ^2)
Nonanatomic	39 (59)	45 (88)	
Anatomic	27 (41)	6 (12)	
Tibial, %			**.001** (K-W)
Mean ± SD	46 ± 8	52 ± 7	
Median (range)	47 (24 to 61)	52 (38 to 69)	
Graft placement, n (%)			**.021** (χ^2)
Nonanatomic	40 (60)	41 (80)	
Anatomic	26 (40)	10 (20)	
Combined grid assessment, n (%)			**.004** (χ^2)
Nonanatomic	10 (15)	10 (20)	
Partial anatomic	48 (73)	41 (80)	
Anatomic	8 (12)	0 (0)	
Coronal angle, deg			.398 (K-W)
Mean ± SD	73 ± 7	74 ± 6	
Median (range)	75 (53 to 87)	75 (52 to 86)	
Graft placement, n (%)			.082 (χ^2)
Nonanatomic	50 (75)	31 (61)	
Anatomic	16 (25)	20 (39)	
Sagittal angle, deg			**.002** (K-W)
Mean ± SD	60 ± 8	65 ± 8	
Median (range)	60 (27 to 73)	65 (49 to 82)	
Graft placement, n (%)			**.022** (χ^2)
Nonanatomic	37 (56)	39 (76)	
Anatomic	29 (44)	12 (34)	
Combined angle assessment, n (%)			.639 (χ^2)
Nonanatomic	29 (44)	26 (51)	
Partial anatomic	29 (44)	18 (35)	
Anatomic	8 (12)	7 (14)	
Grid vs angle assessment (95% CI)			
Weighted kappa within approach	0.074 (–0.82 to 0.23)	–0.006 (–0.86 to 0.163)	
Overall across both approaches	0.041 (–0.74 to 0.156)		

[a] Bolded *P* values indicate a statistically significant difference between approaches ($P < .05$). K-W, Kruskal-Wallis; REV, revision anterior cruciate ligament reconstruction.

change the angle of the ACL graft. Furthermore, even if the angle is correct, the placement may still be faulty if the graft is placed too anteriorly or too posteriorly.[32] The grid measurements were devised so that the measurements in the femur and tibia are independent of the degree of knee flexion. Thus, methodological discrepancies relating to knee flexion may explain the poor agreement between the 2 measurement methods. CT is the more robust modality if one chooses to measure graft placement.

Considering revision ACL reconstruction, previous studies have shown that the anteromedial portal technique yields higher rates of anatomic placement compared with the transtibial technique.[39,45] The transtibial technique is known to cause too high placement in the grid measurements, which was confirmed in our study.[17,43] The combined grid assessment differed significantly between the surgical techniques (P = .004), with no anatomic cases in the transtibial technique group. In addition, the sagittal angle differed between the surgical techniques (P = .002), while the coronal angle measurements and combined angle assessment did not differ within the REV group. Thus, the lack of agreement between the grid and angle measurement methods was also observed within the REV group.

The clinical usefulness of (1) postoperative CT in primary reconstruction to improve a surgeon's learning curve and to serve as a baseline examination and (2) preoperative CT for planning revision surgery has been established.[20,40,49] MRI undoubtedly has a role in planning revision surgery for

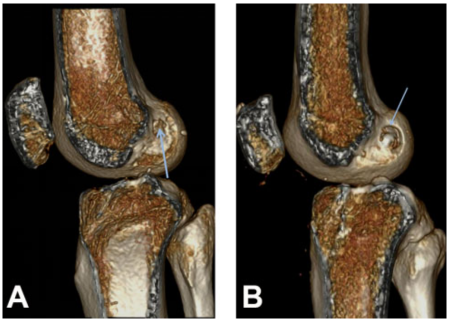

Figure 4. (A) The graft tunnel aperture in reconstruction with a hamstring graft; the aperture center is the same as the graft center (arrow). (B) The graft tunnel aperture looks larger in reconstruction with a bone–patellar tendon–bone graft, but the graft is actually placed slightly deeper than the aperture center (arrow).

identifying recurrent ACL graft ruptures and missed concomitant lesions in other ligaments, menisci, or articular cartilage.[2,22,37] Ducouret et al[10] found that angle measurements did not differ between CT and MRI and suggested that MRI can be used to replace CT for identifying tunnel placement. Grasso et al[14] performed grid measurements on CT and MRI; however, the measurements were conducted on computer-generated models after adding digitized information acquired during revision surgery, not on actual CT or MRI scans. In our view, the clinical usefulness of angle and grid measurements on MRI has not been sufficiently established to date. No studies have examined the clinical benefit of angle measurements in reconstruction using the anteromedial portal technique. Furthermore, our results show that graft angles do not correlate with grid measurements, and they overestimate nonanatomic placement in ACL reconstruction with the anteromedial portal technique. Therefore, MRI currently cannot replace CT to identify anatomic graft placement in ACL reconstruction.

This study highlights the problems that arise because of the lack of consensus on which measurement method to use when assessing ACL graft placement. Several studies have compared graft placement between the transtibial and anteromedial portal techniques, but the studies used several different measurement methods to assess graft placement.[7,21,26,46] This makes a comparison of surgical results difficult, as we now know that the reported rate of nonanatomic tunnel placement varies depending on the method used.

This is the first study comparing grid and angle measurement methods after ACL reconstruction. We have laid bare the major discrepancy between these methods. As previous studies have shown low interrater and intrarater variability in both methods used in our study, we did not assess interrater variability and do not consider this a major limitation.[18,23] The normal ranges of grid and angle measurements are based on a relatively high number of anatomic and imaging cases (>200-300).[3,5,33,36] This limits bias in identifying the appropriate cutoff in our study. As the purpose of our study was to compare 2 methods used for assessing anatomic tunnel placement on imaging, we did not correlate graft placement with clinical or functional assessments of graft laxity and cannot determine whether nonanatomic tunnel placement affects graft laxity.

CONCLUSION

The agreement between angle and grid measurements to identify anatomic ACL graft placement was very low. Compared with grid measurements, angle measurements tended to overestimate nonanatomic tunnel placement. Grid measurements were better in identifying malpositioned ACL grafts. Orthopaedic surgeons and radiologists ought to be aware of the pitfalls of the angle measurement method when assessing ACL graft placement on imaging.

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